# Adaptation to climate change
# In silico ideotyping

# Introduction



Process-based crop models can be used to **support breeding** programs (Boote et al. 2001) via the **definition and test** of in silico **ideotypes**.

Assumption:

- **Close relationship** between model **parameters** and plant **traits** (e.g., Semenov and Stratonovitch 2013).

Possible use of in silico ideotypes:

- **A priori** to **identify traits/complex of genes** on which breeder should focus (Herndl et al. 2007);
- **A posteriori** to **test "modified genotypes"** under different environmental conditions and over long-term periods (Hammer et al. 2002).

# Introduction

- **Parameters**
  - ✓ They describe morphological or physiological features of a species or of a genotype (genetic coefficients) (e.g., specific leaf area) — G
- **Events**
  - ✓ Management practices (e.g., sowing) — M
- **Variables**
  - ✓ **Driving** variables (e.g., global solar radiation) — E
  - ✓ **Rate** variables (e.g., aboveground biomass increase during the time step)
  - ✓ **State** variables (e.g., aboveground biomass at time t, leaf area index at time t, plant height at time t)

  Rate and State variables: G × E × M

# Introduction

Limits:

- **Absence** of explicit **representation of the genetics** behind traits (Hammer et al. 2002)
- …Crop models were **not developed to explicitly target ideotyping** studies… and are simplified representation of systems.
- **Some processes** are often **not simulated**, and sometimes they have a large impact on yields and farmers' income
- In some cases **parameters** do **not** have **clear relationships with traits**… and some traits breeders are working on do not have clear relationships with parameters

  ✓ Possible **discrepancies** between **in silico** improved varieties and their **in vivo** realizations.

  ✓ **Traits** for ideotyping are often **selected** according to "what **the model** can do"

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# Introduction



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**Trait-based model development to support breeding programs. A case study for salt tolerance and rice**

Livia Paleari[1], Ermes Movedi[1] & Roberto Confalonieri[2]

- In some cases **parameters** do **not** have **clear relationships with traits**… and some traits breeders are working on do not have clear relationships with parameters

  - ✓ Possible **discrepancies** between **in silico** improved varieties and their **in vivo** realizations.
  - ✓ **Traits** for ideotyping are often **selected** according to "what **the model** can do"

# Objectives

1. Identifying **key traits** (pathways?) **breeders could focus on** in the coming years
   - ✓ Canopy structure and photosynthetic efficiency
   - ✓ Resistance to fungal pathogens
   - ✓ Tolerance for pre-flowering and flowering temperature shocks inducing sterility
   - ✓ Grain quality
2. **Defining** ideotypes and **testing** their performance **at district level**
3. Evaluate **whether it is worth undertaking breeding pathways** with respect to
   - ✓ **spatial heterogeneity** (also among districts) and
   - ✓ **changes in climate** (breeders target something in the coming 15-25 years) (Zheng et al. 2012)

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# Objective 1: Methods

Sistemi Colturali

## Which breeding pathway?

Received: 29 October 2016 | Revised: 24 February 2017 | Accepted: 27 February 2017

DOI: 10.1111/gcb.13682

PRIMARY RESEARCH ARTICLE

WILEY Global Change Biology

# Surfing parameter hyperspaces under climate change scenarios to design future rice ideotypes

Livia Paleari[1] | Ermes Movedi[1] | Giovanni Cappelli[2*] | Lloyd T. Wilson[3] | Roberto Confalonieri[4]

# Objective 1: Methods

## Which breeding pathway?

- **Sensitivity analysis**:
  - ✓ **Objective**: quantifying the role of uncertain input factors in explaining the variability of model outputs.
  - ✓ It is often used to **identify** the model **parameters** that have the **largest effect** on model outputs.
  - ✓ **Traditionally**, it was used to identify the parameters on which **concentrate the efforts** for parameterization.
- The first idea could be:
  - ✓ **Dividing** the biophysical **range** of each input in a certain number of **regular intervals**.
  - ✓ For each input, running simulations assigning to the input the value of each interval.
    - *N*-dimensional grids (*N* being the number of inputs)

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# Objective 1: Methods

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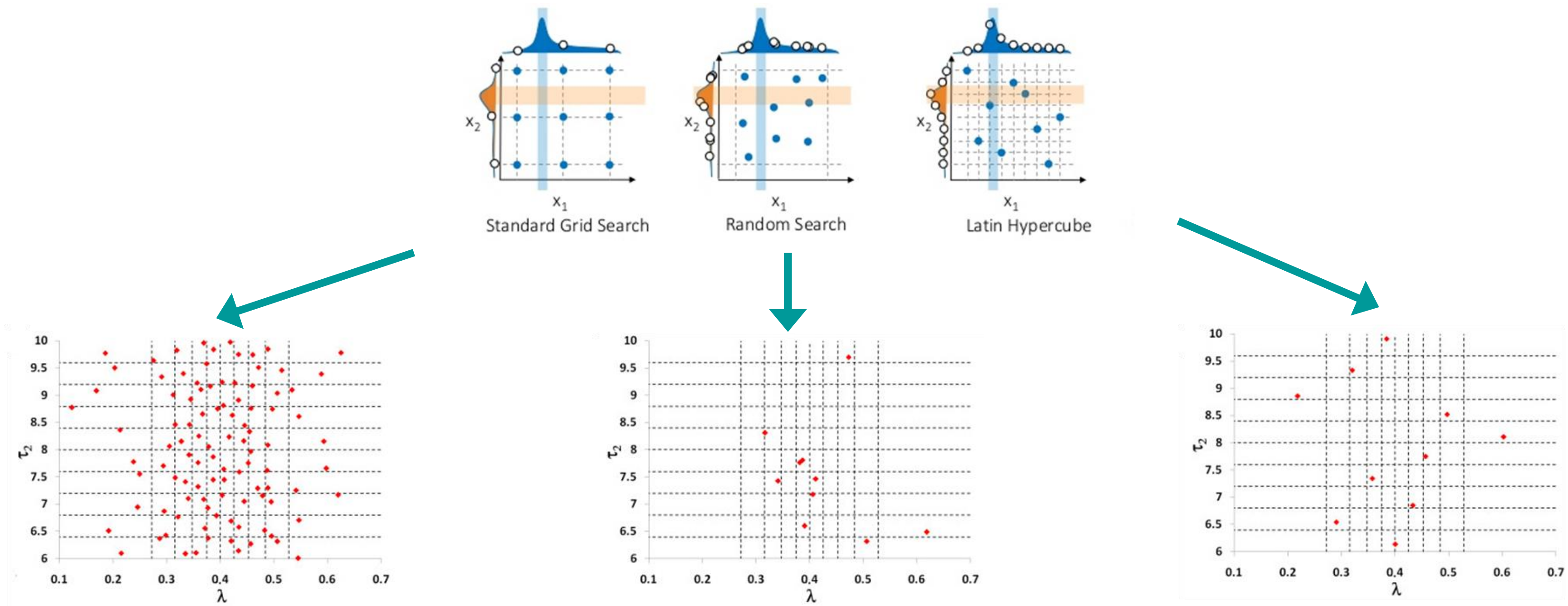
## Which breeding pathway?

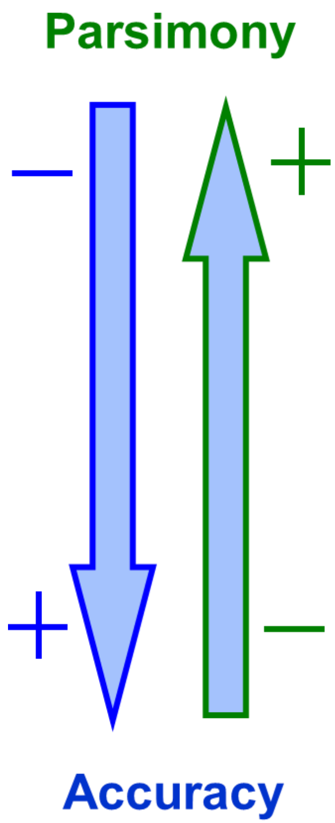
- **Sensitivity analysis**:
  - ✓ **Problems**:
    - **How many intervals**? (response functions often discontinuous)
    - **If many** intervals and ***N*-dimensional grids** → the number of simulations can be **huge**



# Objective 1: Methods

## Which breeding pathway?

- **Sensitivity analysis**:
  - ✓ **Sensitivity analysis methods** were proposed to efficiently **explore** the parameter **hyperspace**




- **Screening** methods (mean and standard deviations of incremental ratios)
  - ✓ Morris
- **Regression-based** methods
  - ✓ Latin Hypercube Sampling, random…
- **Variance-based** methods
  - ✓ Sobol'
  - ✓ Fourier Amplitude Sensitivity test (FAST)
  - ✓ Extended FAST

# Objective 1: Methods

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## Which breeding pathway?

- **Sensitivity analysis**:
  - ✓ Method: Sobol' (1993) – Total order effect
  - ✓ Method parameterization (Confalonieri et al. 2010):
    - Lowest value of $q \mid M > (\gamma \cdot n)$
    - with:
      - $M = 2^{q+3}\,(2n + 2)$
      - $q = \{1, 2, 3, \ldots.\ Q\}$
      - $\gamma$ = model runs for each parameter (500)
      - $n$ = number of factors in the sensitivity analysis
  - ✓ **Variable analyzed**: Value ha$^{-1}$ $\rightarrow Y_L \cdot V - Y_L \cdot [(1\text{-}HR)+C] \cdot V/2$
    - $Y_L$ (t ha$^{-1}$): yield limited by biotic/abiotic factors
    - $V$ (euros t$^{-1}$): value of entire and non chalky grains
    - $HR$ (-, 0-1): head rice yield
    - $C$ (-, 0-1): chalkiness

More than 6.6 million simulations

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# Objective 1: Methods

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## Which breeding pathway?

- **Modelling solution**: WARM (e.g. Confalonieri et al. 2009)
  - ✓ **Growth and development**, micrometeorology:
    - Parameterization: Li et al. 2015; Confalonieri et al. 2009
  - ✓ **Cold/heat shocks** before and around flowering:
    - Parameterization: EU FP7 MODEXTREME
  - ✓ Leaf and neck **blast**:
    - Parameterization: Paleari et al. 2015; Bregaglio et al. 2016
  - ✓ **Grain quality**
    - Parameterization: Cappelli et al. 2014

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# Objective 1: Methods

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## Which breeding pathway?

- **Parameters/traits**:

| Parameter | Relevance for breeding (e.g.) | Distribution | Source |
|---|---|---|---|
| Radiation use efficiency (RUE; g $MJ^{-1}$) | Peng et al. 2008; Dingkhun et al. 2015 | Normal (m 2.7; s 0.1) | Kiniry et al. 2001; Boschetti et al. 2006 |
| Extinction coefficient (k; -) | Peng et al. 2008; Sheehy et al. 2013 | Normal (m 0.47; s 0.04) | Casanova et al. 1998; Dingkhun et al. 1999; Kiniry et al. 2001; Boschetti et al. 2006 |
| SLA at emergence (SLAini; $m^2$ $kg^{-1}$) | Peng et al. 2008; Kush et al. 2012 | Normal (m 41.6; s 5.9) | Kropff et al. 1994; Ash et al. 1998; Confalonieri and Bocchi 2005 |
| SLA at tillering (SLAtill; $m^2$ $kg^{-1}$) | Ashikari et al. 2005; Peng et al. 2008; | Normal (m 28.7; s 3.9) | Laza et al. 2015; Boschetti et al. 2006 |
| Threshold T for cold sterility (T-ColdSter; °C) | Suh et al. 2010; Sanchez et al. 2014 | Normal (temp. m 13.5; s 1.4) (trop. M 16.6; s 1.2) | Satake 1969; Da Cruz et al. 2006; Farrel et al. 2006; Thakur et al. 2010; Deng et al. 2011; Dreni et al. 2012; National Rice Authority |
| Threshold T for heat sterility (T-HeatSter; °C) | Matsui 2009; Jagadish et al. 2010 | Normal (m 34.4; s 1.5) | Yoshida 1981; Satake 1995; Nakagawa et al. 2002; Matsui 2009; Ishimaru et al. 2010; Jagadish et al. 2010; Shah et al. 2011; Maruyama et al. 2013 |
| Blast resistance (BlastRes; -; 1 to 3) | Fisher et al. 2005; Fukoka et al. 2009 | Discrete (1, 2, 3) | National Rice Authority |
| Threshold T for chalkiness (T-Chalkiness; °C) | Yamakawa et al. 2007; Usui et al. 2014 | Normal (m 26.4; s 0.9) | Wakamatsu et al. 2007; Yamakawa et al. 2007; Morita et al. 2008; Madan et al. 2012; Usui et al. 2014; Matsutomi et al. 2015 |
| Threshold T for grain breakage (T-HeadRIce; °C) | Siebenmorgen et al. 2013; Sreenivasulu et al. 2015 | Normal (m 23.9; s 2.1) | Ambardekar et al. 2011; Okada et al. 2011; Siebenmorgen et al. 2013 |

# Objective 1: Methods



## Which breeding pathway?

- Pay attention to distributions!
- Uncertainty in distributions can markedly alter the results of the analysis!

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Contents lists available at ScienceDirect

Ecological Modelling

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Sensitivity analysis of a sensitivity analysis: We are likely overlooking the impact of distributional assumptions

Livia Paleari [a], Roberto Confalonieri [b,*]

[a] University of Milan, DISAA, Cassandra lab, via Celoria 2, 20133 Milano, Italy
[b] University of Milan, DEMM, Cassandra lab, via Celoria 2, 20133 Milano, Italy

# Objective 1: Methods

## Which breeding pathway?

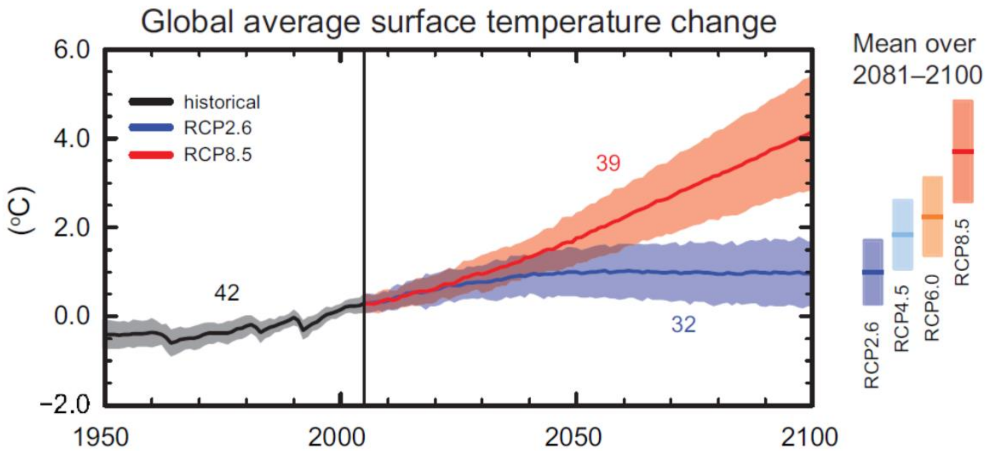
- **Sites**:

| | Los Baños | Ludhiana | Nanjing | Shizukuishi | Milan |
|---|---|---|---|---|---|
| Country | Philippines | India | China | Japan | Italy |
| Coordinates | 121°9'E, 14°6'N | 75°48'E, 30°54'N | 118°59'E, 32°56'N | 140°57'E, 39°41'N | 8°41'E, 45°4'N |
| Climate type | Tropical, humid | Subtropical, semiarid | Subtropical, semihumid | Cool temperate, humid | Temperate, semiarid |
| Mean T max (°C) | 30.2 | 29.3 | 20.3 | 13.7 | 18.2 |
| Mean T min (°C) | 23.2 | 16.8 | 12.0 | 5.1 | 8.6 |
| Mean rad (MJ $m^{-2}$) | 15.9 | 18.7 | 14.1 | 12.1 | 14.6 |
| Rainfall (mm) | 2060 | 703 | 1076 | 1557 | 698 |
| Emberger continentality (Tmax warmest month – Tmin coldest month) | 11.0 (oceanic insular) | 31.8 (semi-continental) | 32.3 (semi-continental) | 33.1 (semi-continental) | 31.1 (semi-continental) |
| SAM Aridity index (ET0-Rain)/(ED0+Rain) | 0.13 | -0.39 | -0.20 | -0.01 | -0.36 |

# Objective 1: Methods

## Which breeding pathway?

- **Climate**:
  - ✓ 20-year time frames: 1986-2005 (baseline), 2030, (2050, 2070)
  - ✓ IPCC AR5:
    - RCP2.6 (emissions peak in 2010-2020, decline later)
    - RCP8.5 (emissions continue to rise)




  - ✓ GCMs:
    - HadGEM2 (Collins et al. 2011),
    - GISS-ModelE2 (Schmidt et al. 2006)
  - ✓ Weather generator: CLIMAK (Danuso 2002)

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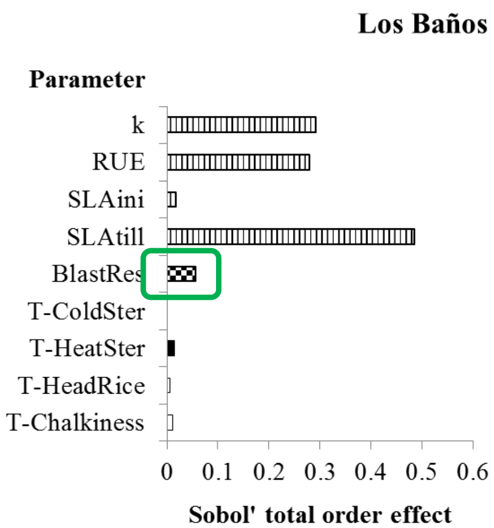
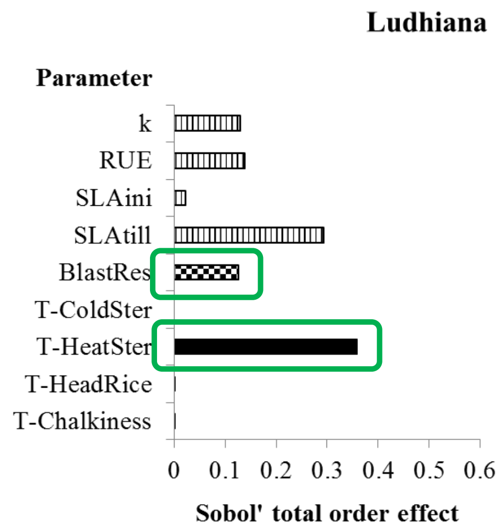
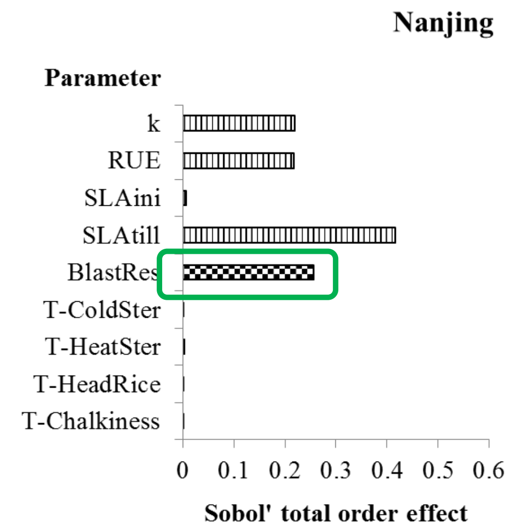
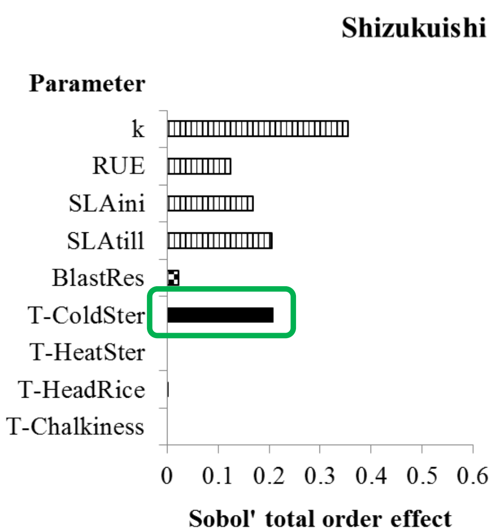
# Objective 1: Results

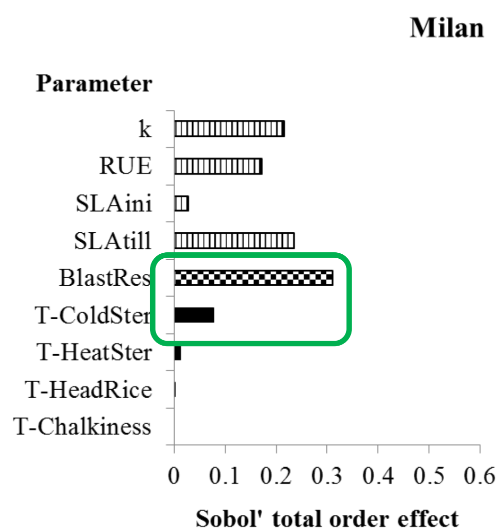
## Which breeding pathway?



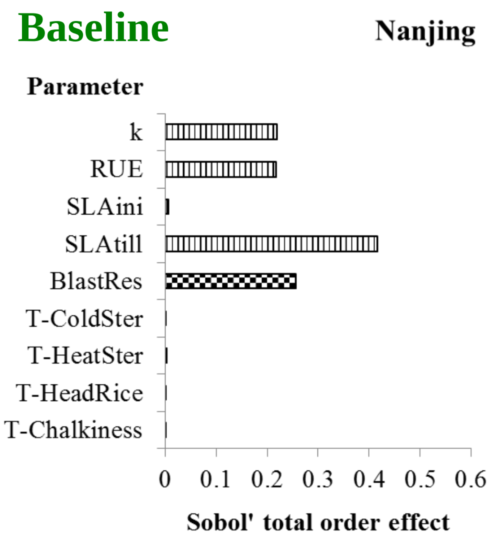



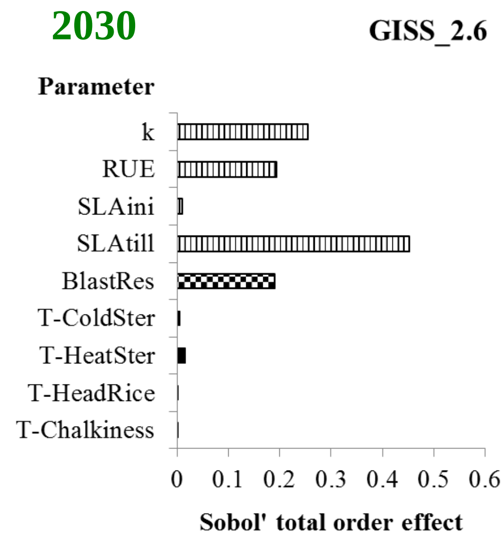




Low model sensitivity to a parameter does not mean that the impact of the process involved is negligible!

# Objective 1: Results

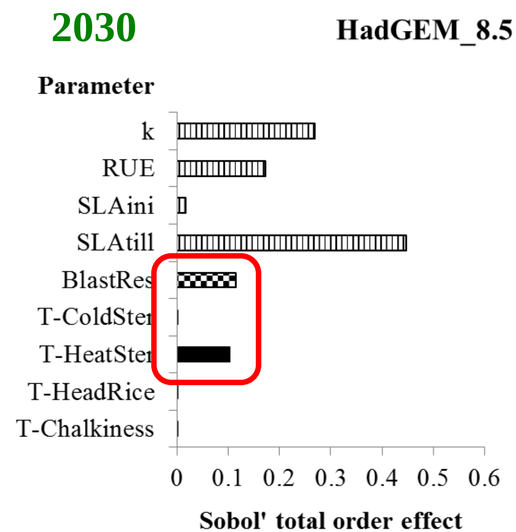
## Which breeding pathway?




Results can be totally different while changing climate scenarios, for both

- current vs “future”
- different future projections



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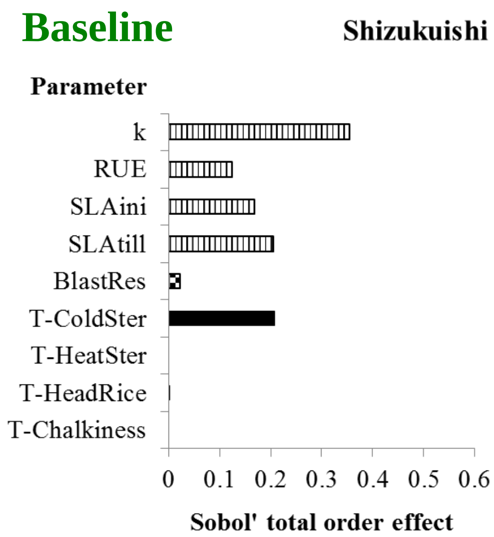


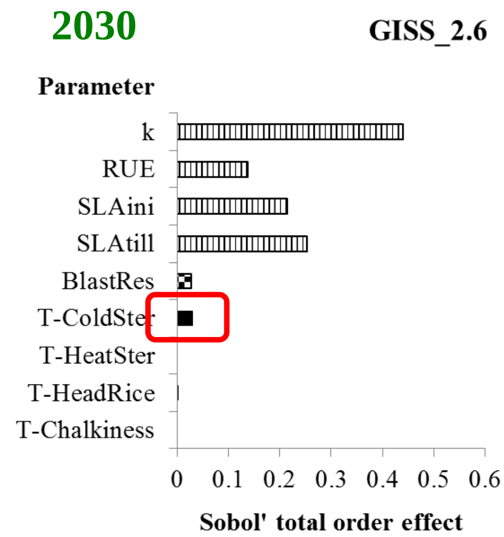


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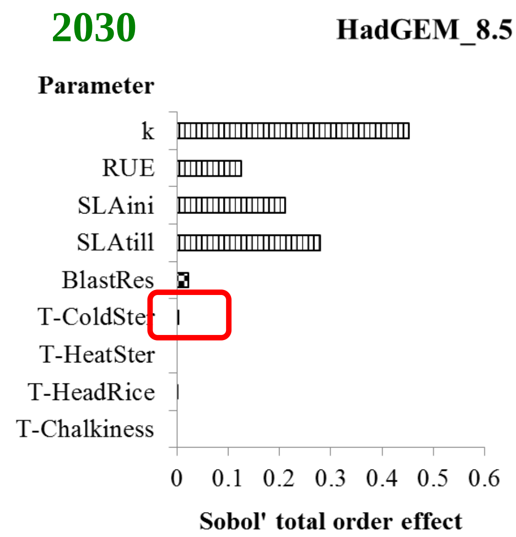

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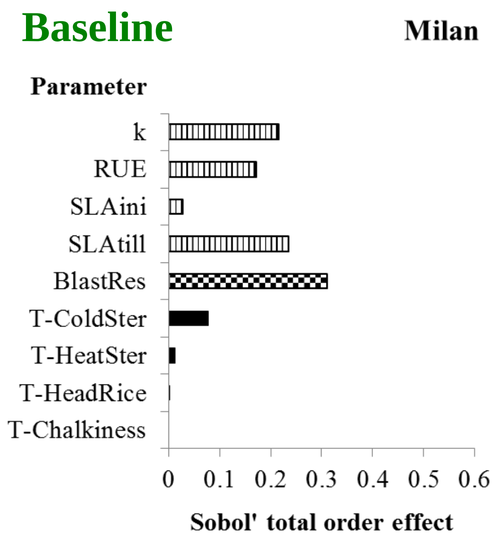
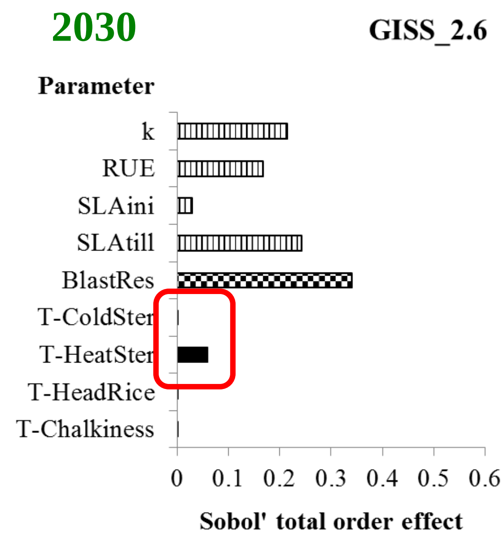
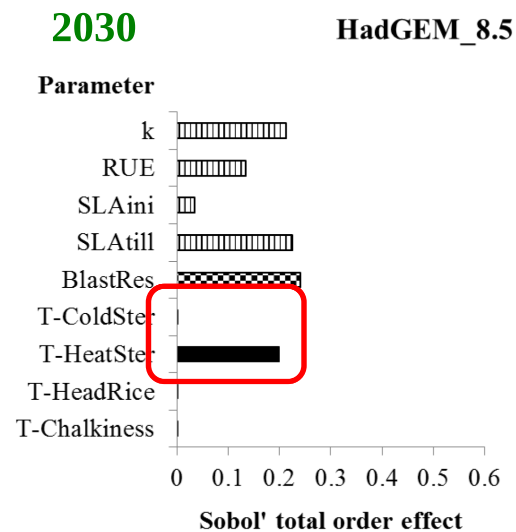
# Objective 1: Results

## Which breeding pathway?

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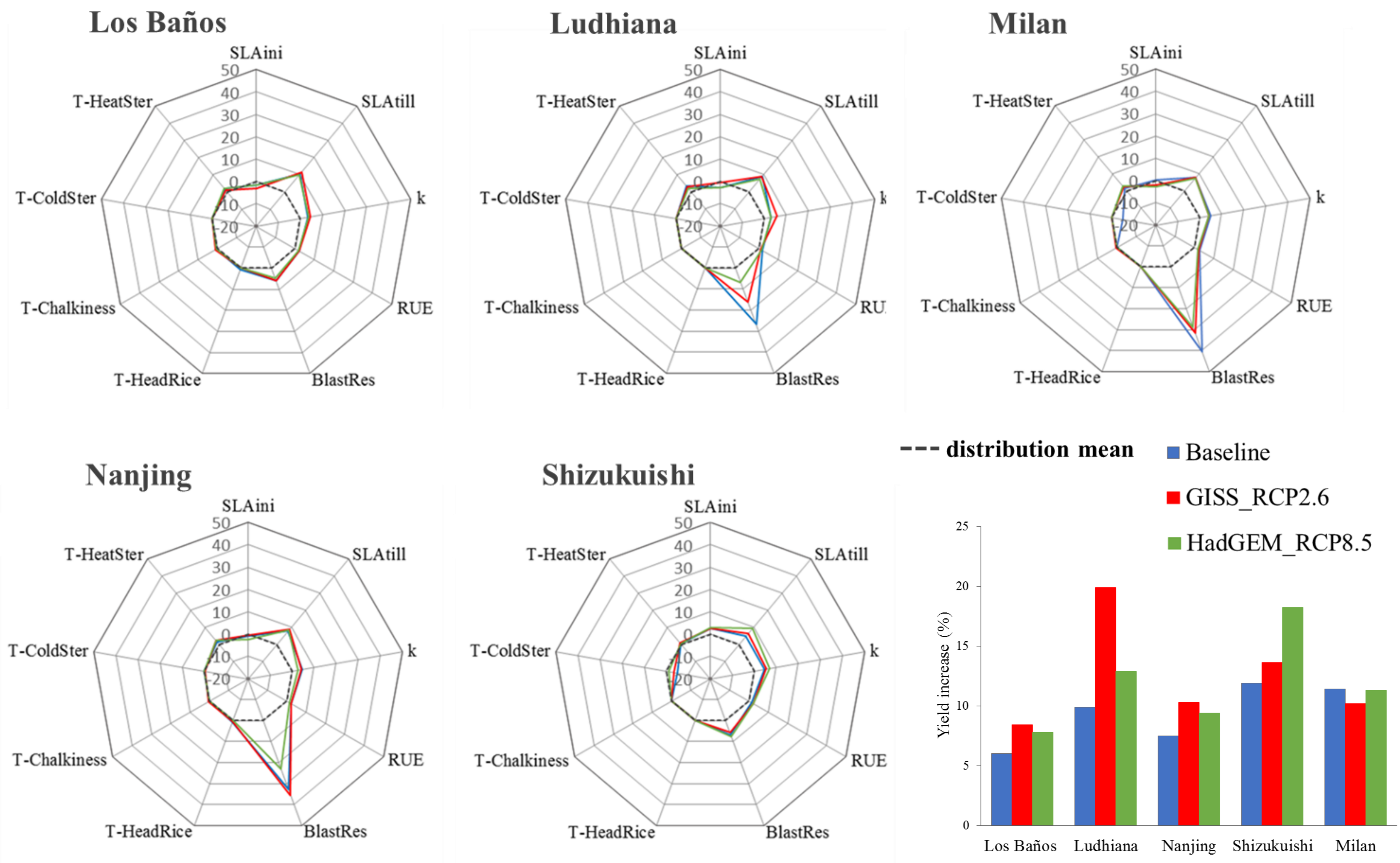
# Objective 1: Results

Sistemi Colturali

## Which breeding pathway?



# Objectives

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   - ✓ Canopy structure and photosynthetic efficiency
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# Objective 2: Methods

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## Ideotypes' performance

Climatic Change
DOI 10.1007/s10584-015-1457-4

CrossMark


**District specific, in silico evaluation of rice ideotypes improved for resistance/tolerance traits to biotic and abiotic stressors under climate change scenarios**

L. Paleari[1] · G. Cappelli[1] · S. Bregaglio[1] · M. Acutis[1] · M. Donatelli[2] · G. A. Sacchi[3] · E. Lupotto[4] · M. Boschetti[5] · G. Manfron[3,5] · R. Confalonieri[1]

Computers and Electronics in Agriculture 128 (2016) 46–49

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Application note

ISIde: A rice modelling platform for *in silico* ideotyping

CrossMark

L. Paleari[a,*], S. Bregaglio[a], G. Cappelli[a], E. Movedi[a], R. Confalonieri[b]

[a] *Università degli Studi di Milano, DiSAA, Cassandra Lab, via Celoria 2, 20133 Milan, Italy*
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# Objective 2: Methods

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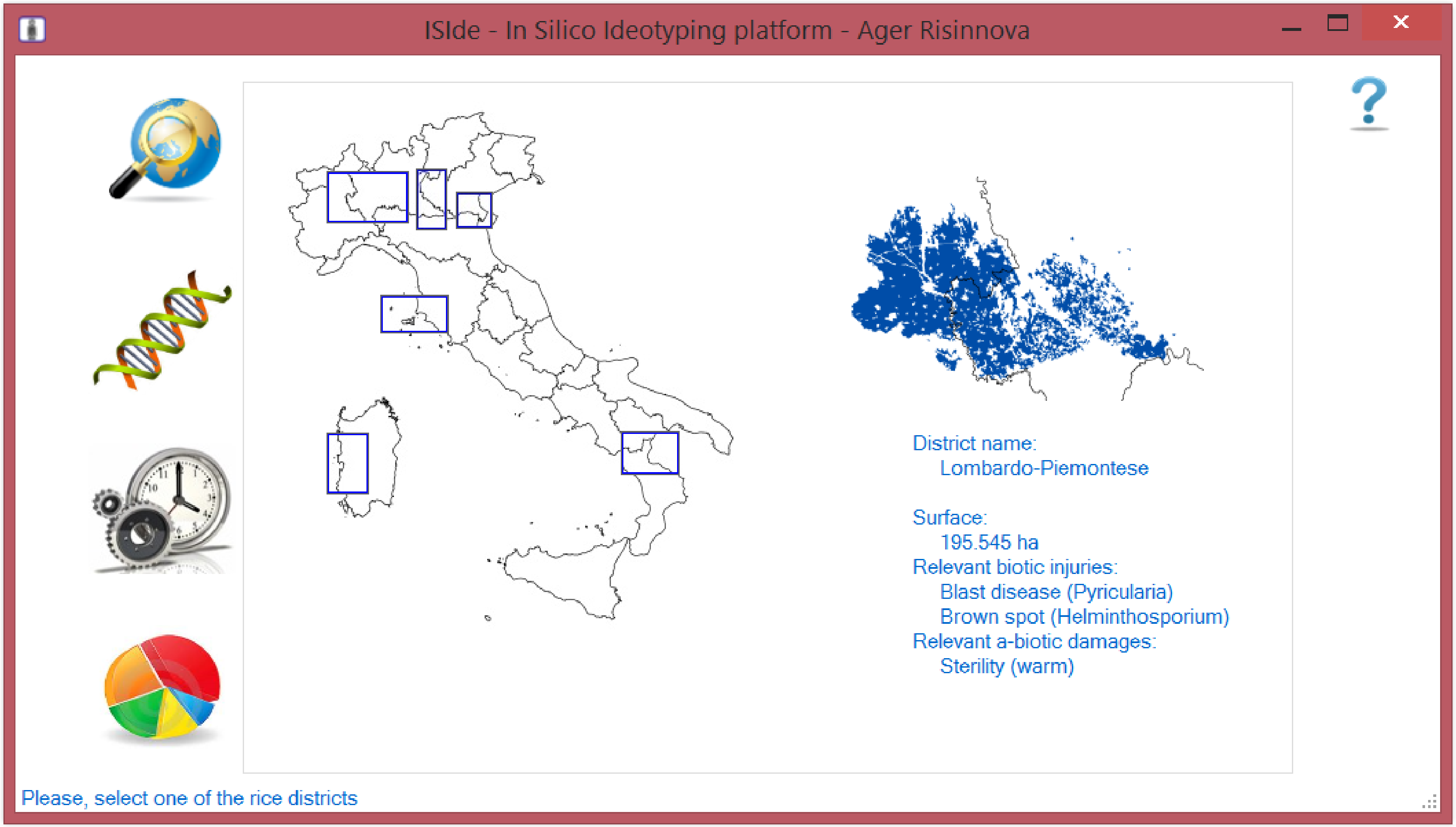
## Ideotypes' performance



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# Objective 2: Methods

## Ideotypes' performance

- **Modelling solutions**: those used for the sensitivity analysis.
- **Climate scenarios**: same time frames, RCPs (+ RCP4.5 and RCP 6.0), GCMs and weather generator used for the sensitivity analysis.
- **Rice distribution**: from European Corine Land Cover (class "Rice").
- **Sowing dates**: 10-year median from time series of MODIS 8-Day composite images (MOD09A1 at 500 m resolution) (Boschetti et al. 2009).
- **Varieties and management information**: most representative **34 varieties** in 2006-2010 – **characterized** for many traits, including **blast resistance** (National Rice Authority, www.enterisi.it).
- **Elementary simulation unit**: 5 km × 5 km grid cells.
- **Ideotype definition**: **introgression** (trait values available in current rice genotypes).

More than 2.3 million simulations

# Objective 2: Results

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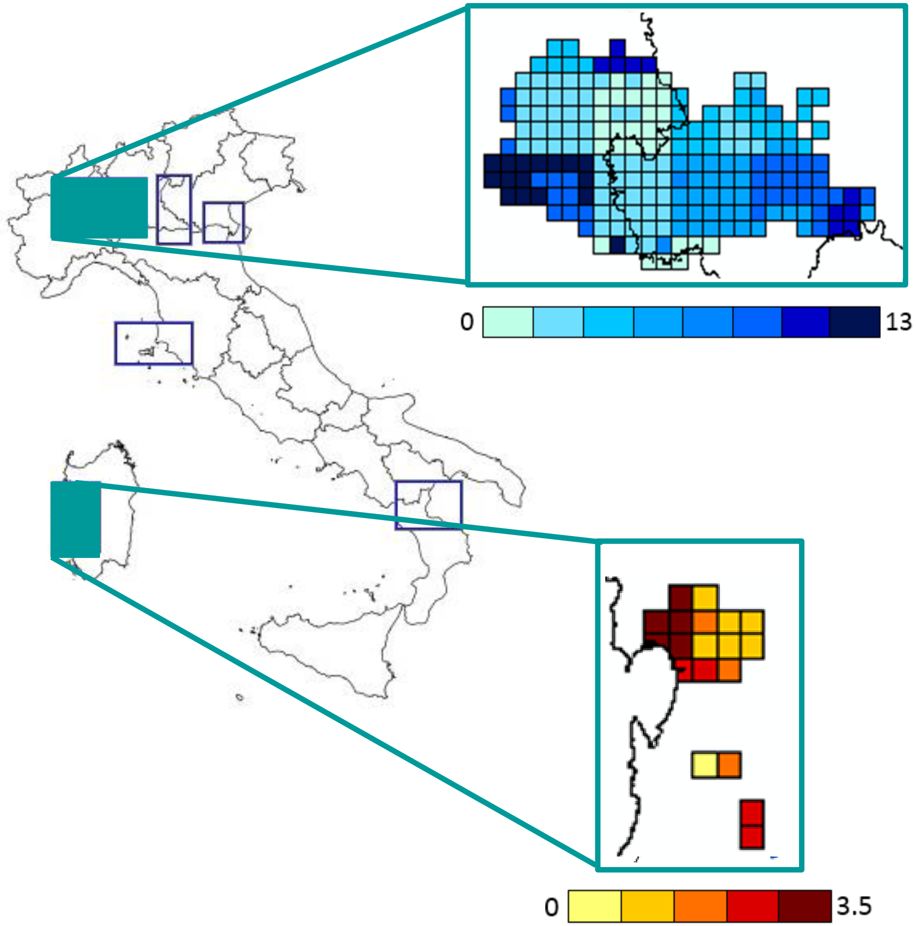
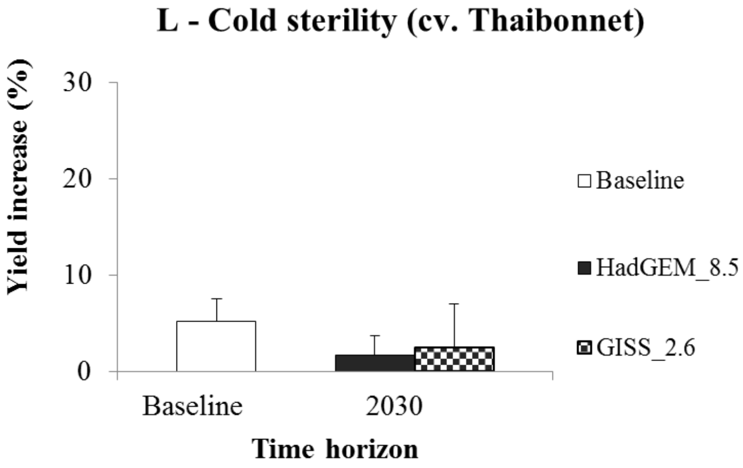
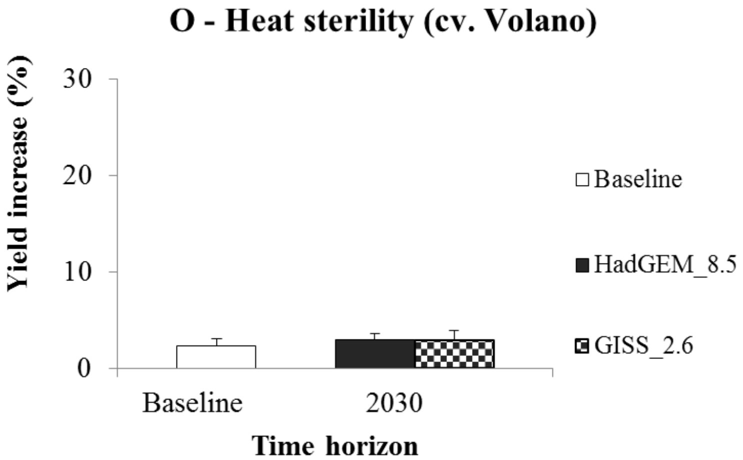
## Ideotypes' performance



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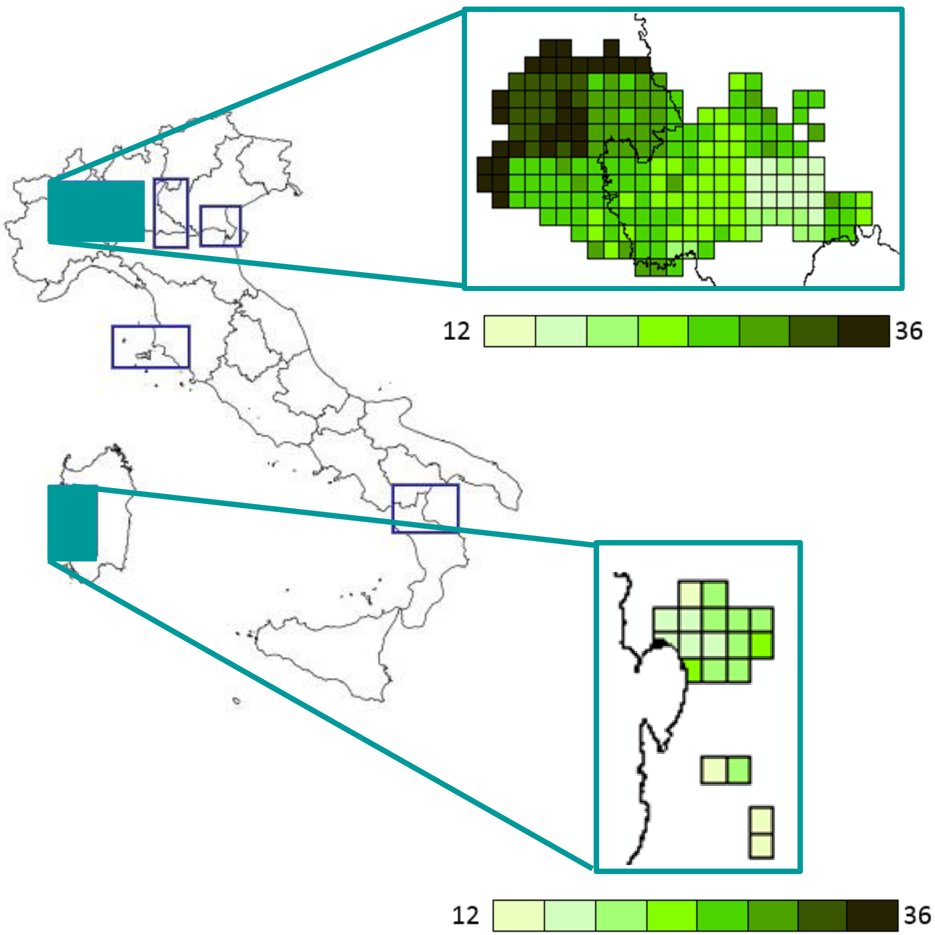
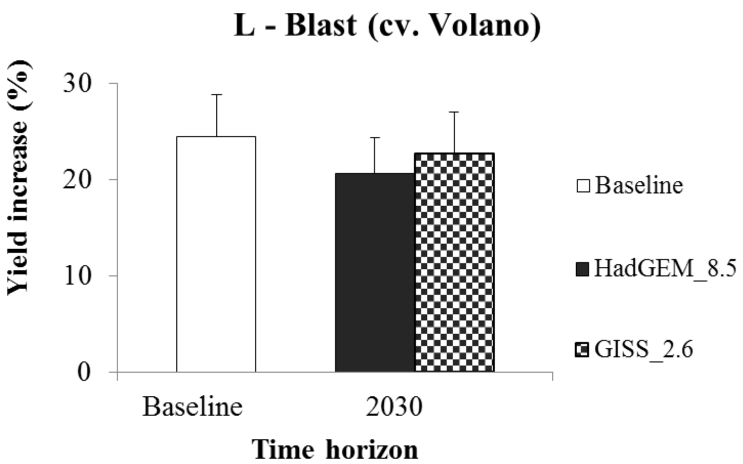
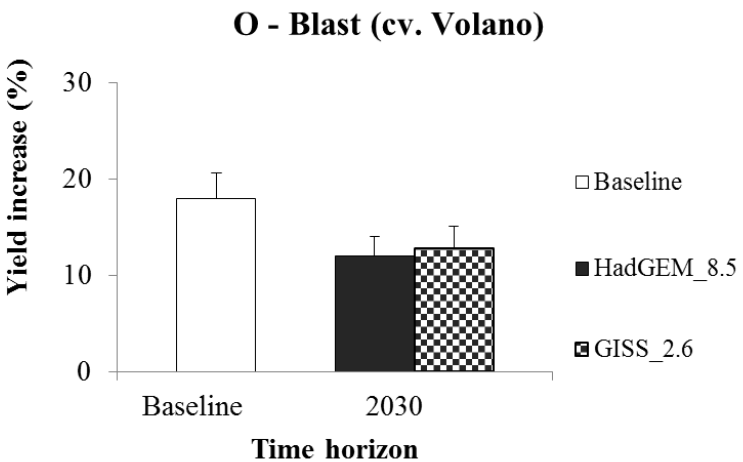
# Objective 2: Results

## Ideotypes' performance



# Objective 2: Results

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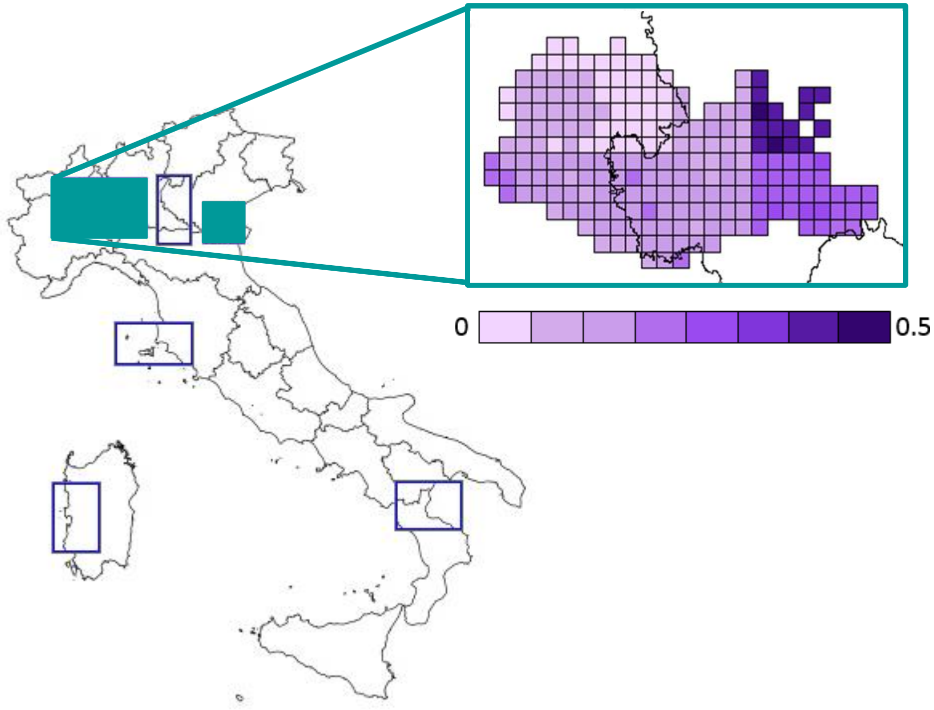


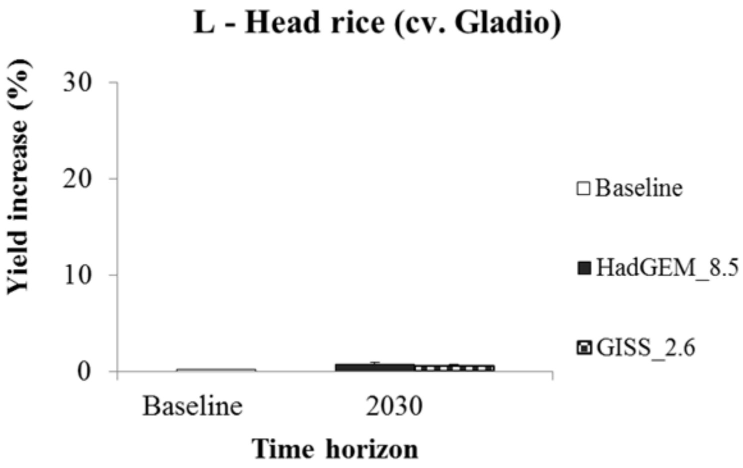

# Objective 2: Results

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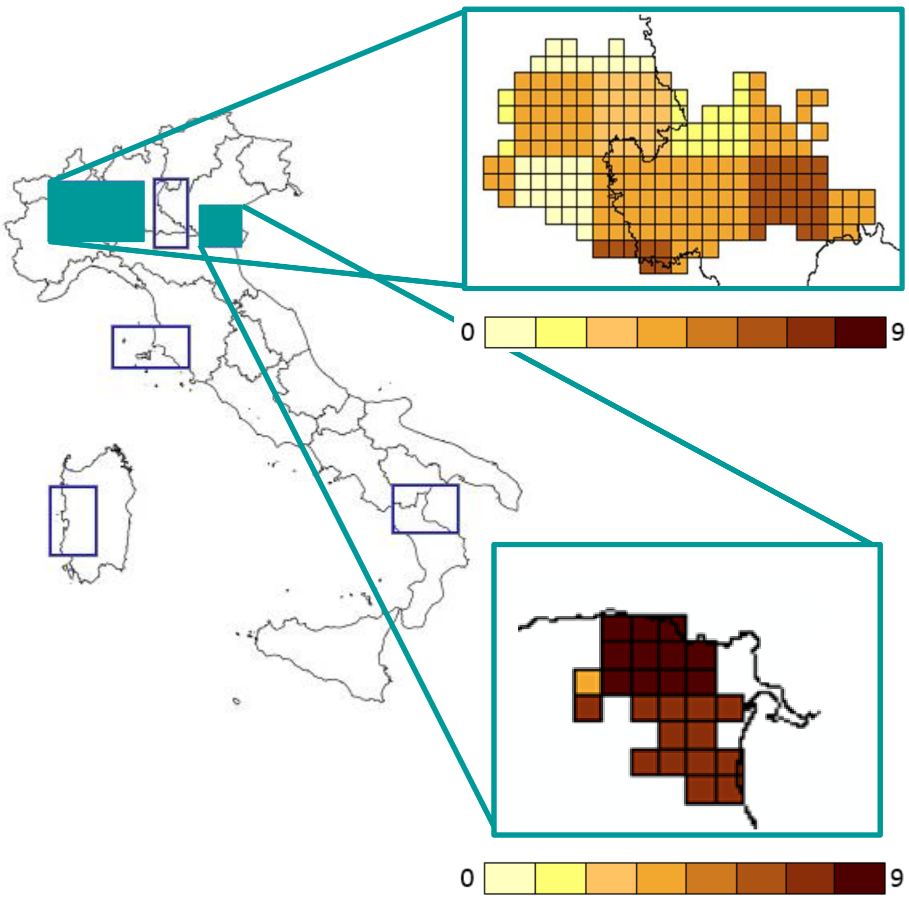


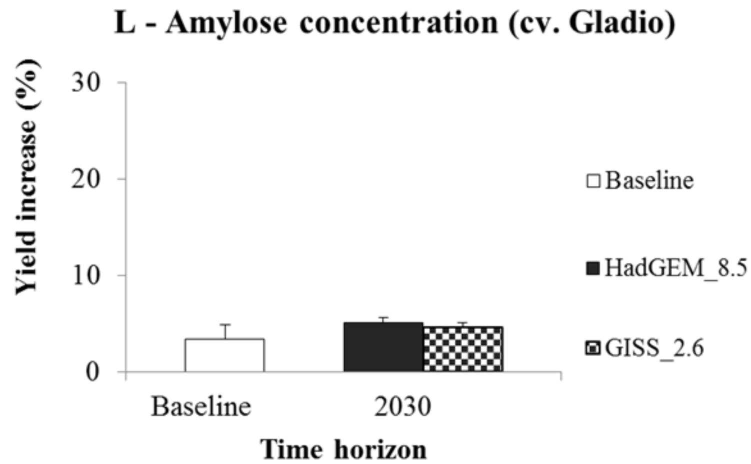


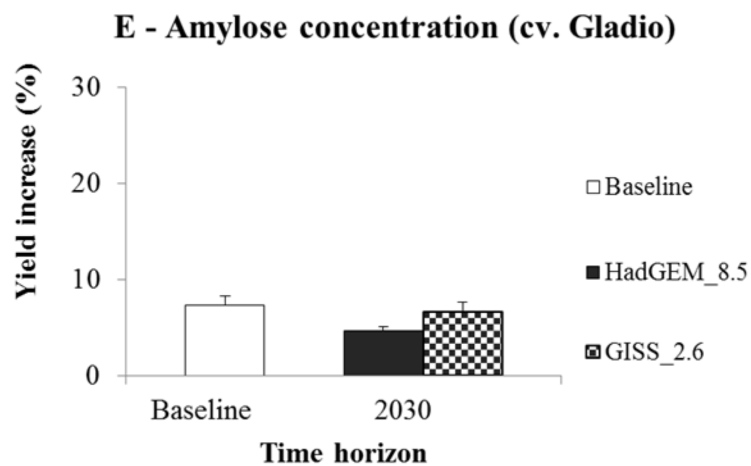

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# Objective 3: Methods

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## On which traits is it worth breeding?

**Nested ANOVA (Italy)**

- Main factor:
  - ✓ district
    - 6 levels
- Nested factors:
  - ✓ genotype
    - 2 levels: current varieties, ideotype (improved)
  - ✓ climate scenario
    - 3 levels: baseline, 2030 RCP2.6 GISS-ModelE2, 2030 RCP8.5 HadGEM2
- Replicates: 20 seasons for each climate scenario
- Variables:
  - ✓ yield limited - biotic/abiotic factors,
  - ✓ grain quality variables

*Tests for:*

- *Autocorrelation among replicates: no autocorrelation*
- *Normality, homoscedasticity (grain quality variables transformed)*

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# Objective 3: Results

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## On which traits is it worth breeding?

### ANOVA: Results (Italy)

| Variable | *p*-value {eta squared, $\eta^2$} | | | | |
|---|---|---|---|---|---|
| | Genotype (District) | Climate scenario (District) | District | Genotype × Scenario (District) | Note |
| Blast-limited yield | <0.01 {**0.378**} | <0.01 {0.080} | <0.01 {**0.407**} | n.s. | |
| Cold-sterility limited yield | n.s. | <0.01 {**0.344**} | <0.01 {**0.666**} | n.s. | |
| Heat-sterility limited yield | n.s. | <0.01 {**0.326**} | <0.01 {**0.400**} | n.s. | |
| Head rice | <0.01 {**0.035**} | <0.01 {0.179} | <0.01 {**0.284**} | n.s. | Significant but not "relevant" (low variability in data: even small differences are significant) |
| Non chalky grains | <0.01 {**0.211**} | <0.01 {**0.503**} | <0.01 {**0.364**} | n.s. | |
| Protein content | n.s. | <0.01 {**0.314**} | <0.01 {**0.234**} | n.s. | |

# Conclusions



- **Breeding** for **traits** involved with **resistance/tolerance** to biotic/abiotic stressors **could guarantee benefits similar** to those coming from canopy improved for structure or photosynthetic efficiency.
- Breeding programs should account for (models!)
  - ✓ Heterogeneity in **space** (production districts)
  - ✓ **Climate change**

  **They could largely frustrate breeding** programs by **hiding the benefits** coming from improved genotypes.

  - This is what we obtained for traits involved with **grain quality**.

# Limits

- **Parameters for blast** (those not involved with plant resistance but with pathogen physiology) **can probably be refined for Asian sites** (likely **races** with different features).
- **Evolutionary potential** of the pathogen was not considered.
- **Models for grain quality more empiric**: this could have a larger effect on uncertainty in parameterization compared to other sub-models.
- **Many processes interacting** and **not all of them simulated** (e.g. no effect of **N fertilization** on susceptibility to blast was simulated).

Cassandra
models for change

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