Intercropping cereals and legumes to stabilise yield in the tropics: evaluation of the STICS soil-crop model to simulate bi-specific intercrops

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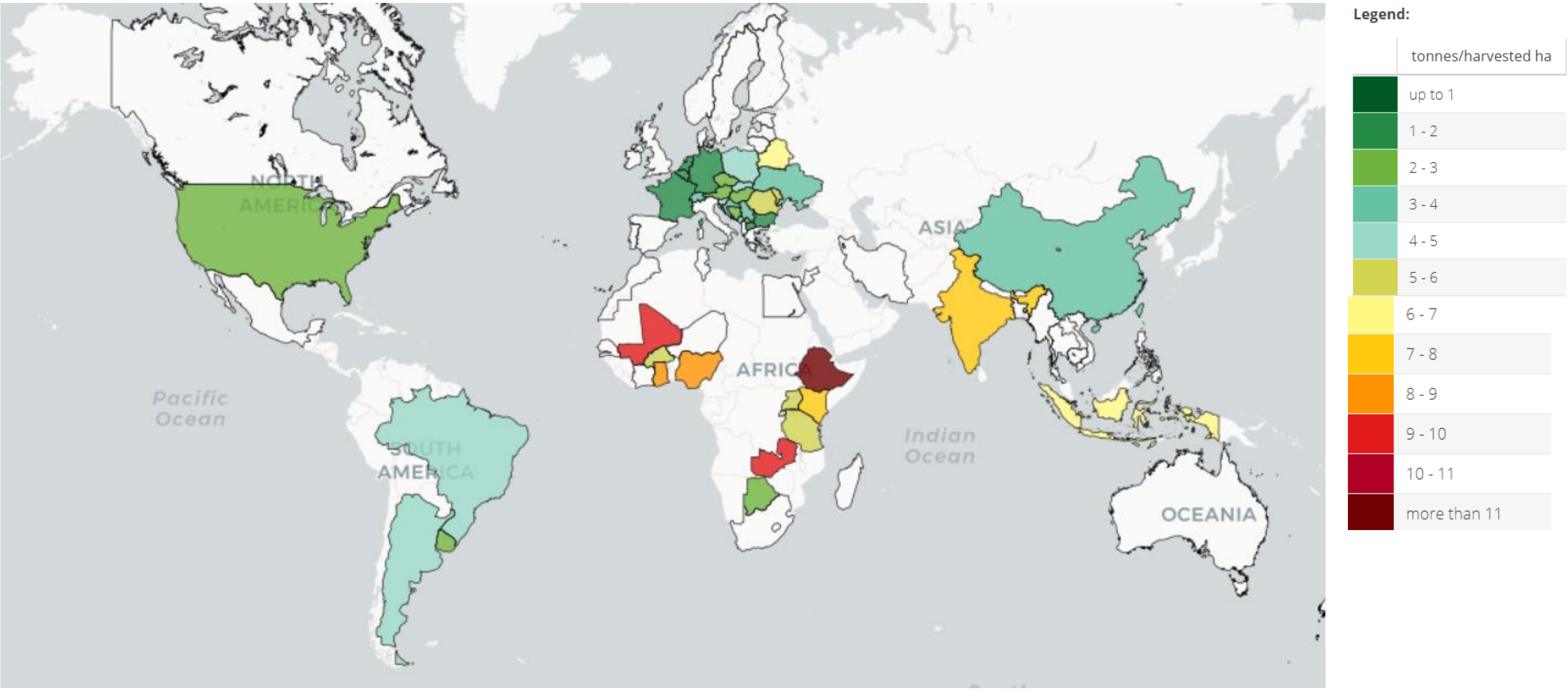
Supervisors: A. Couëdel, M. Christina, G. Falconnier, E. Justes

cirad
LA RECHERCHE AGRONOMIQUE POUR LE DÉVELOPPEMENT

INTERCROP VALUES

AgroParisTech
Talents d'une planète soutenable

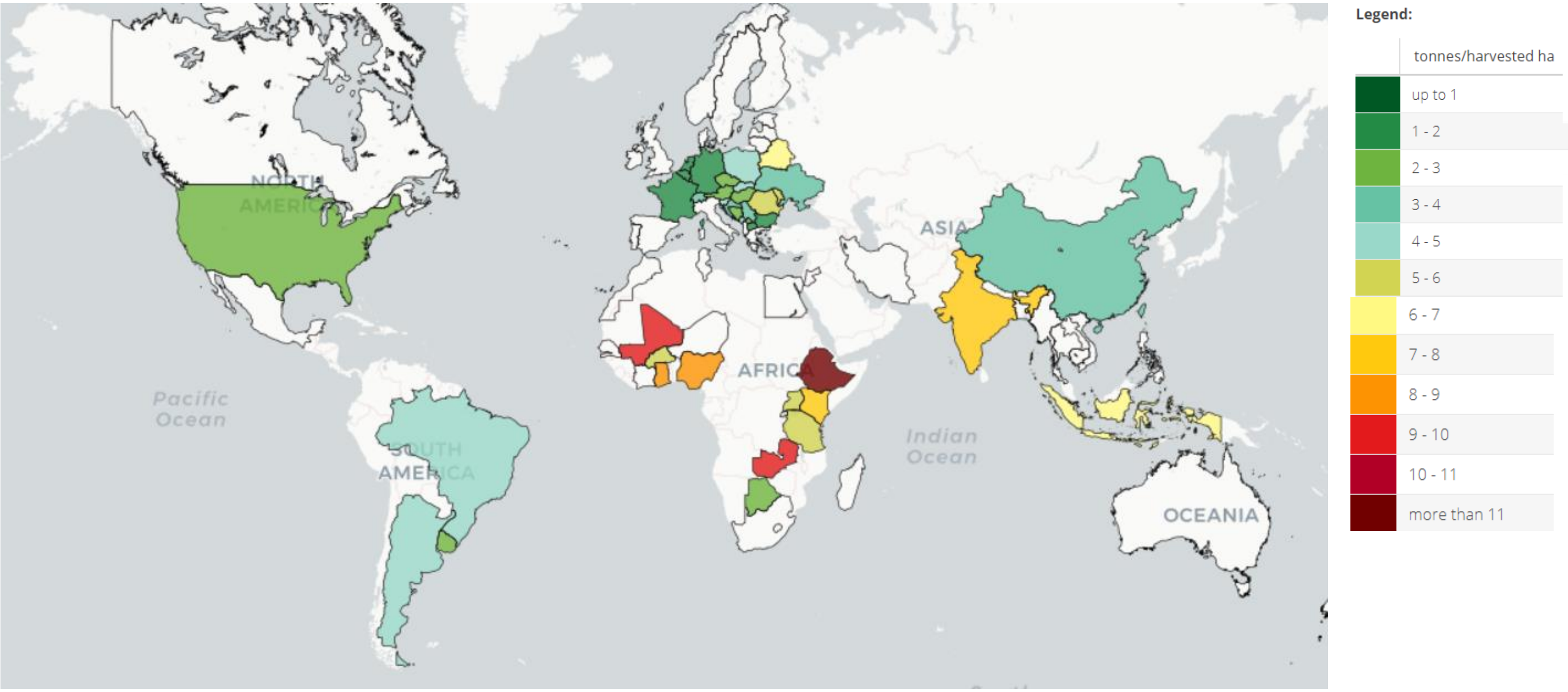
Study area: sub-Saharan Africa



Global Yield Gap Atlas, Van Ittersum et al., 2016 - maïs

Challenge: sustainable agricultural intensification in the face of climate change

Study area: sub-Saharan Africa



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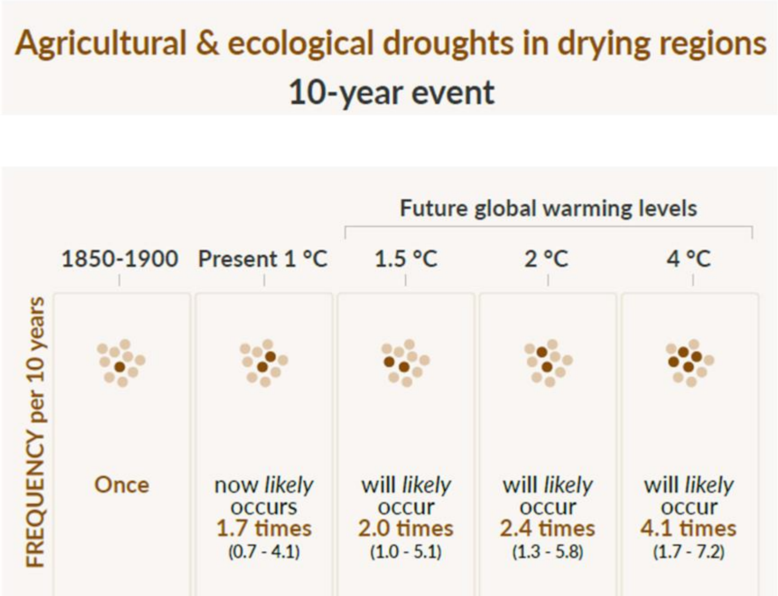


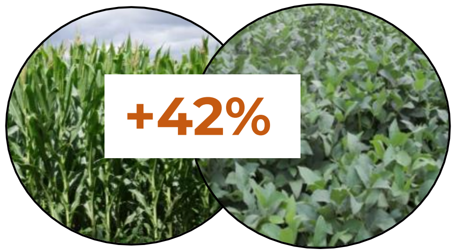
Challenge: sustainable agricultural intensification in the face of climate change

Cereal-legumes intercropping

- **Increased production for the same cultivated area**
  Area required for pure crops to produce as much as in intercropping :
  Literature review by Namatsheve et al, 2020

Sorghum/Cowpea

Millet/Cowpea



Maize/Cowpea

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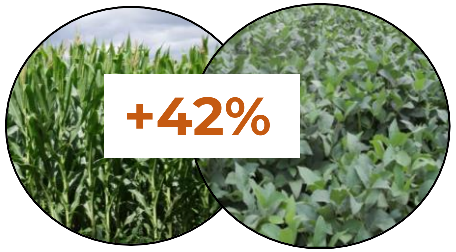


Maize/Cowpea

- **Stabilising yields in the face of climate variability** (Raseduzzaman et al., 2017)

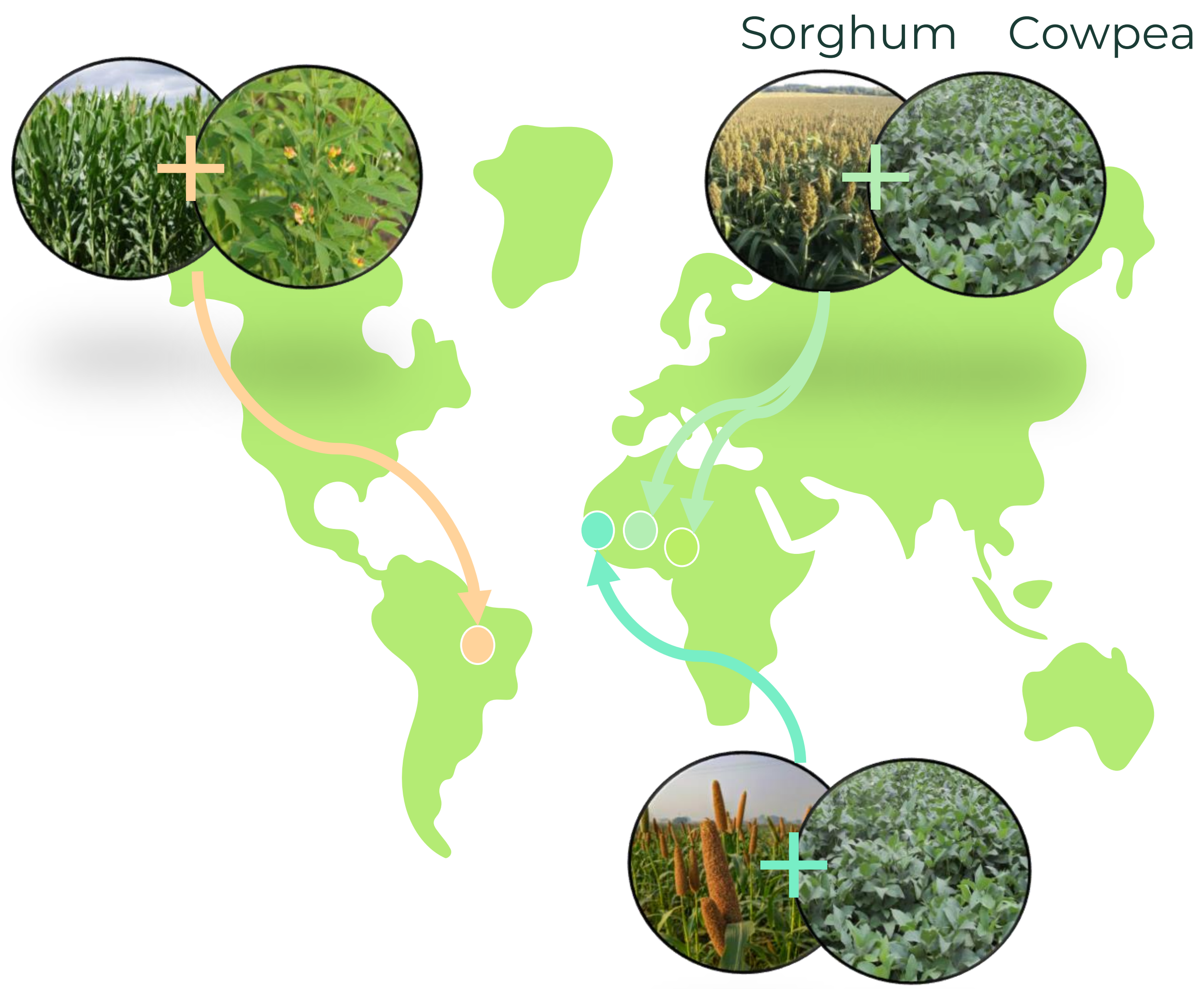
Data collected

Contrasting sites :

Data collected

Contrasting sites :

- **Burkina Faso** (Ganame, 2022)
- **Mali** (Traoré et al., 2022)



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Contrasting sites :

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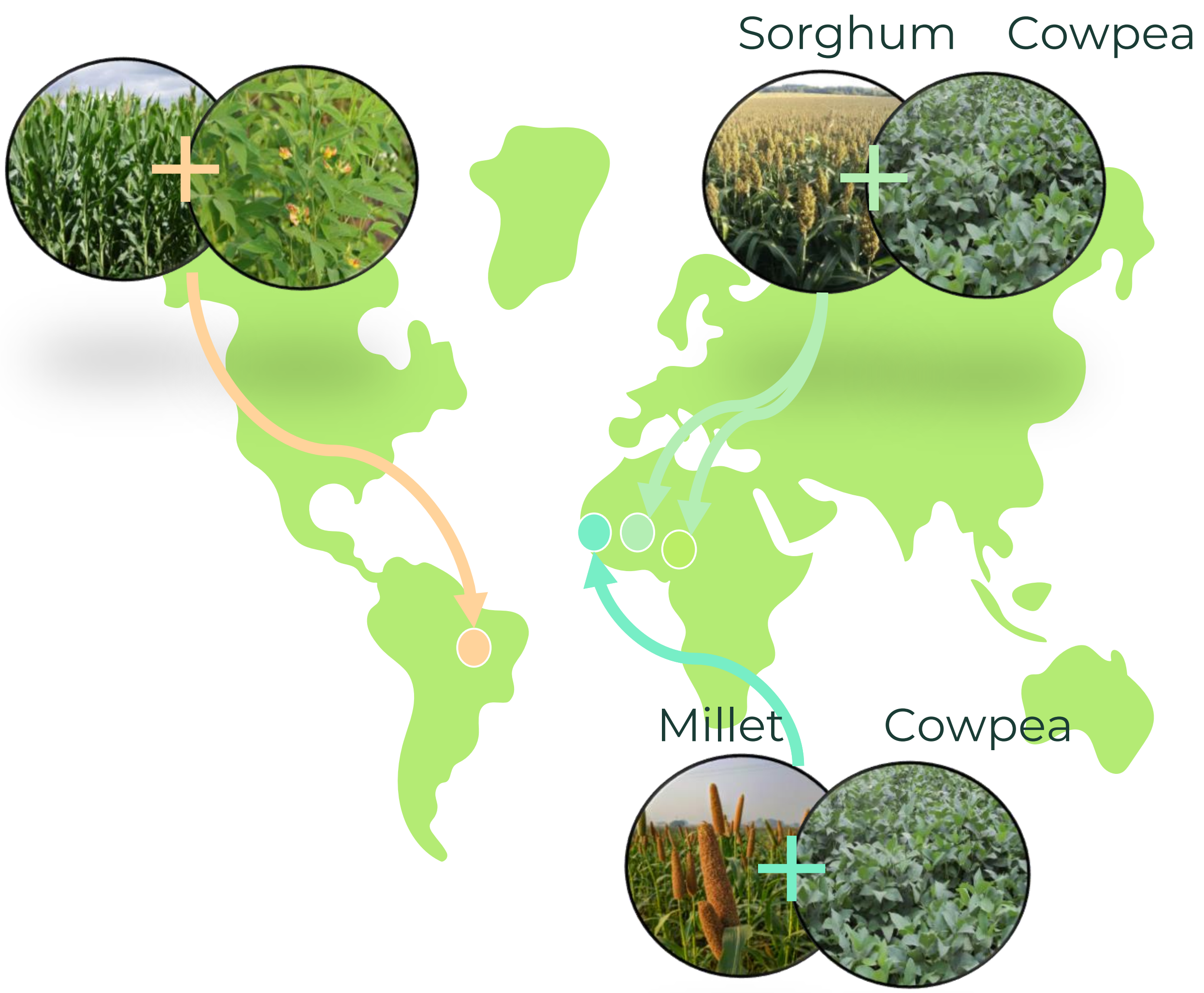
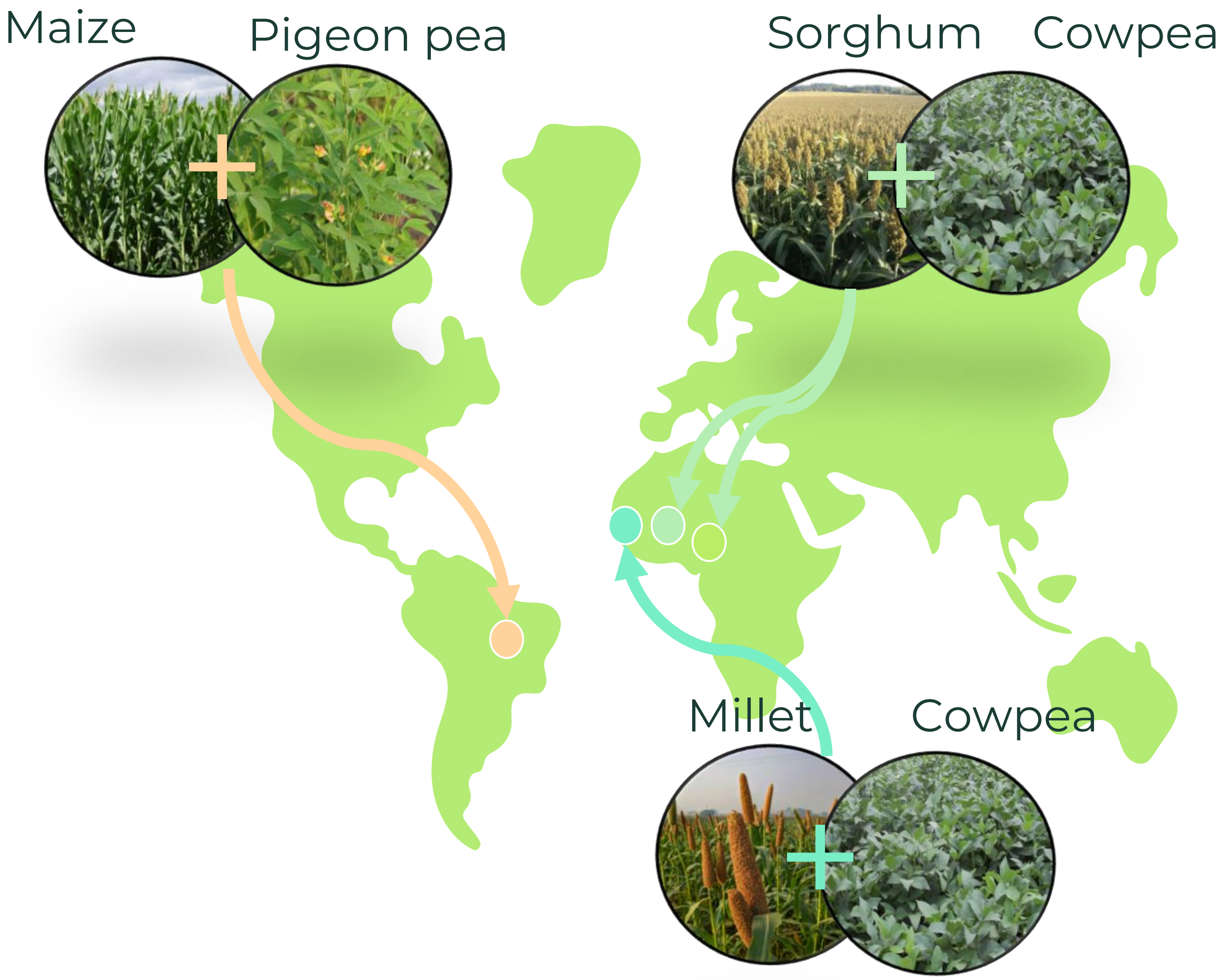


Data collected

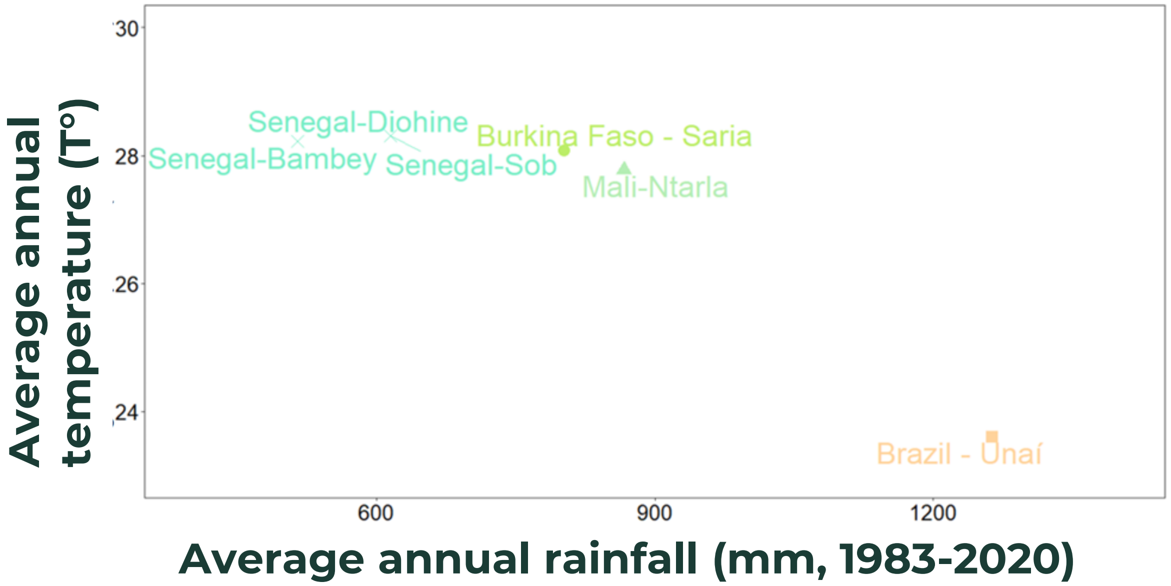
Contrasting sites :

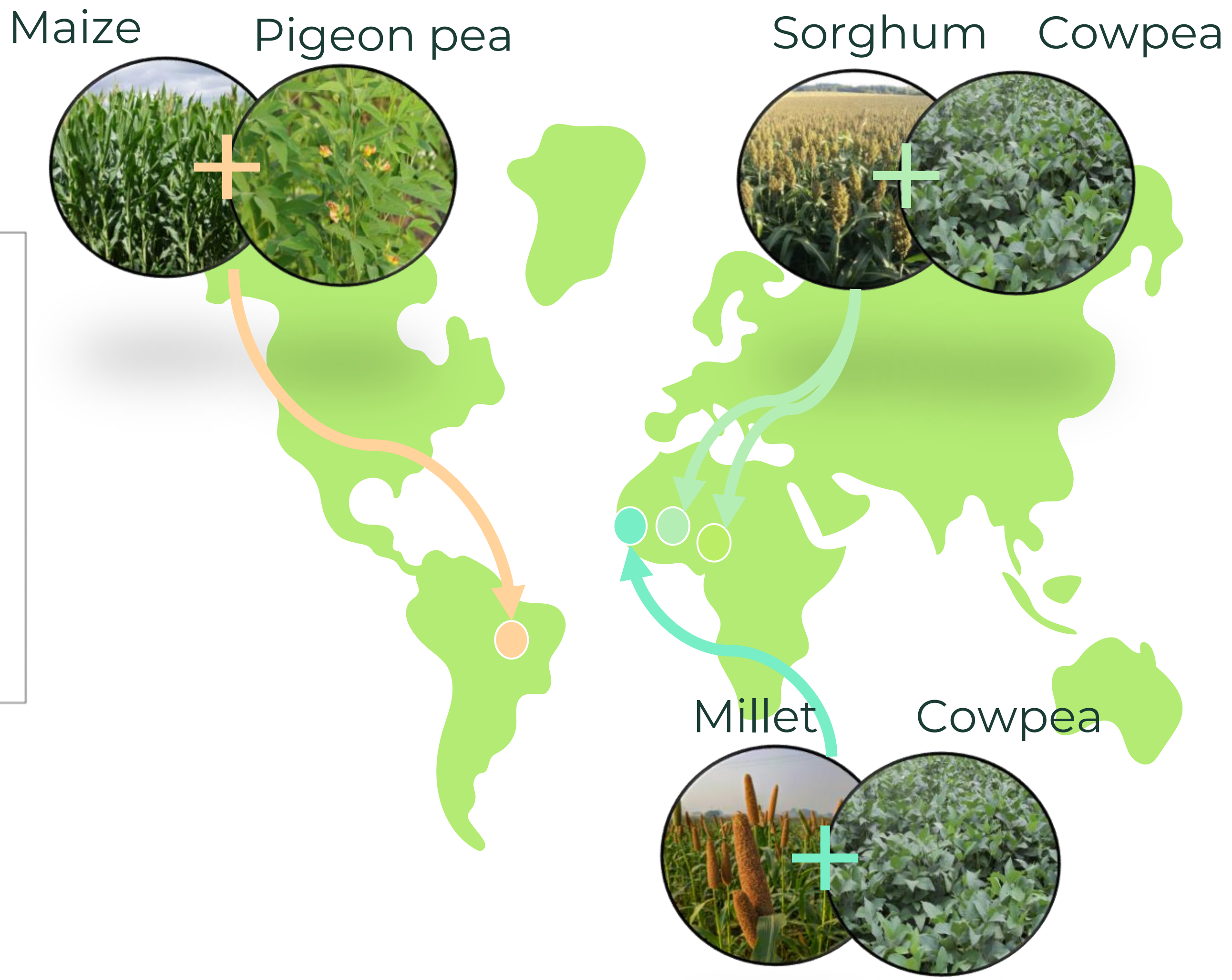
- **Burkina Faso** (Ganame, 2022)
- **Mali** (Traoré et al., 2022)
- **Sénégal** (Senghor et al., 2023)
- **Brazil** (Baldé et al., 2011)



Data collected

Contrasting sites :





Parameters calibration

Adjustment of previous calibrations in version 10 of STICS :

Calibration of most parameters on sole crops

+

Calibration of the parameter governing competition for light on intercropping (Ktrou : extinction coefficient of PAR through the crop)

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Formalisms used in sole cropping and intercropping :

- intercepted radiation calculated with the radiative transfer method,
- evapotranspiration calculated with the resistive approach

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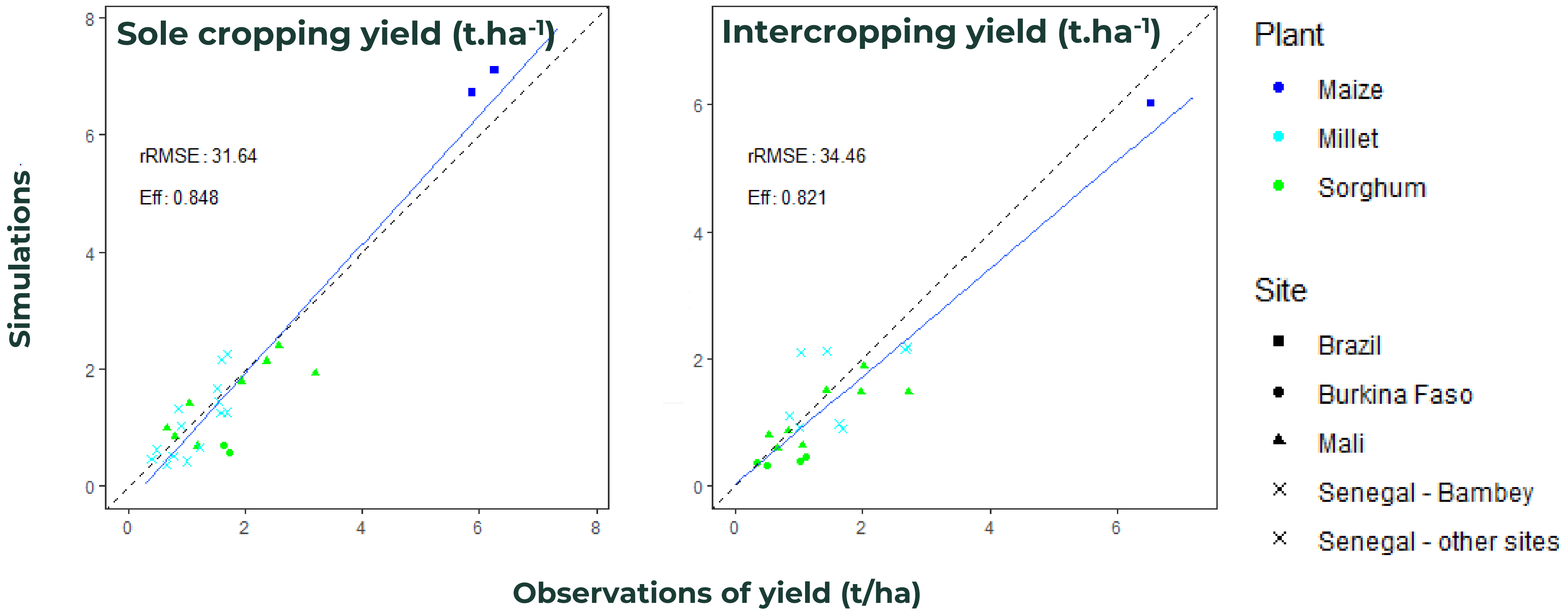
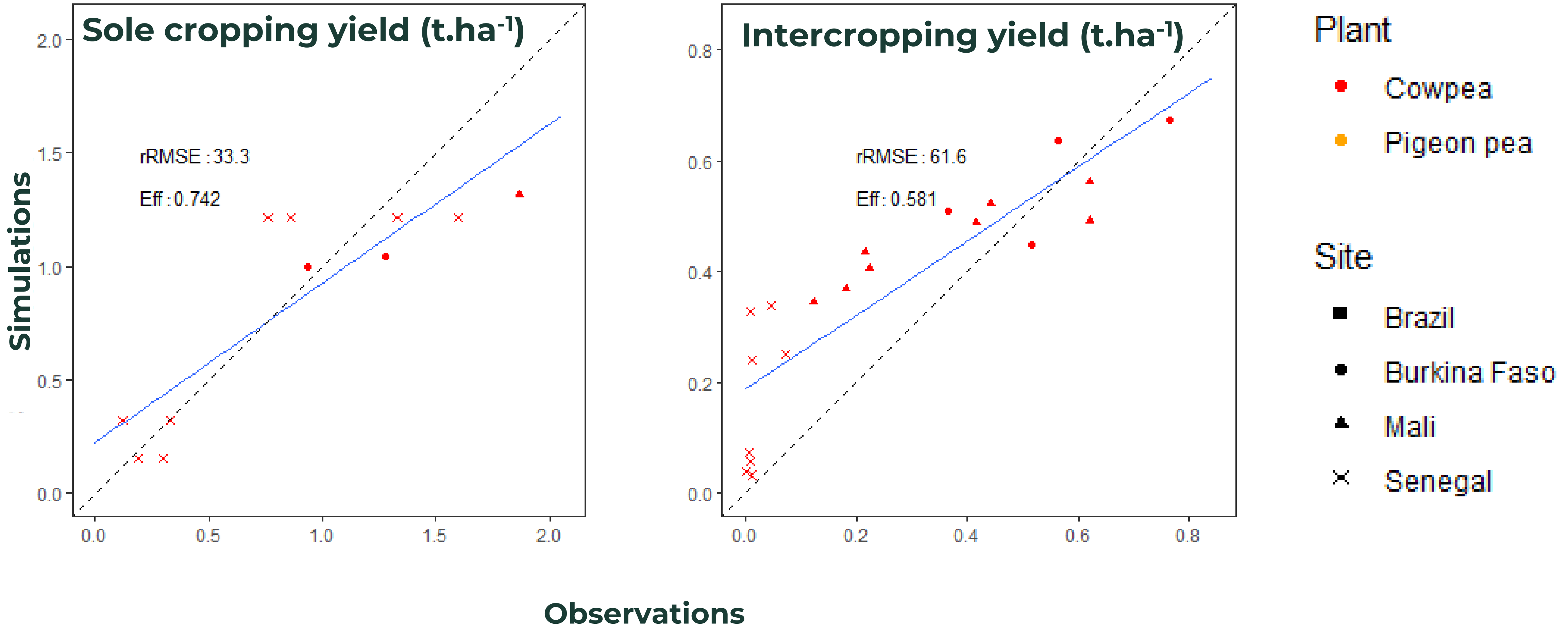
Validation step – to be done

Calibration Cereals

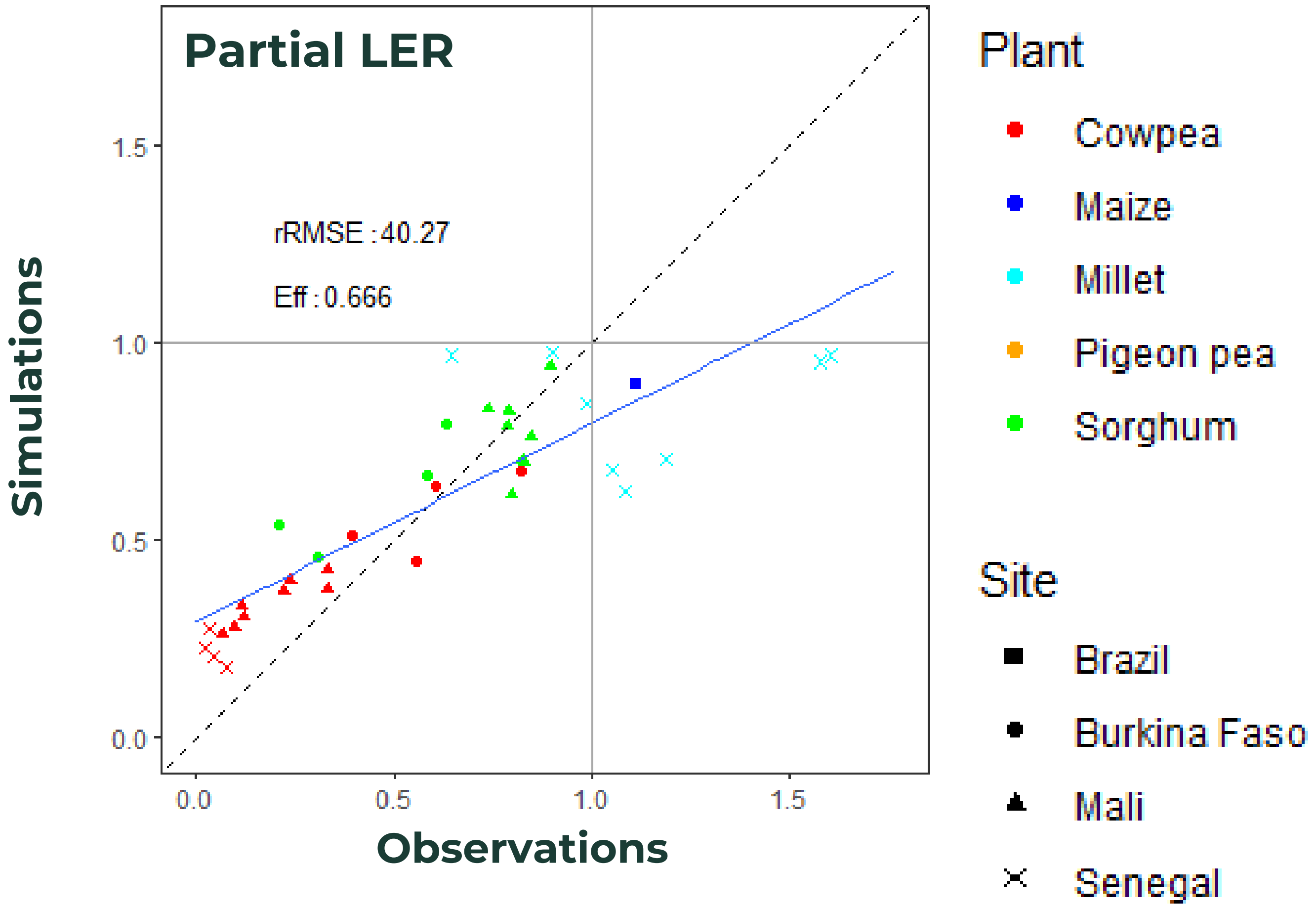


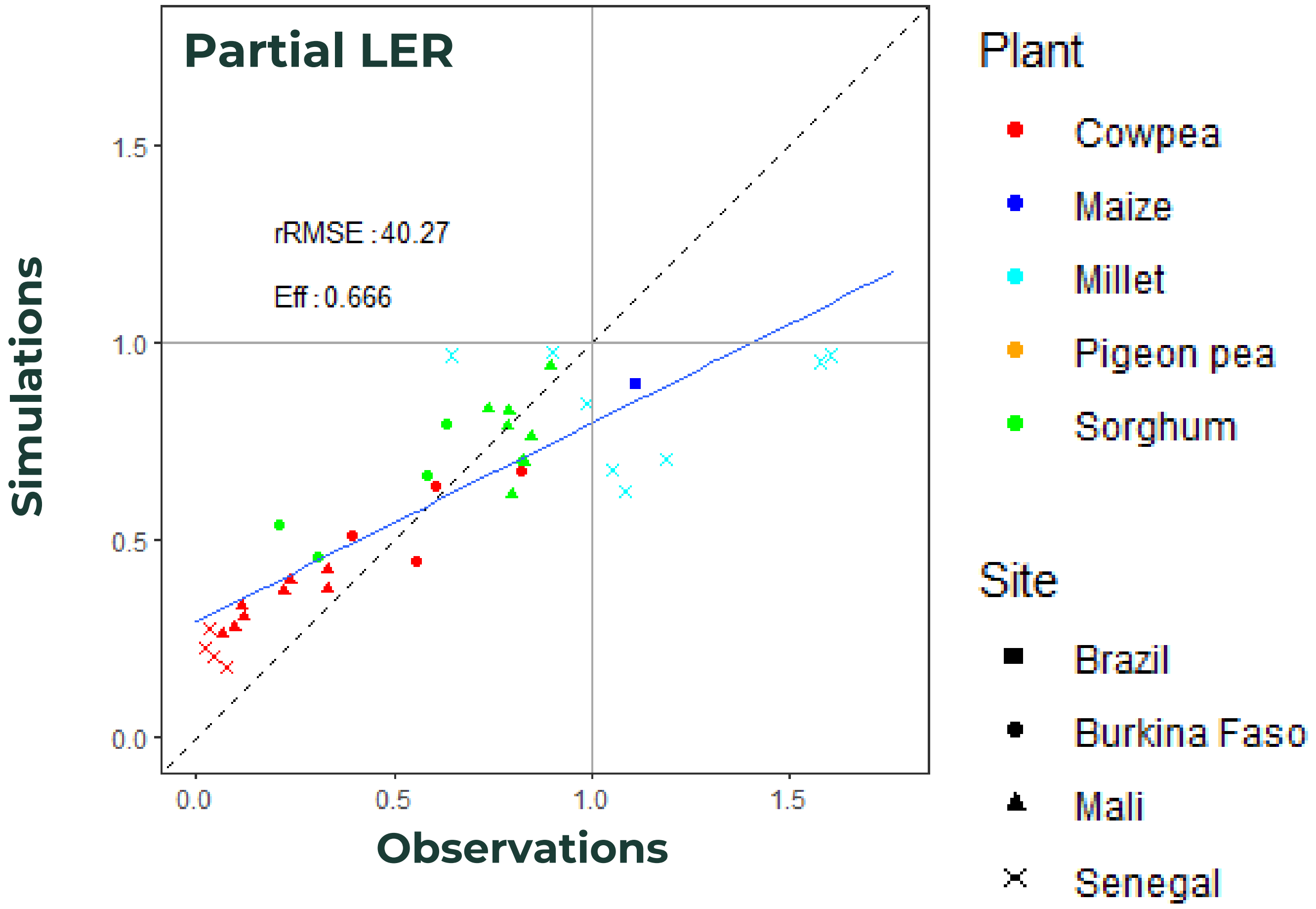
- Model accuracy as good in sole crop simulations as in intercropping simulations

Calibration Légumes



- Model accuracy reduced in intercropping
- Overestimation of low intercropping yields


Partial LER
rRMSE : 40.27
Eff : 0.666
Simulations
Observations
0.0
0.5
1.0
1.5
Plant
Cowpea
Maize
Millet
Pigeon pea
Sorghum
Site
Brazil
Burkina Faso
Mali
Senegal



Partial LER

$$= \frac{Yield\ in\ IC}{Yield\ in\ SC}$$

(Willey, 1979)

- **Overestimation of low partial LERs**
- **No simulation of partial LER > 1**

What are the benefits of cereal-legume intercropping compared with cereal sole cropping with and without N fertilisation ?

Virtual experiment

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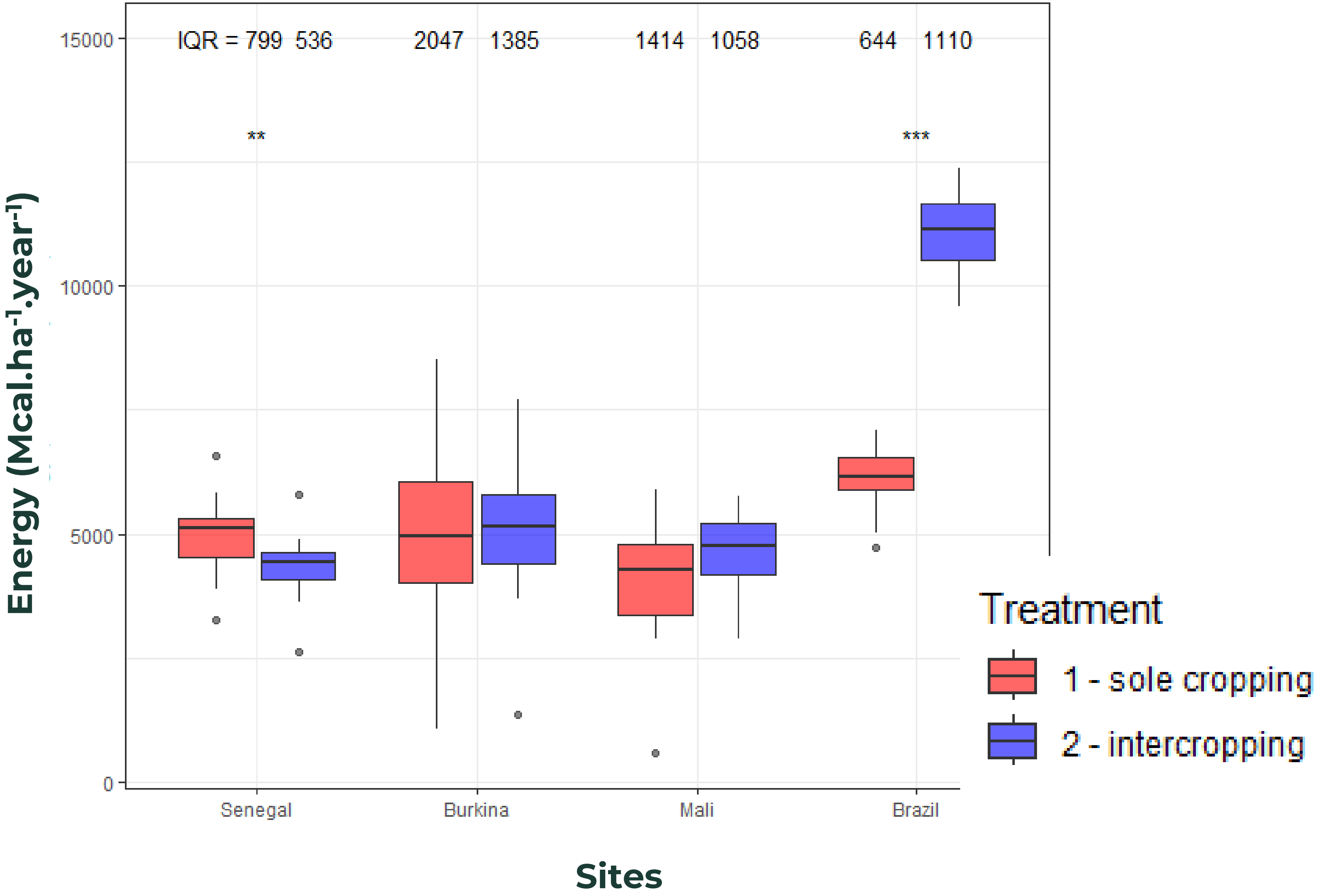
Hypotheses 2: the benefits of cereal-legume intercropping compared to cereal sole cropping decrease when the level of nitrogen fertilisation increases.

Virtual experiment

Cropping system	Crops (improved varieties)	Fertilisation (N)kg.ha^{-1}	Simulation years
Sole cropping	Cereals	0, 20, 40, 60, 80, 100, 120, 140, 160, 180	20
	Legumes	0	
Intercropping	Cereals + Legumes	0, 20, 40, 60, 80, 100, 120, 140, 160, 180	20

N = 0kg/ha

Virtual experiment



Context | Data collected | Calibration | Virtual expe | Discussion | Conclusion

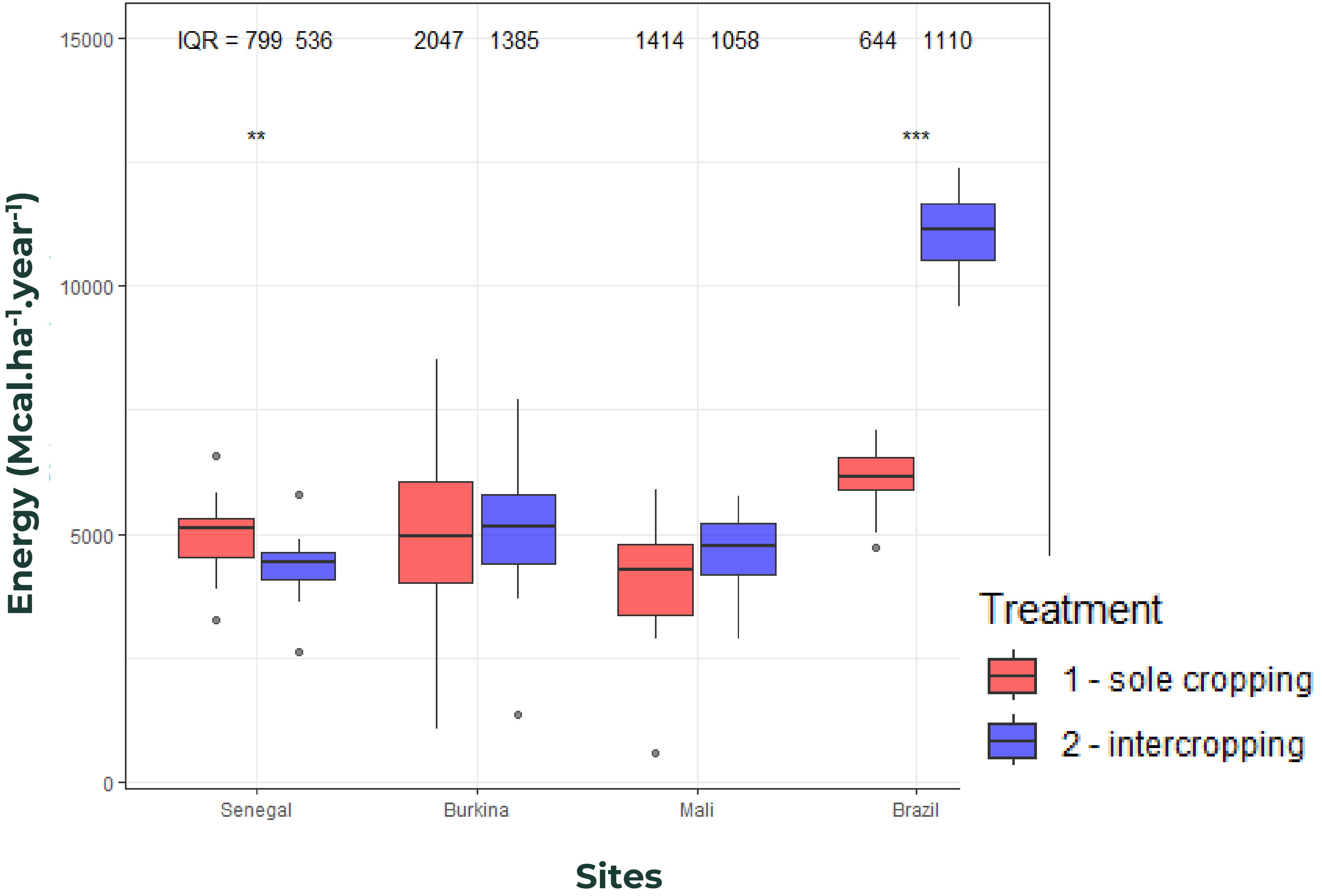
N = 0kg/ha

Virtual experiment

Productivity

- **No reduction in calorie yield**
- **Increase in protein yield**

Except in Senegal



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Virtual experiment

Productivity

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- Increase in protein yield

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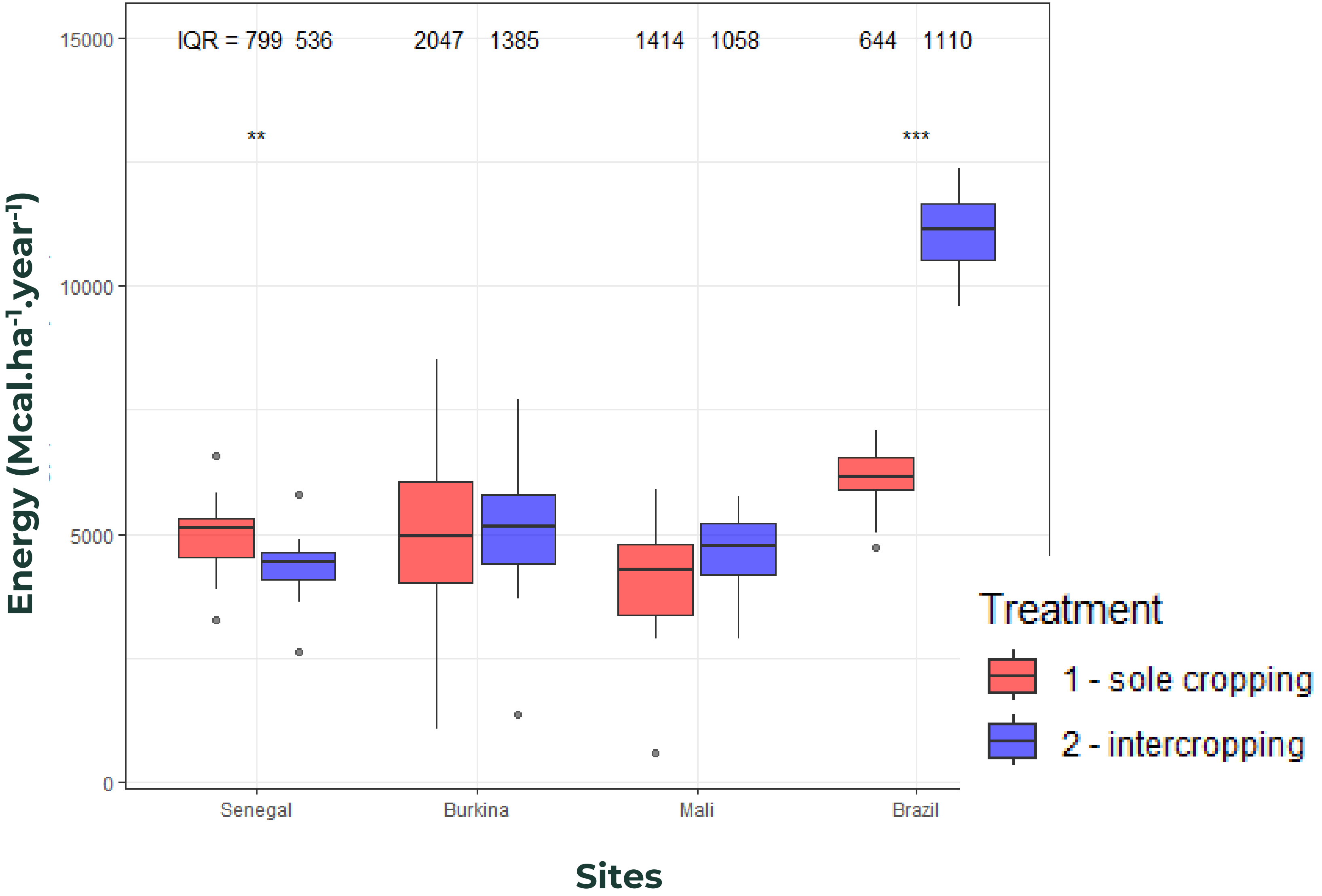
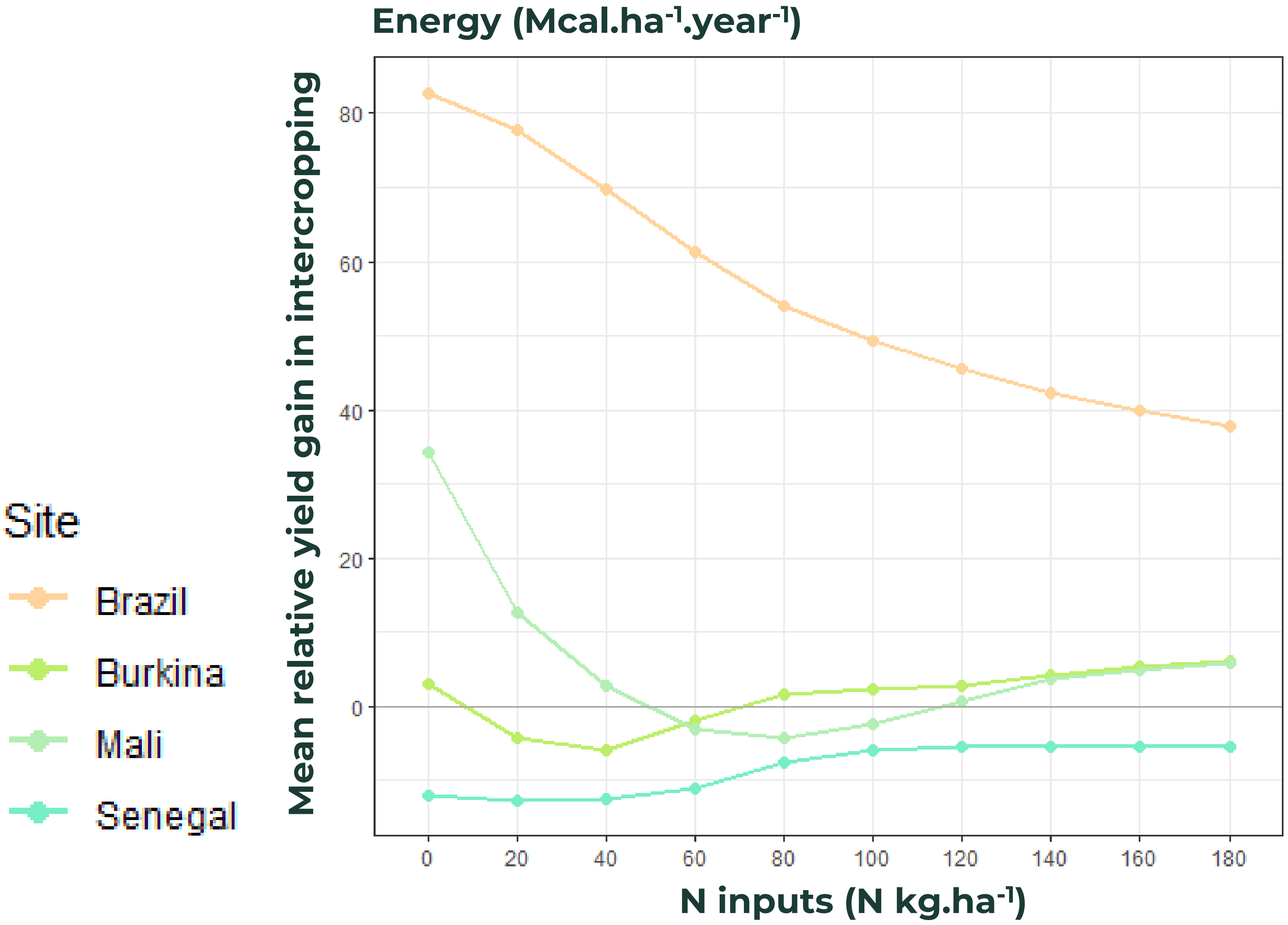
Stability

- Stabilisation of energy and protein yields in sub-Saharan Africa



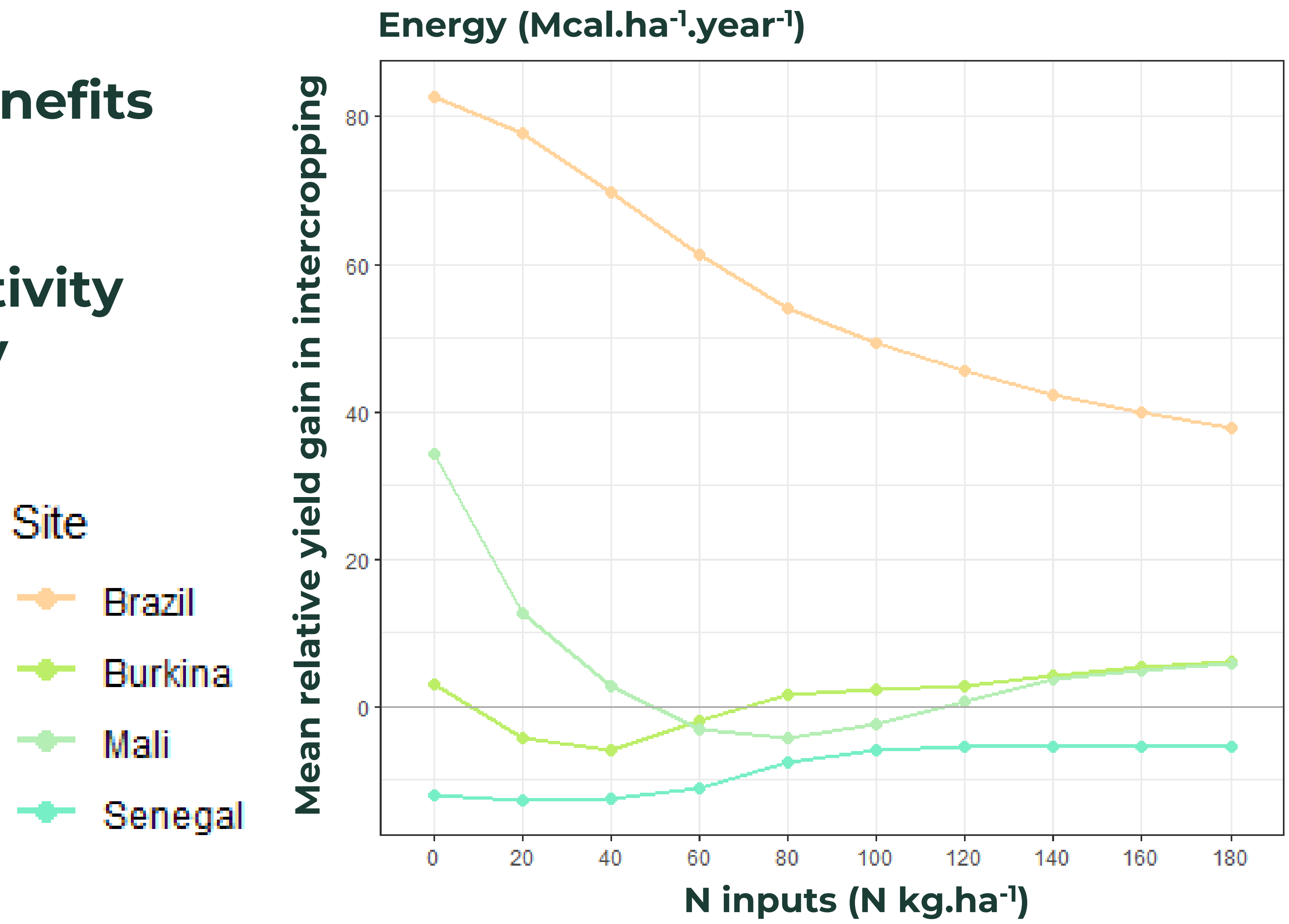
Fertilisation

Virtual experiment



Fertilisation

- **Fertilisation reduced benefits of intercropping in sub-Saharan Africa :**
  - **- in terms of productivity**
  - **- in terms of stability**



Confidence in simulations

Plot of maize intercropped with cowpea in Moamba, Mozambique, Mathilde de Freitas, 2023

Reproduction of literature results:

- Reduced yields for each crop in intercropping
- Intercropping is more land-efficient

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Reproduction of literature results:

- Reduced yields for each crop in intercropping
- Intercropping is more land-efficient

But …

- Underestimation of important competition effects on legumes
- No simulated partial LER >1 : no simulation of facilitation effects

Technical problems with the STICS model

Factorial trial in Sabie, Mozambique - CIRAD - Eduardo Mondlane University, Mathilde de Freitas 2023

- Troubles simulating **cumulated mineralized nitrogen** in the soil (Clivot equation - Beaudoin et al., 2023)

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- **Simulation of the senescence of all leaves** when leaf area index was maximum in intercropping

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- Troubles simulating **cumulated mineralized nitrogen** in the soil (Clivot equation - Beaudoin et al., 2023)
- **Simulation of the senescence of all leaves** when leaf area index was maximum in intercropping
- Trouble with the **inversion of dominance** in intercropping

Conclusion

- STICS has satisfactorily reproduced the performance of intercropping on contrasting sites in tropical regions

- Confirmation of central hypotheses
  - Increased productivity and stability ✓
  - Benefits reduced by N fertilisation ✓

References

Baldé, A. B., Scopel, E., Affholder, F., Corbeels, M., Da Silva, F. A. M., Xavier, J. H. V., & Wery, J. (2011). Agronomic performance of no-tillage relay intercropping with maize under smallholder conditions in Central Brazil. *Field Crops Research*, 124(2), 240-251.

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Willmott, C. J., Ackleson, S. G., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., ... & Rowe, C. M. (1985). A simulation study for assessing yield optimization and potential for water reduction for summer-sown maize under different climate change scenarios. *Journal of Geophysical Research*, *90*, 8995-9005.

Plot of maize intercropped with cowpea in Moamba, Mozambique, Mathilde de Freitas, 2023

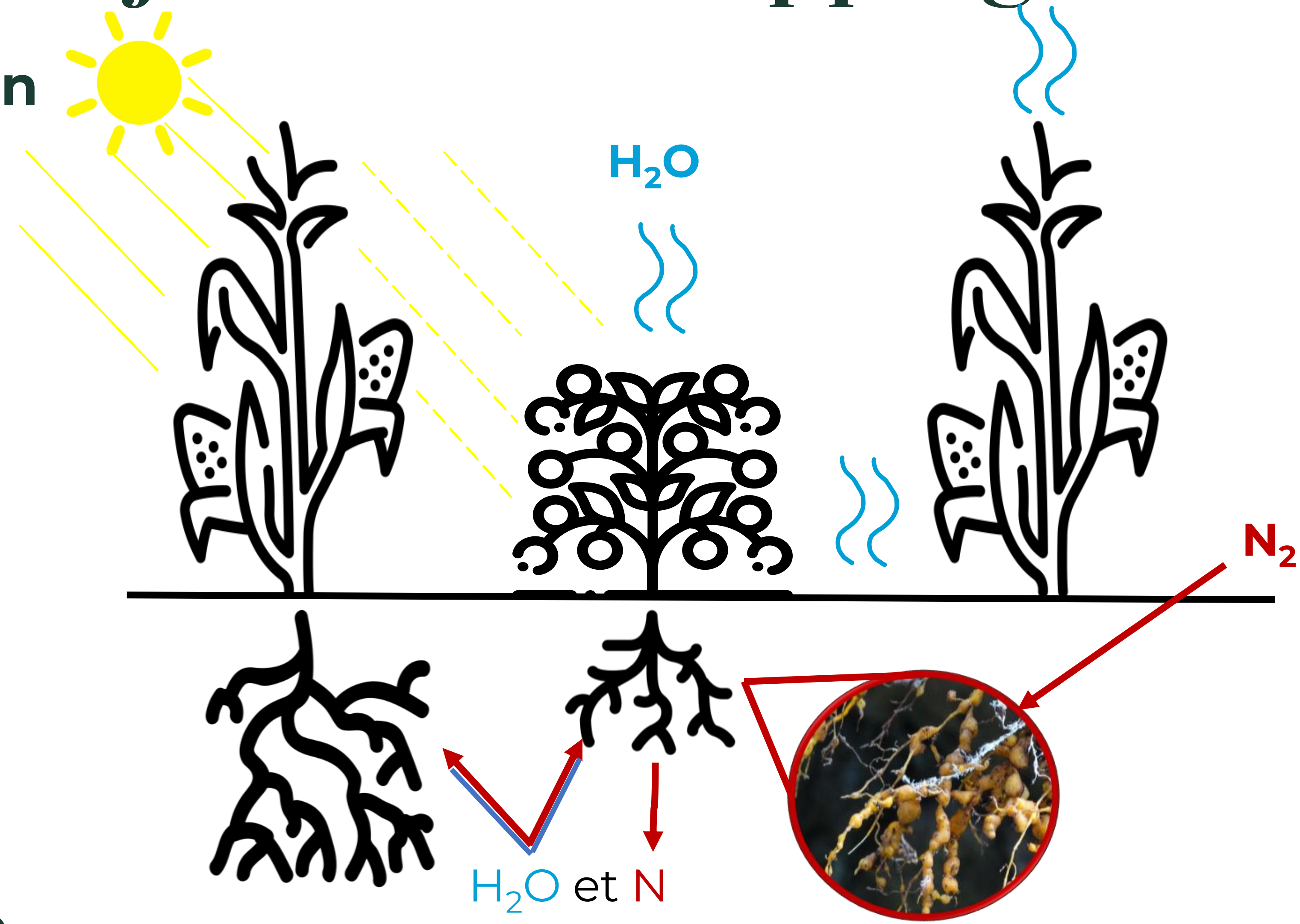
Thank you for your attention

Study object : intercropping

Competition

Intercepted radiation

Water and nutrients



Complementarity

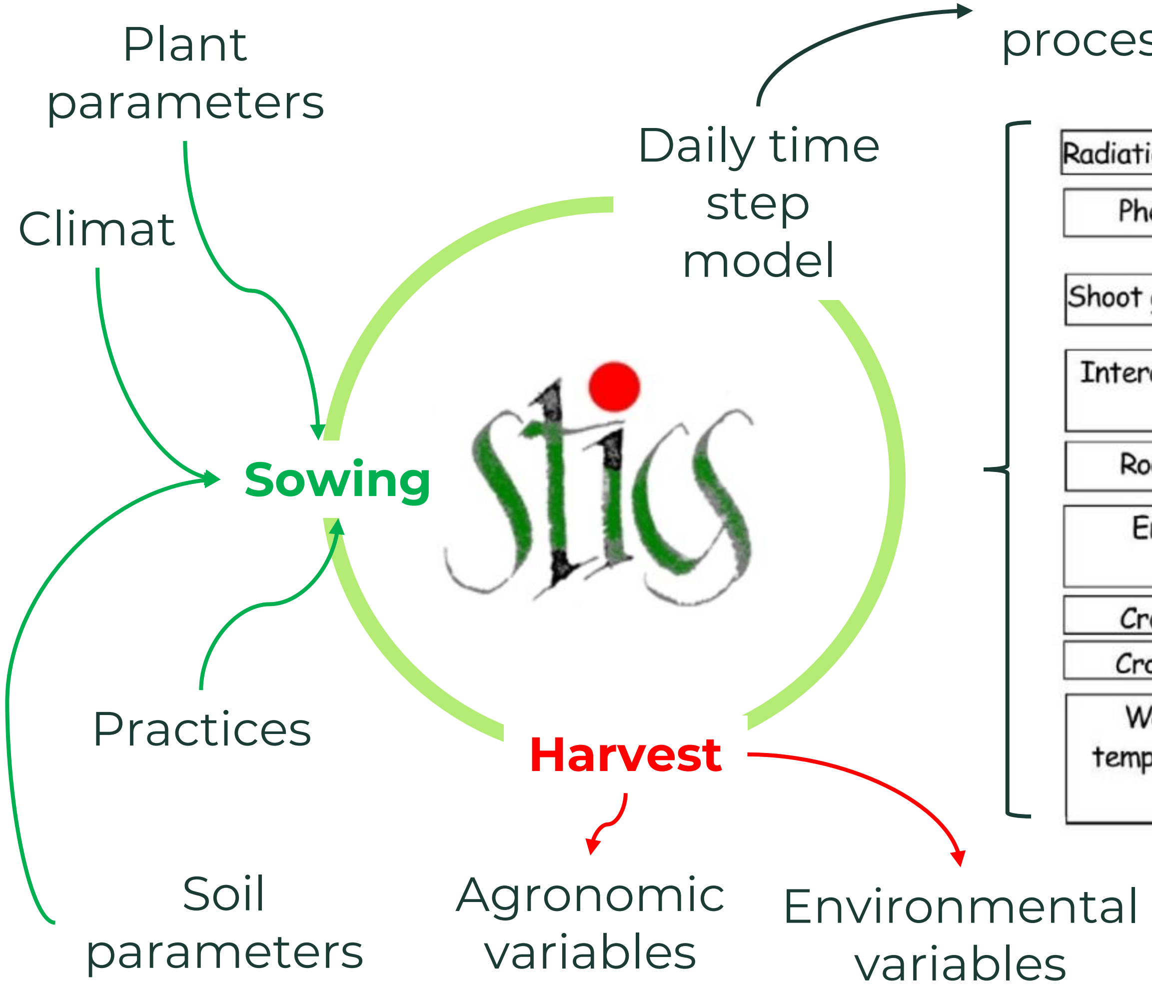
Different sources of N

Water and nutrients from different horizons

+ Increased soil cover:

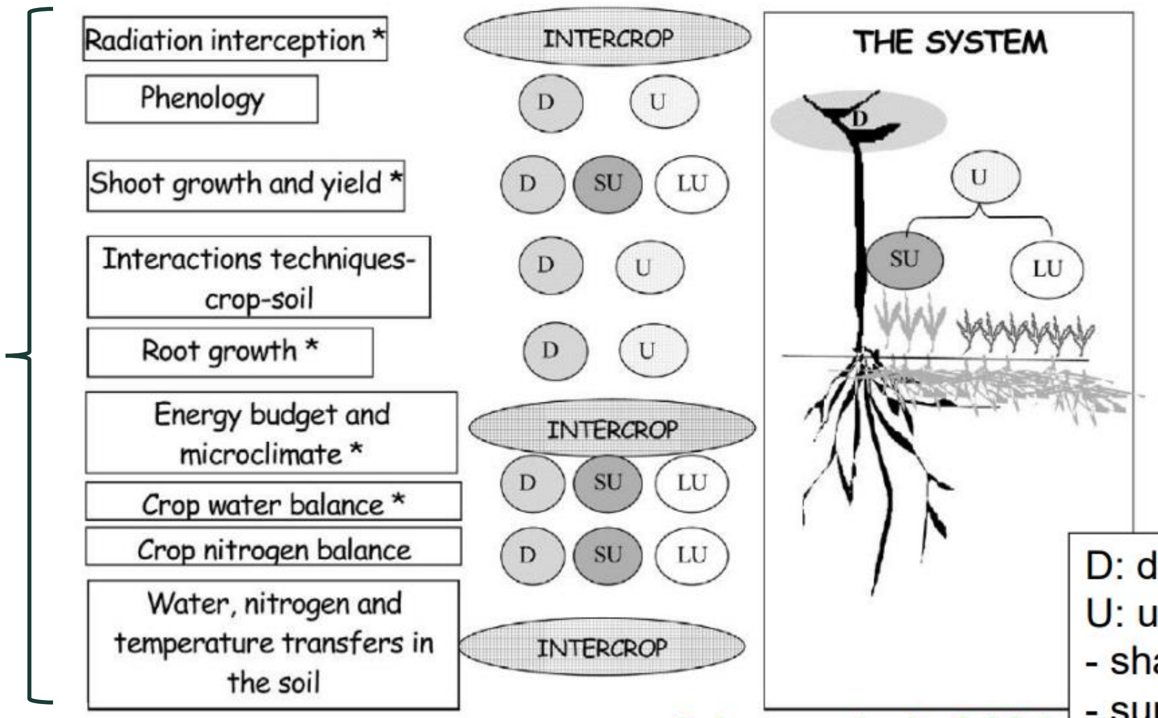
+ Intercepted radiation
+ Transpiration
- Soil evaporation

STICS model



Modelled processes

Adapatation to intercropping



Brisson et al., 2004

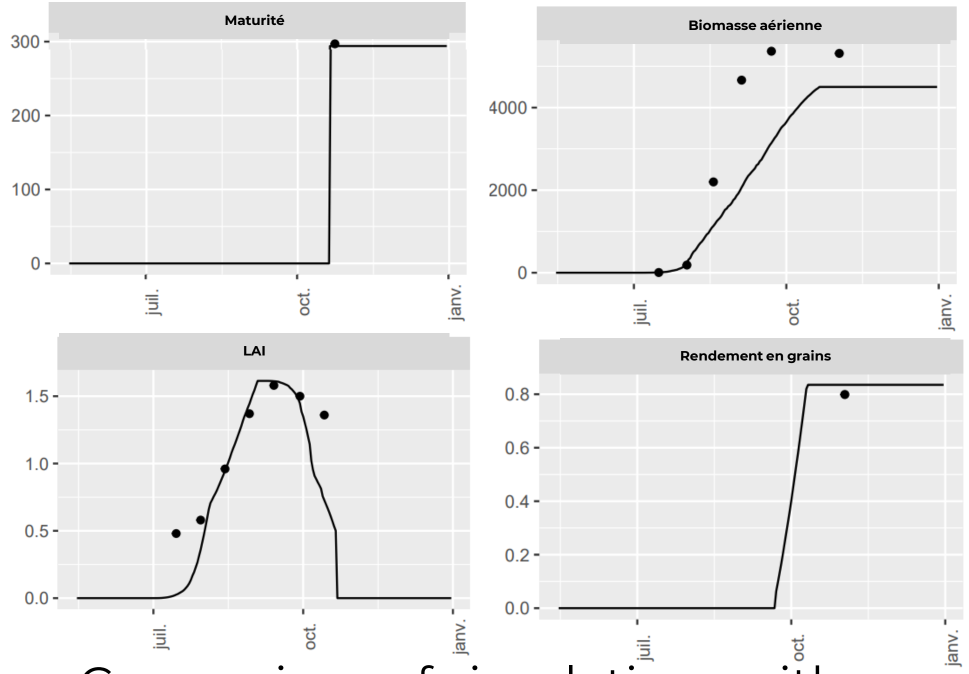
D: dominant crop;
U: understorey crop
- shaded part: SU
- sunlit part: LU

Parameters calibration

Parameters of the following processes on sole crops :

- phenology
- soil water and nitrogen
- leaf area (LAI)
- nitrogen absorbed by crops
- above-ground biomass
- number of grains
- grain yield

Calibration of the parameter of competition for light in intercropping
Maximising model accuracy.



Comparison of simulations with observations of sorghum grown as a pure crop in Mali, using SticsRPacks

Calibration des paramètres du modèle

Mesures de la précision du modèle

$$\text{Ef} = 1 - \frac{\sum_i^n (S_i - O_i)^2}{\sum_i^n (O_i - \bar{O})^2}$$

$$\text{rRMSE} = \sqrt{\sum_i^n \frac{(S_i - O_i)^2}{n}} \cdot \frac{1}{\bar{O}} \cdot 100$$

S_i : simulation
O_i : observation
$\bar{O}$: moyenne des observations
n : nombre d'observations / simulations

What are the benefits of cereal-legume intercropping compared with cereal sole cropping with and without fertilisation in the face of inter-annual rainfall variability?

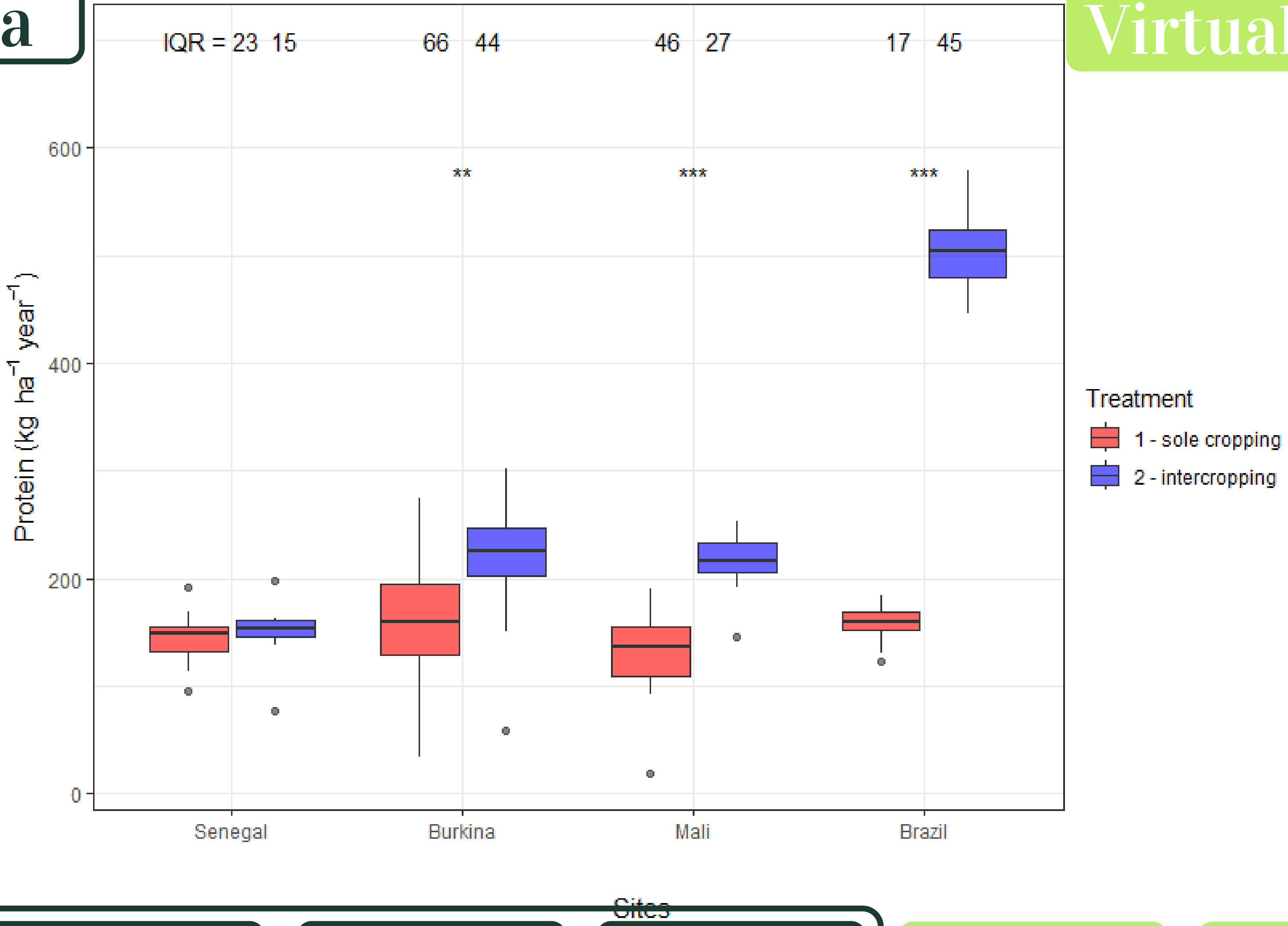
Hypotheses 1 : higher and more stable grain yields produced by intercropping compared to cereal sole cropping without fertilisation.

Hypotheses 2: the benefits of cereal-legume intercropping compared to cereal sole cropping decrease when the level of nitrogen fertilisation increases.

Hypotheses 3: the yield gain of intercropping compared to cereal sole cropping decreases with increasing annual rainfall.

N = 0kg/ha

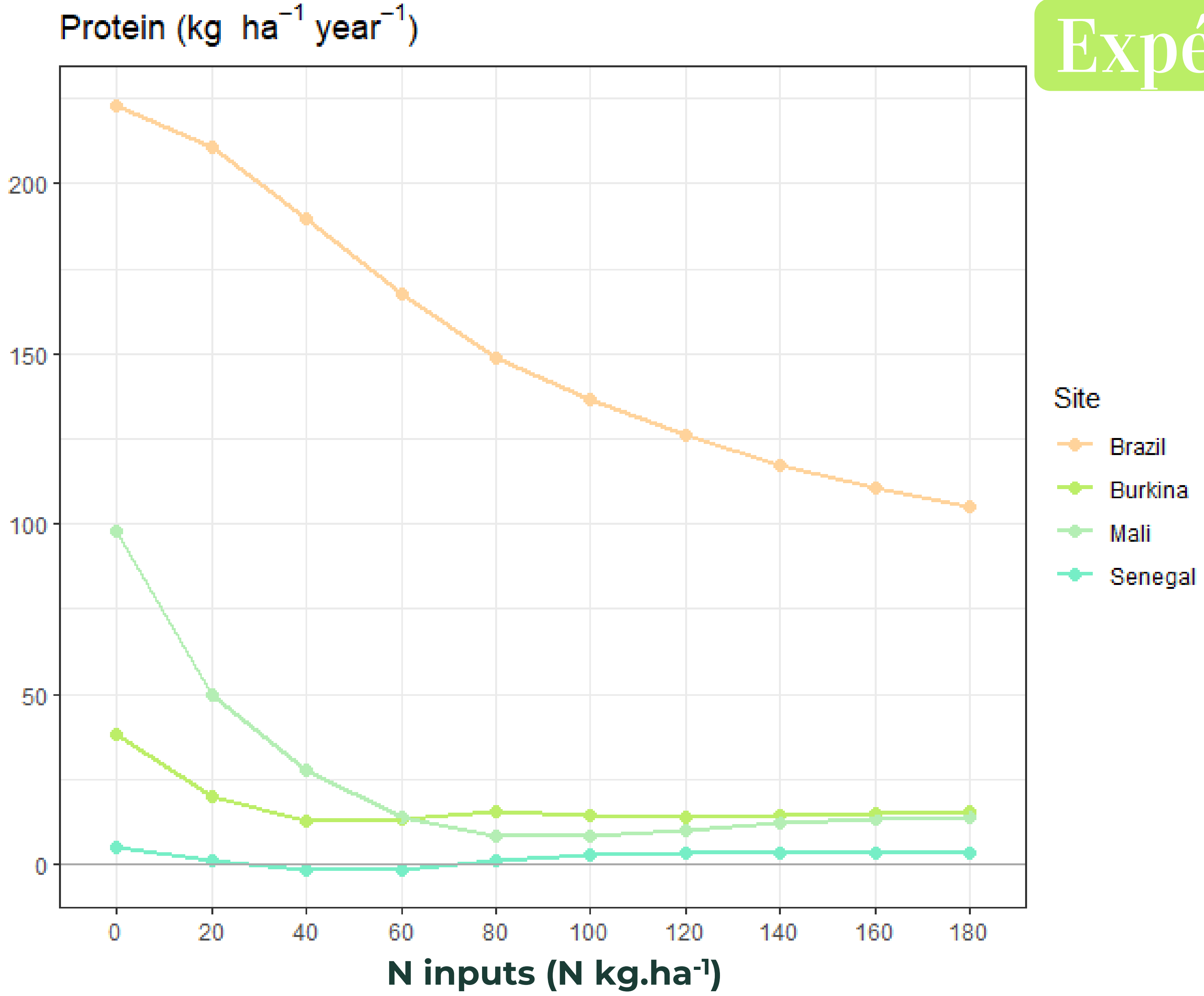
Virtual exp



Fertilisation

Expé virtuelle

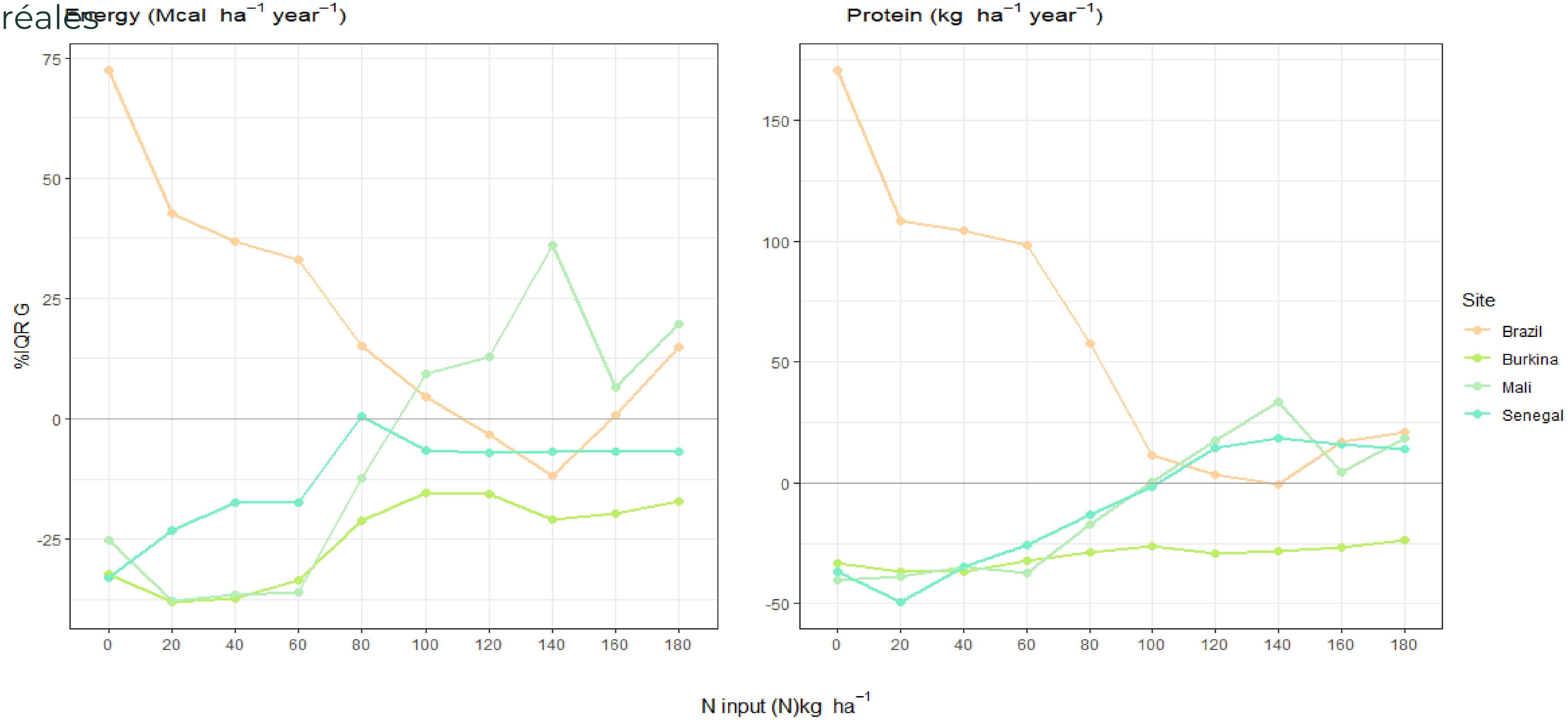
Effet de la fertilisation sur le gain relatif moyen de productivité en association par rapport à la culture pure de céréales



Fertilisation

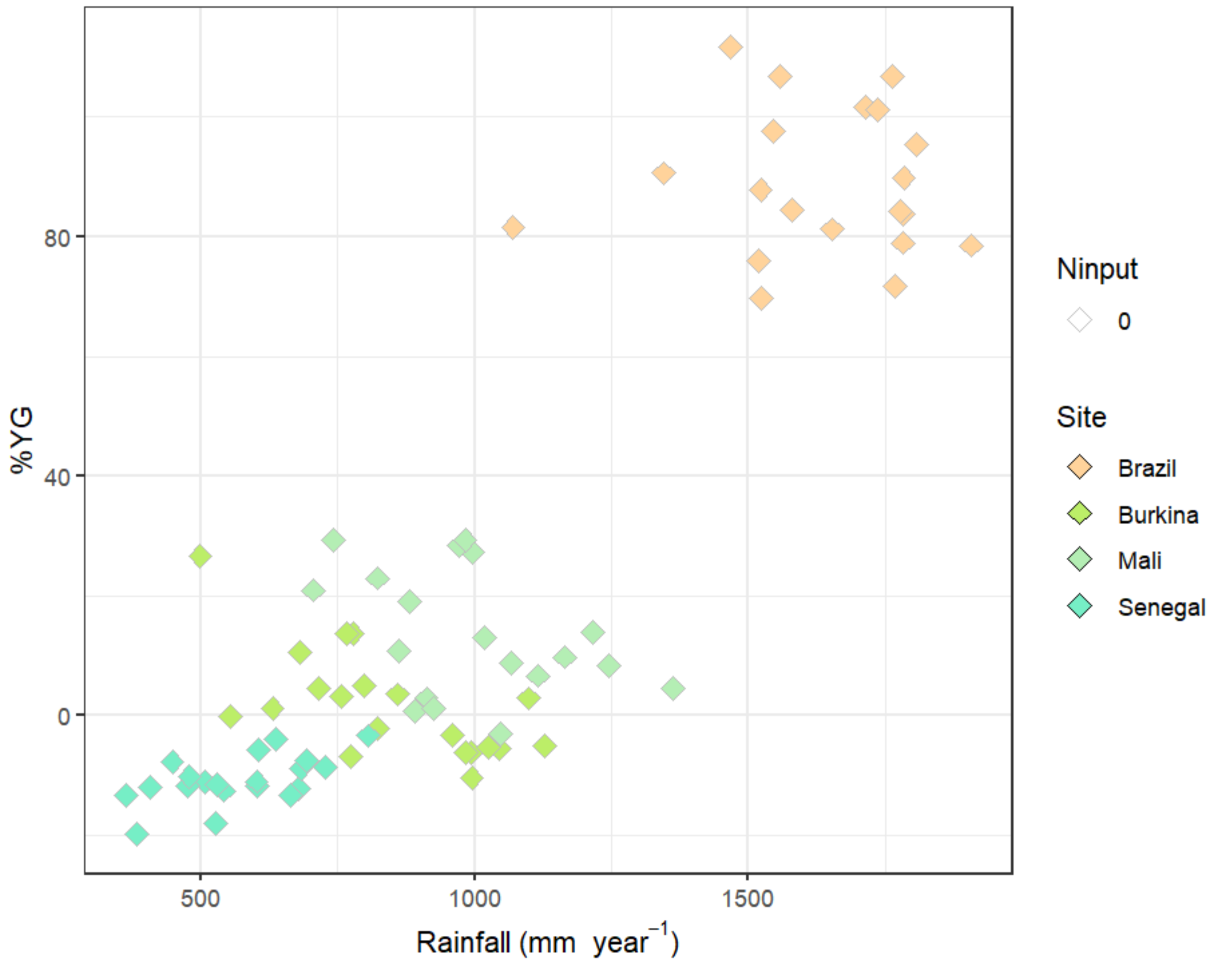
Expé virtuelle

Effet de la fertilisation sur le gain relatif moyen de variabilité en association par rapport à la culture pure de céréales



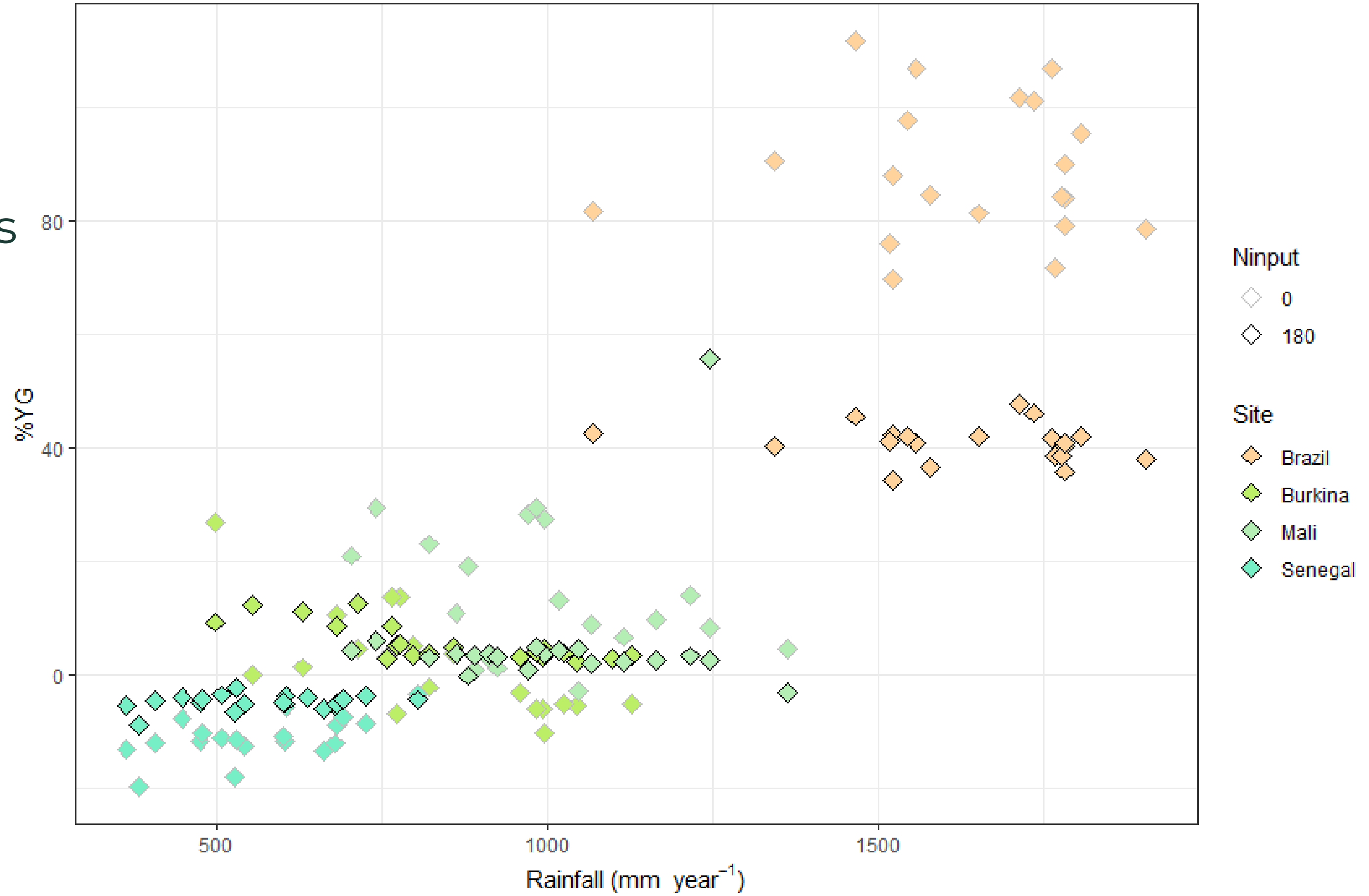
Contexte | Problématique | Démarche | Résultats | Discussion | Conclusion

Effect of rainfall on the mean relative gain in grain productivity in intercropping compared to cereal sole cropping.

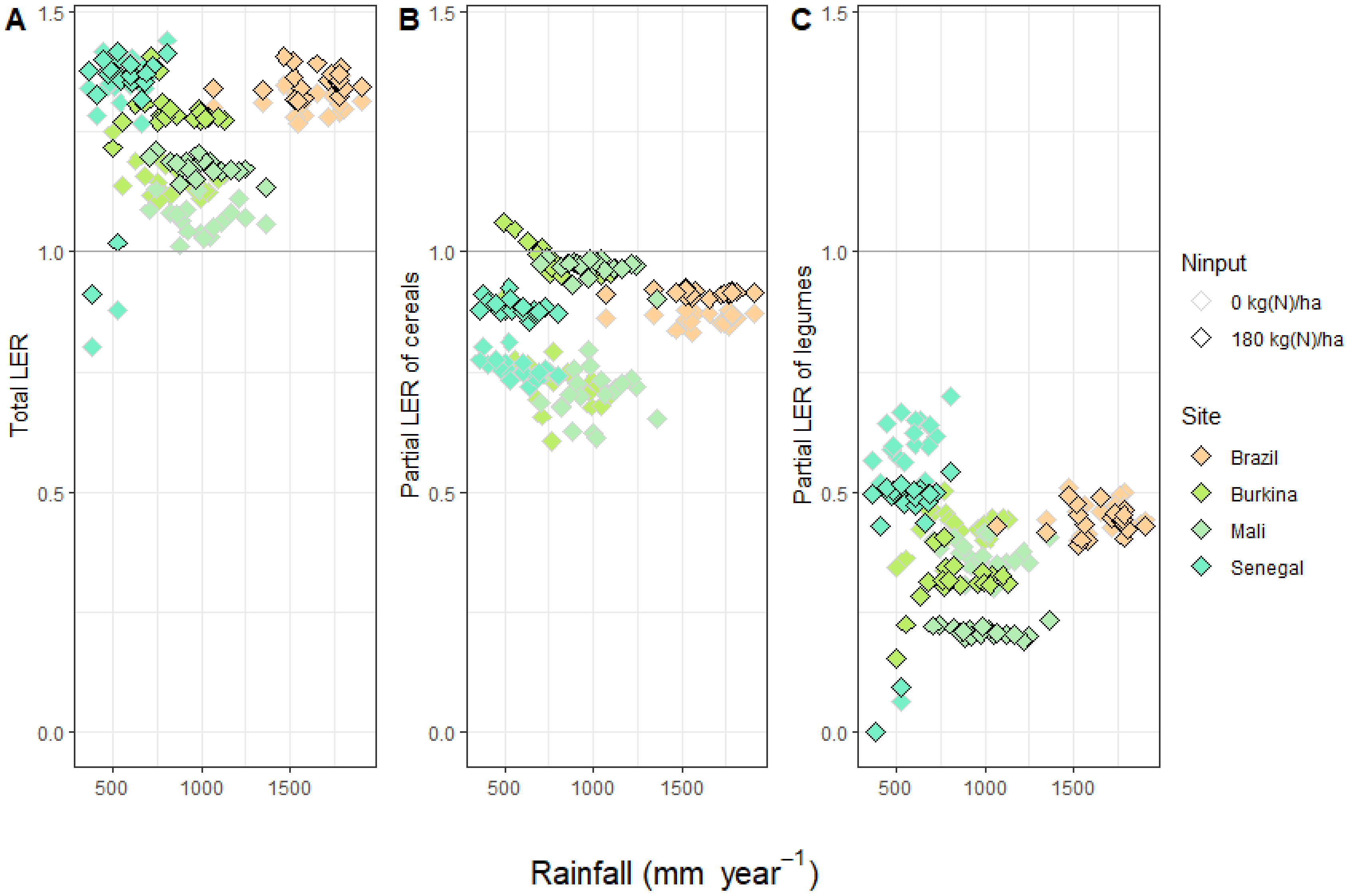


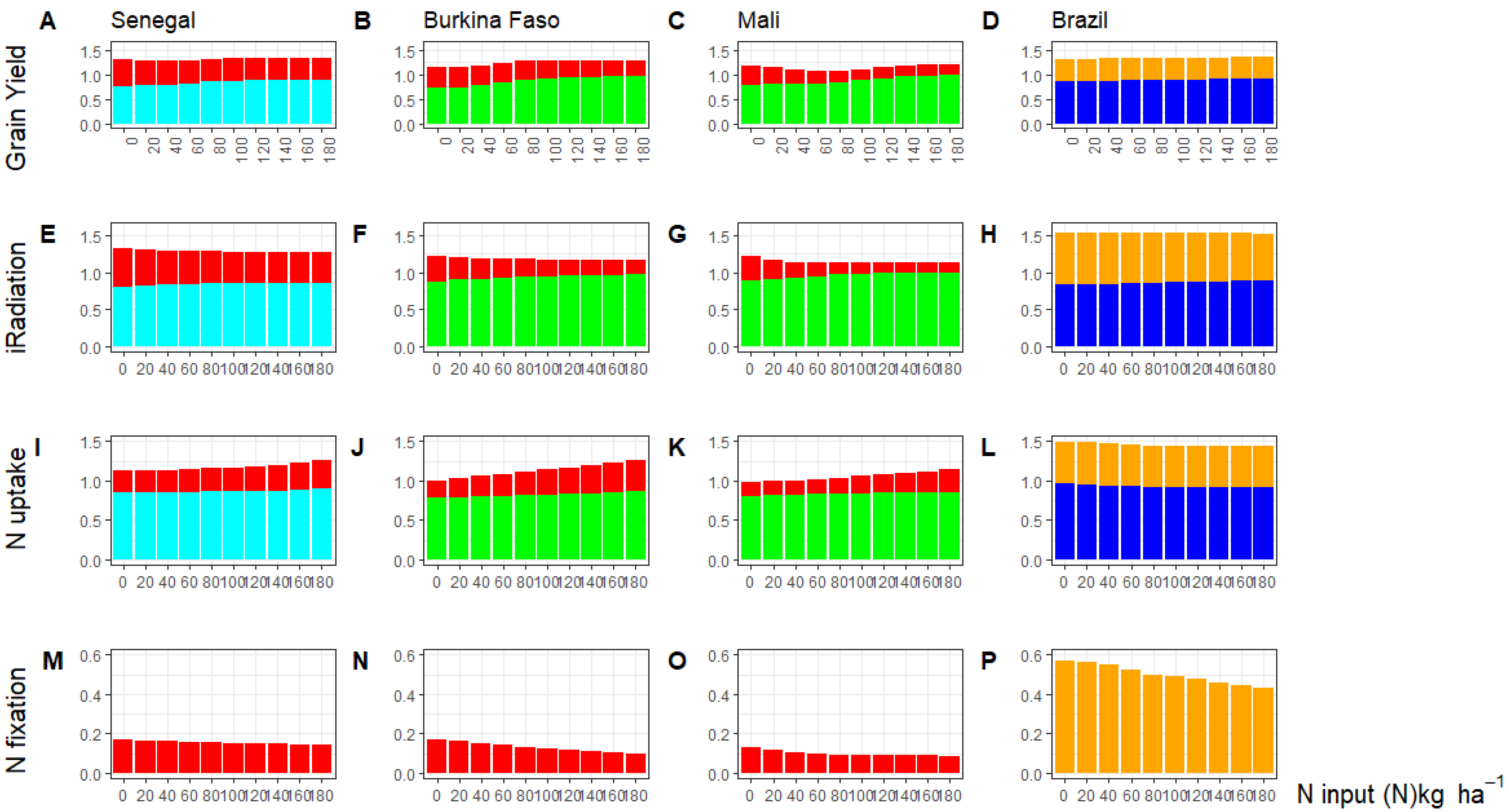
- **Significant positive effect of rainfall on productivity gains in unfertilised intercropping**

Effet des précipitations sur le gain relatif moyen de productivité en grains en association par rapport à la culture pure de céréales



- **Effet positif significatif des précipitations sur le gain de productivité en association non fertilisée**
- **Pas d'effet significative des précipitations lorsque l'association est fertilisée**

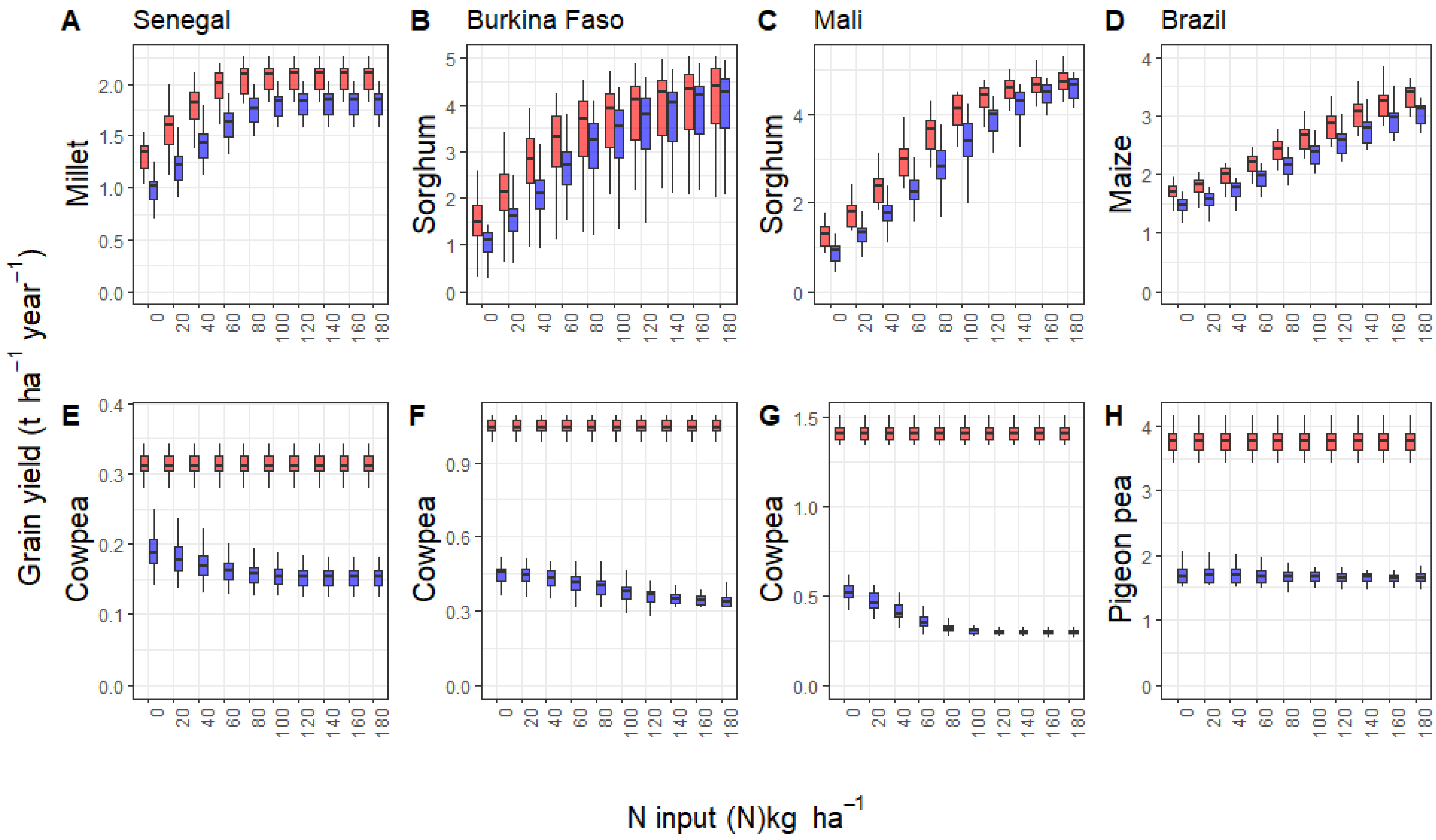

A
B
C
Total LER
Partial LER of cereals
Partial LER of legumes
0.0
0.5
1.0
1.5
500
1000
1500
Ninput
0 kg(N)/ha
180 kg(N)/ha
Site
Brazil
Burkina
Mali
Senegal
Rainfall (mm year^{-1})



A Senegal
B Burkina Faso
C Mali
D Brazil
Grain Yield
iRadiation
N uptake
N fixation
E
F
G
H
I
J
K
L
M
N
O
P
N input (N)kg ha^{-1}

Average LER for transpiration of cereals and legumes for fertilised and unfertilised conditions. Average was calculated over twenty simulated cropping seasons

Site	Variable	Mean LER for 0 (N)kg/ha	Mean LER for 180 (N)kg/ha
Brazil	Transpiration	1.14	1.11
Burkina Faso	Transpiration	1.05	1.07
Mali	Transpiration	1.07	1.07
Senegal	Transpiration	0.99	0.94


A Senegal
B Burkina Faso
C Mali
D Brazil
Millet
Sorghum
Sorghum
Maize
E
F
G
H
Cowpea
Cowpea
Cowpea
Pigeon pea
Grain yield (t ha−1 year−1)
N input (N)kg ha−1

Mean fraction of intercepted radiation by cereals and legumes in intercropping over the twenty simulated years in Senegal (A), Burkina Faso (B), Mali (C) and Brazil (D)