A semi-mechanistic phosphorus module for the STICS soil-crop model: Formalization and multi-site evaluation on maize in temperate area

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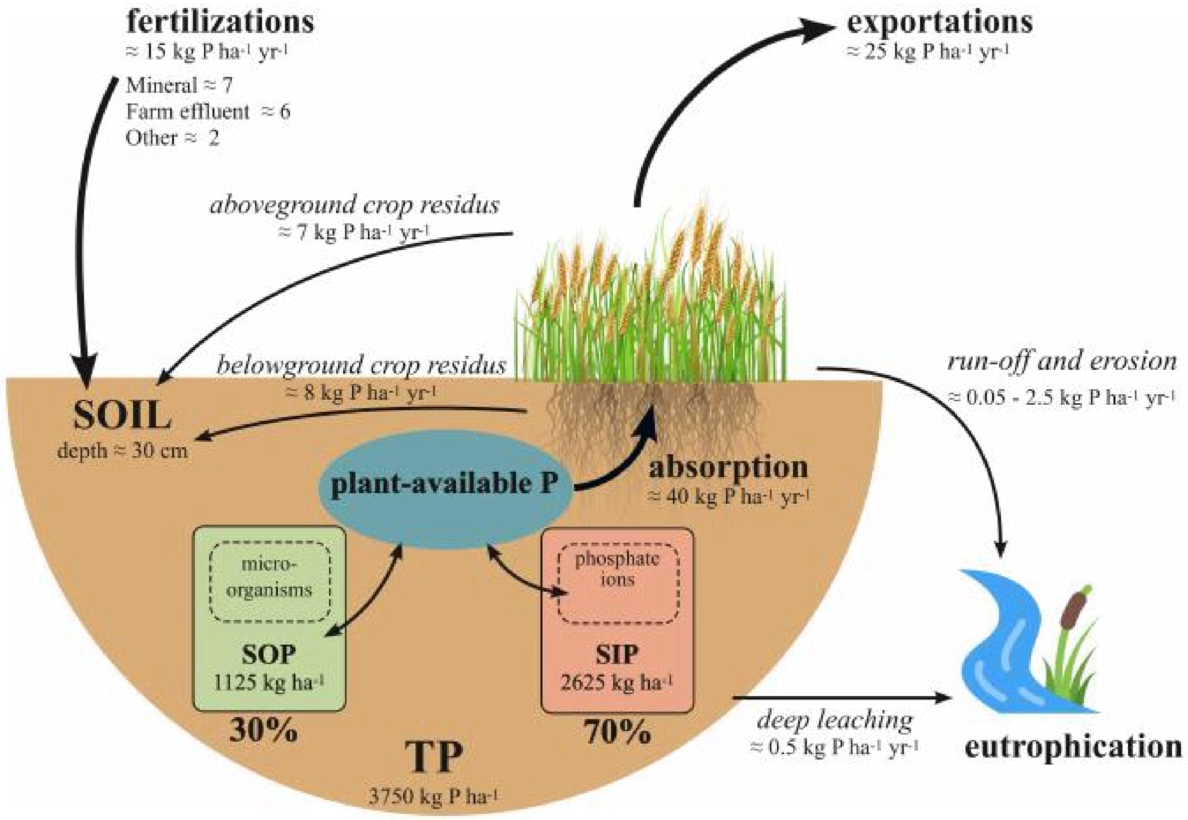
18th Congress of the European Society for Agronomy in Rennes, France

Context

Management of crop phosphorus nutrition is one of the key sustainability challenges

Understanding the biogeochemical P cycle and processes involved has significantly progressed



Raguet, 2023

Soil-crop models are useful tools for bringing these knowledges together to improve nutrient use efficiency and adapt practices to challenges such as agroecological transition & climate change

Issues

- Few crop model accounts for P (compared to N)
- Most models focus on the rhizospheric P and short time
- Crop P response is poorly managed

Objectives

Development and incorporation of soil and plant P modules in the STICS soil-crop model :

Plant P module

Root P uptake module

Soil P module

Assess the performance of the model on predicting P uptake and crop growth :
Evaluation in four long-term P fertilisation experiments on maize

Model summary

STICS, a functional process-based soil-crop model

Main inputs

Daily climatic conditions
- Temperature: minimum and maximum
- Solar radiation
- Rainfall
- Air humidity
- Wind speed
- CO_2 concentration

Crop management
- Sowing: date, depth & density
- Soil tillage
- Exogenous organic matter inputs
- Irrigation & fertilization: date, amount & type
- Special techniques: pruning, cutting, …
- Harvest: date & residue management

Cultivated plants
- Species and cultivars
- Ecophysiological properties
- Initial status

Soil permanent and initial properties
- Soil depth
- Water content at wilting point & field capacity
- Bulk density
- Stone content
- Clay content , $CaCO_3$, pH , organic N, C:N ratio
- Initial water and N contents
- …

STICS modules

Crop ecophysiology
- Crop phenology & leaf dynamic
- Above- and belowground growth
- Yield elaboration

Crop microclimate
- Soil temperature
- Crop temperature

Plant, soil & management interactions
- Water demand and management
- Nitrogen demand, fixation and management
- Organic matter cycling and management

Soil – root interactions
- Root density profile
- Water balance
- Nitrogen & carbon balance
- Water, nitrogen and heat transfer

Main outputs

Plant development
- Phenological development
- Leaf area index
- Plant/tiller density
- …

Root system growth
- Root front growth
- Root density profile
- Root biomass

Aboveground growth
- Aboveground biomass & organs' repartition
- Yield components
- Yield quality (water, protein, oil, …)
- Plant N uptake & grain N content

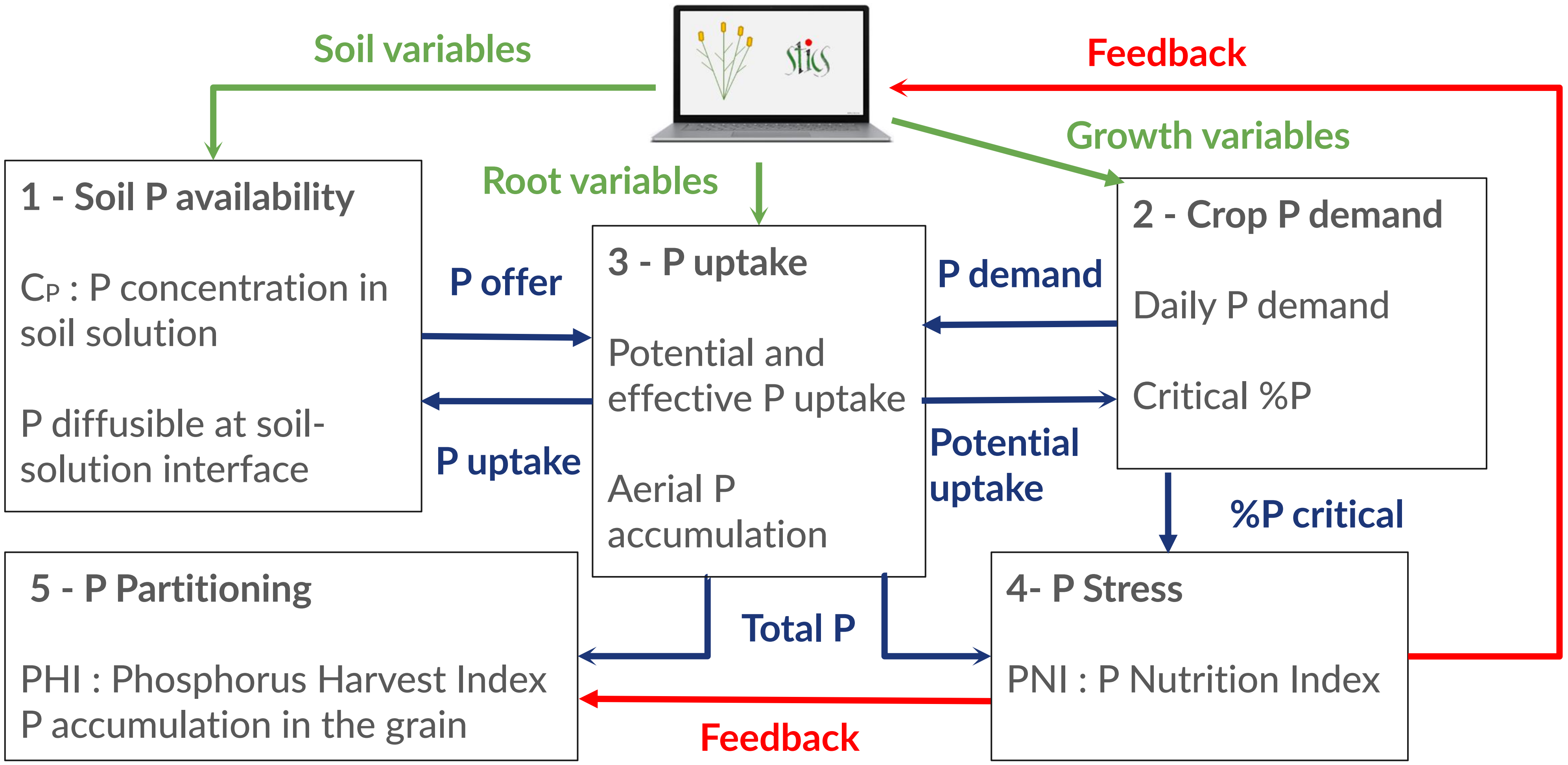
Plant sensed stresses
- Water (deficit and anoxia) stress indices
- Nitrogen stress index
- Frost and high temperature stress indices

Soil water & nitrogen balances
- Soil water content, soil/mulch evaporation and plant transpiration
- Soil mineral N, soil organic C and N stocks, soil CO_2 and N_2O emissions
- Water drainage & N leaching

Soil structure
- Compaction and fragmentation

Beaudoin et al. (2023) – adapted from Lenoir (2024)

Model Summary



Soil P availability

Amount of soil available P for each soil layer *E* (mg P kg^{-1}) is calculated as :

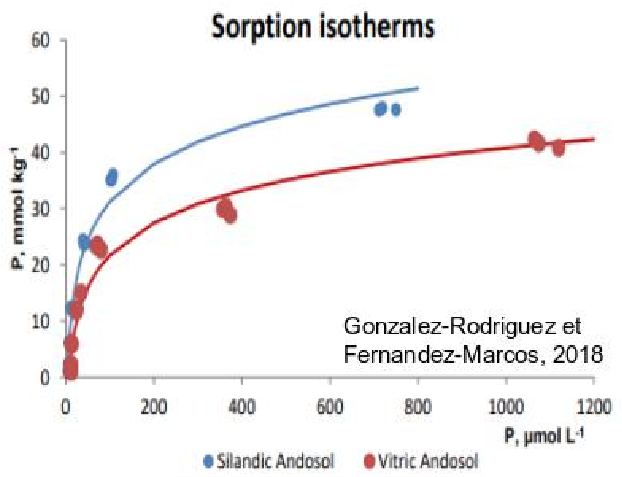
$$E = Q_w + P_r$$

Q_w (mg P kg^{-1}) Content of orthophosphate ions in soil solution

$$Q_W = \theta \times C_P$$

P_r (mg P kg^{-1}) The quantity of P that can resplenish the soil solution in one day from the solid phase
Described by **Freundlich kinetic isotherm**
→ **Soil buffer capacity**

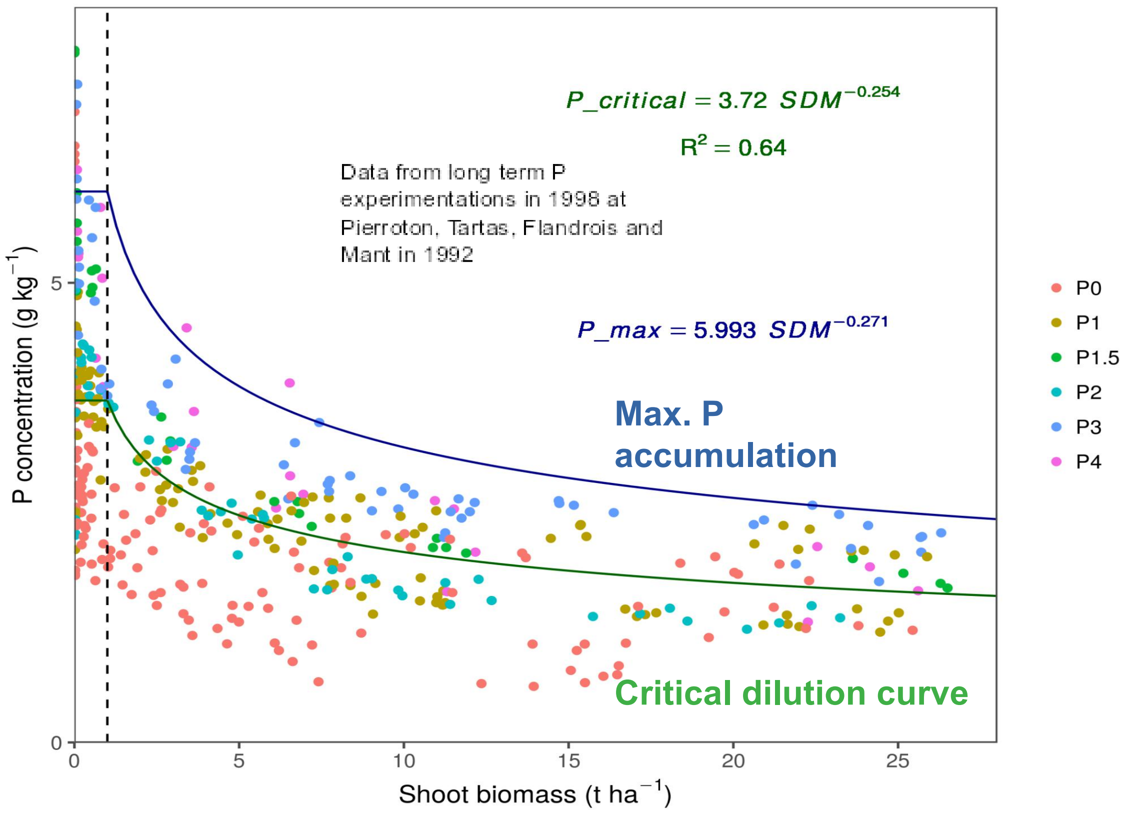
$$P_r = vC_P^W t^p$$



Does not account for organic P **(Raguet et al., 2023)**

Does not account for rhizospheric processes e.g (Mycorrhizae, Citrates, Phosphatases...)

Plant P demand



P dilution is observed in maize crops from a threshold of 1t ha^{-1}

Dilution Curves : %P = a x W^{-b}

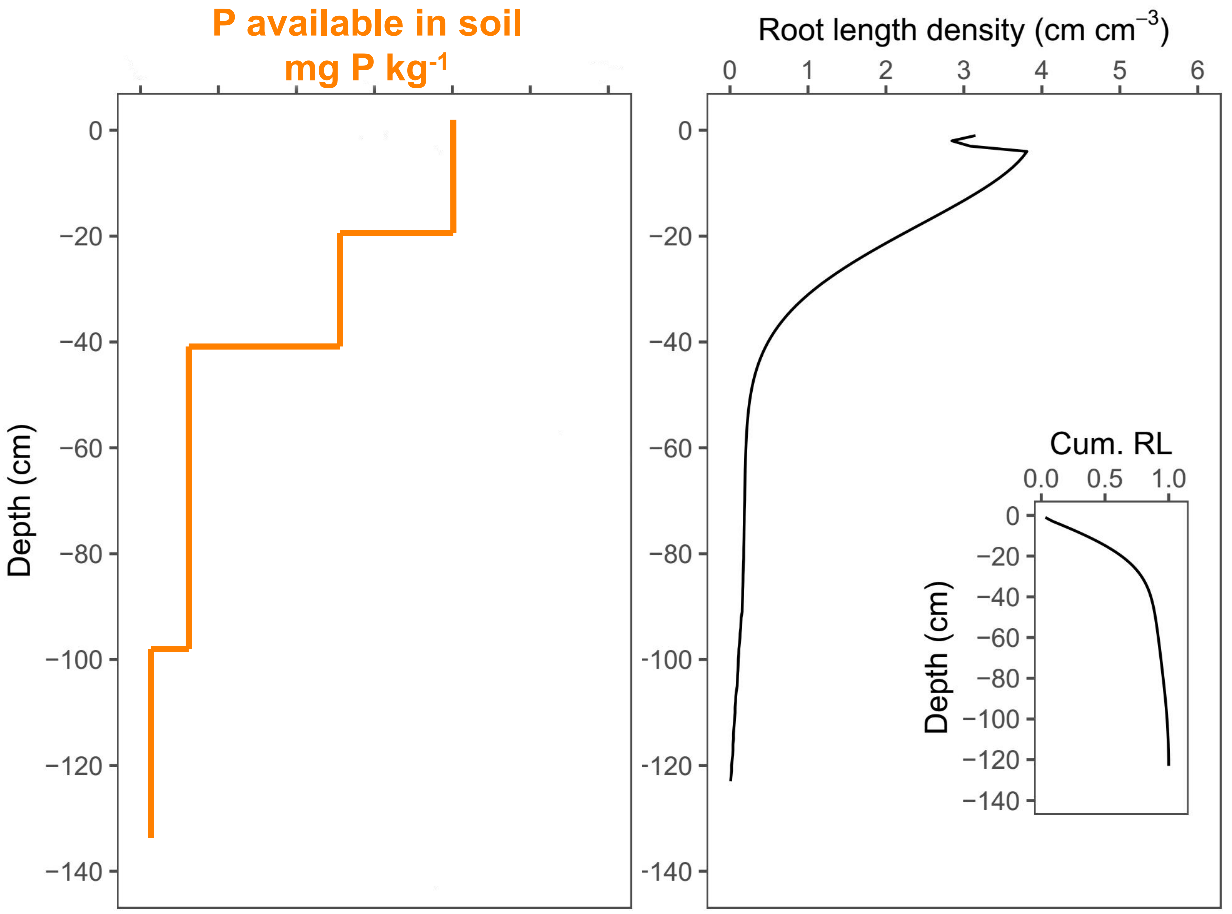
Critical dilution curve (Optimum) → Below which the crop is deficient in P

→ **Daily plant P demand** is driven by biomass production

Shoot P demand = (ΔBiomass x a_{crit} x (1-b_{crit}) x $Biomass^{-bcrit}$)

Root P demand = root P % parameter x Δ root_biomass x PNI

Root P uptake



Root P uptake is computed for each 1 cm soil layer

Each layer is characterized by :

- Soil Properties
- Root Length density & Root radius

Soil P transport

- Diffusion and advection

$$\left(\frac{\delta Q}{\delta C} + \theta\right)\frac{\delta C}{\delta t} = \frac{1}{R}\frac{\delta}{\delta r}\left(rD\frac{\delta C}{\delta R}\right) - V\frac{\delta C}{\delta R}$$

Root absorption

- Assumed to behave as « **zero sink** »

$$A_{max} = 2\pi \Delta z L_{rv} D \frac{(\rho^2 - 1)}{G(\rho, \sigma)} \overline{C_P}$$

Analytical solution for advection and diffusion of nutrients to a root with zero-sink uptake (de Willigen et al., 1994)

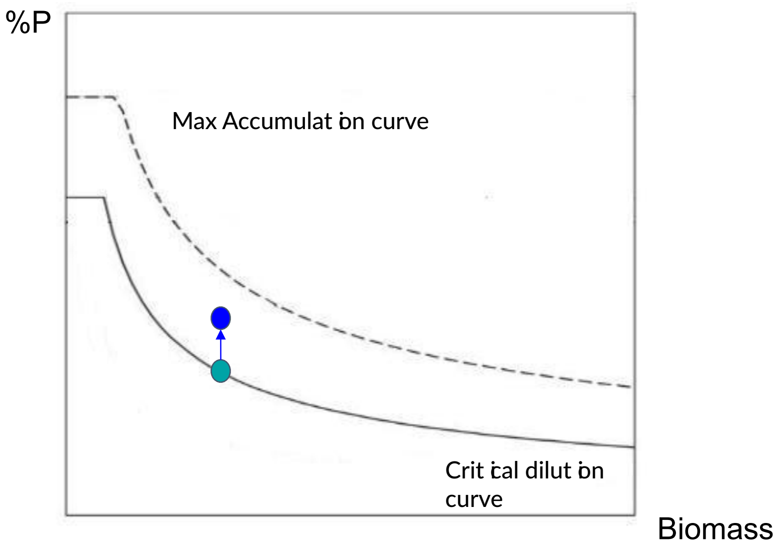
Crop P response

Effective P uptake = min (max P uptake, crop P demand)

Potential P uptake > crop P demand

Uptake = Crop P demand + surplus x coef

With surplus = Pot. P uptake – P demand



Potential P uptake < crop P demand

Crop growth P limitation

Delayed and reduced Leaf area expansion

Reduced life span of leaves

→ lower biomass accumulation

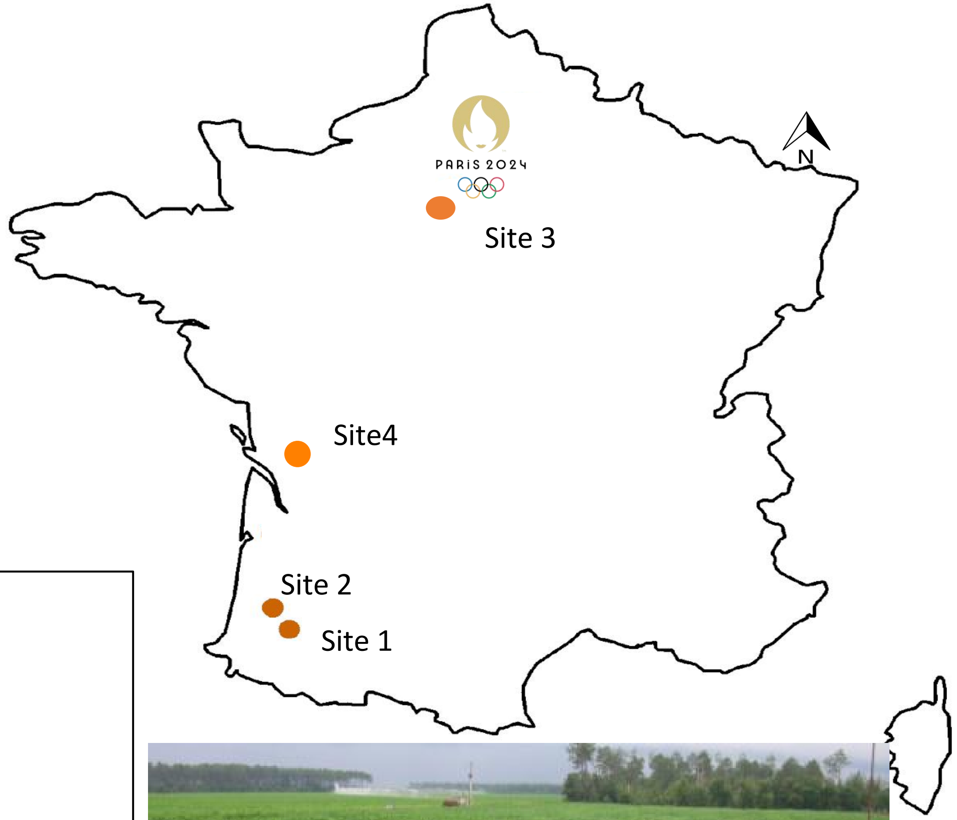
Longer and thinner roots

→ Increase root surface

Higher P harvest Index

Field dataset for evaluation of the STICS P model

Site	Name and location
1	Tartas - Carcarès Sainte-Croix (1972-2004)
2	Mant (1975-1992)
3	Folleville (1958-2022)
4	Saint-Felix (Flandrois 1979-2009)



Measurements

~1-2 cropping cycle

5-6 shoot sampling dates

LAI, Biomass, N and P content analysis

Soil P availability : C_P and Freundlich kinetic parameters / layer

Treatments

3-4 P fert. treatments (superphosphate) :
P0 - P1 - P2

Four replications

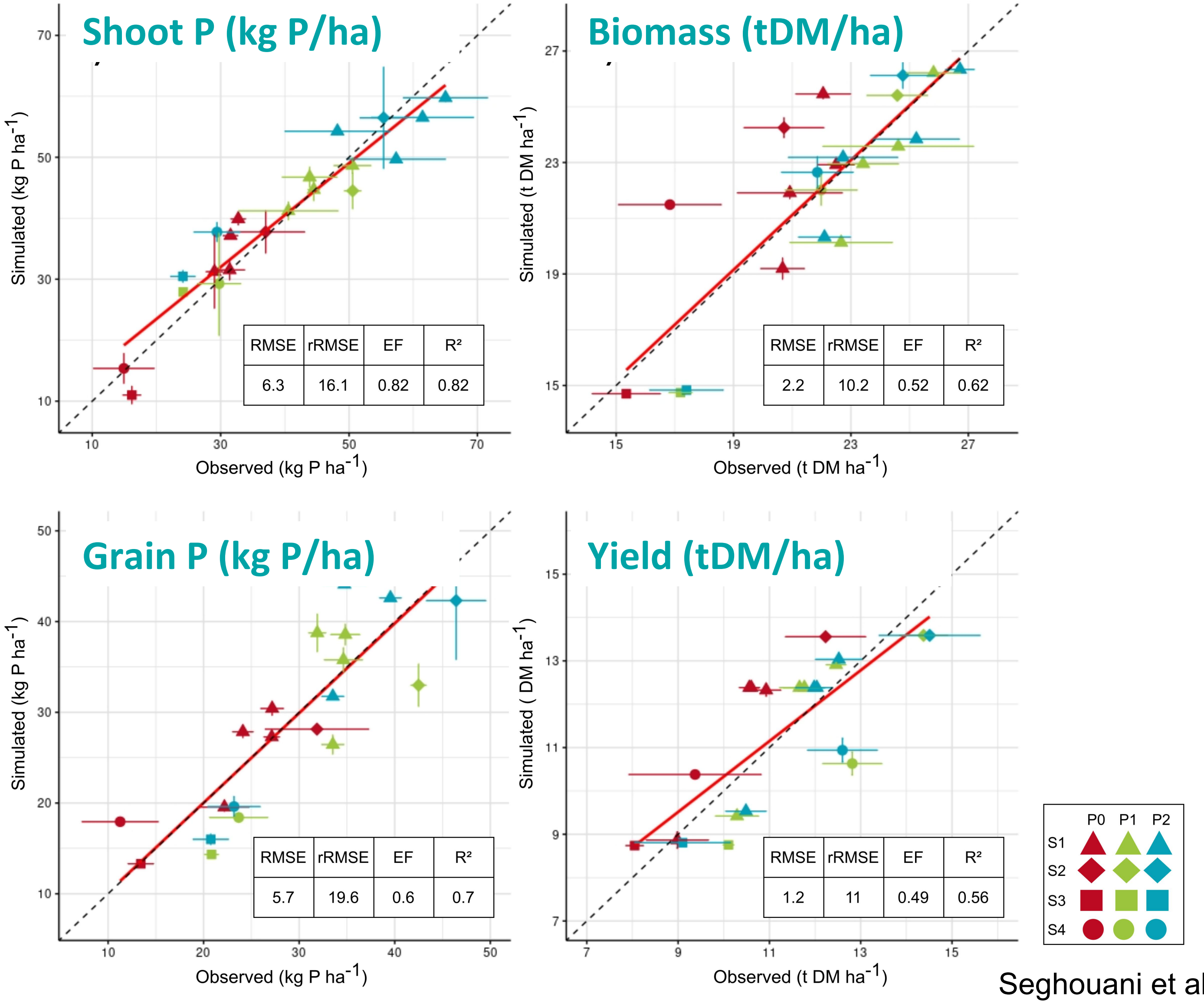
Maize cultivation

S1-S2-S4 irrigated

N fertilisation according local recommendations

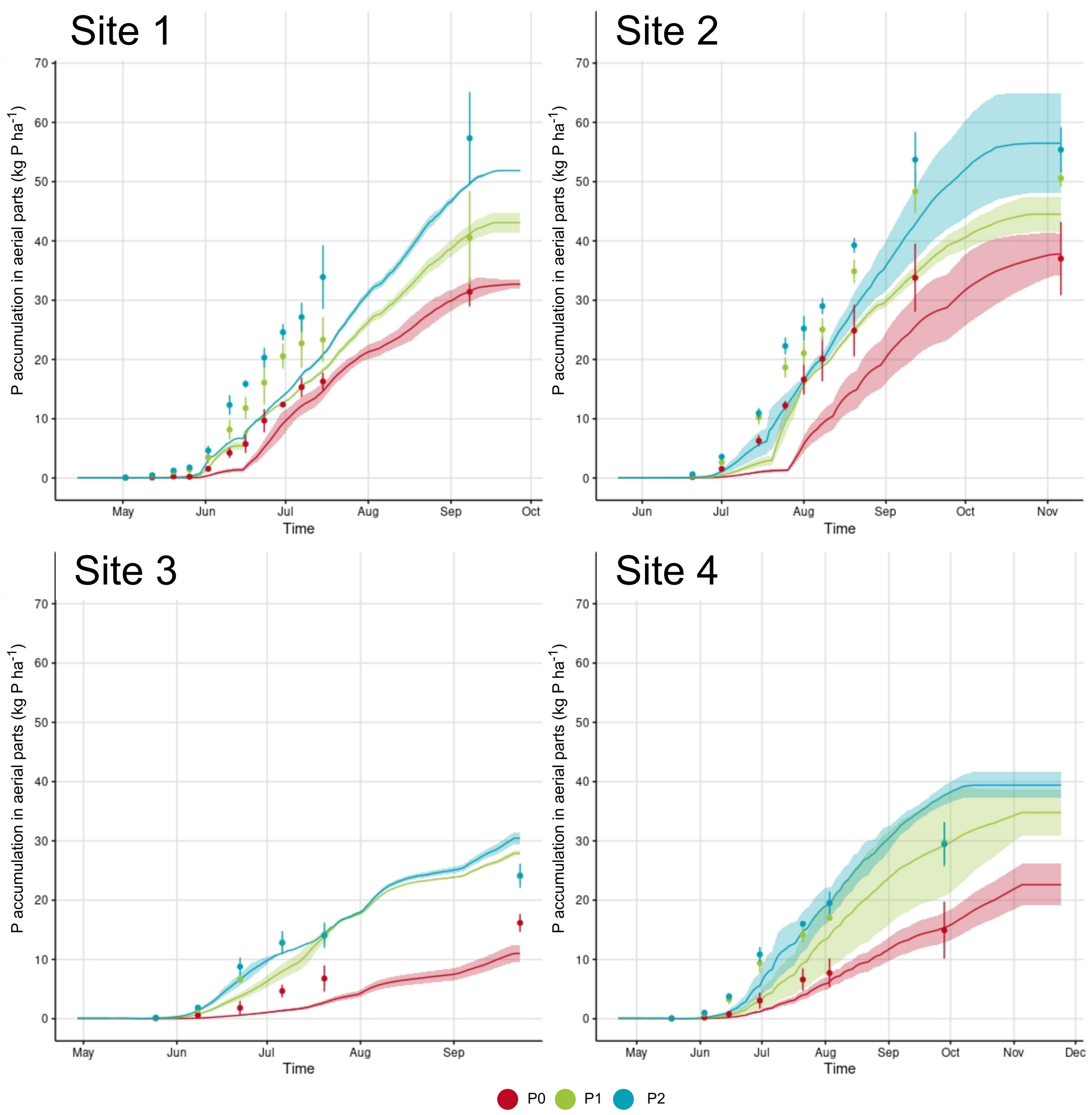
Model performances

Predictions in final P accumulation and biomass are overall good with rRMSE ranging from 10 % to 19 %



Seghouani et al 2024 under review (EJA)

Model performances



P accumulation dynamics

Underestimation of early P uptake,

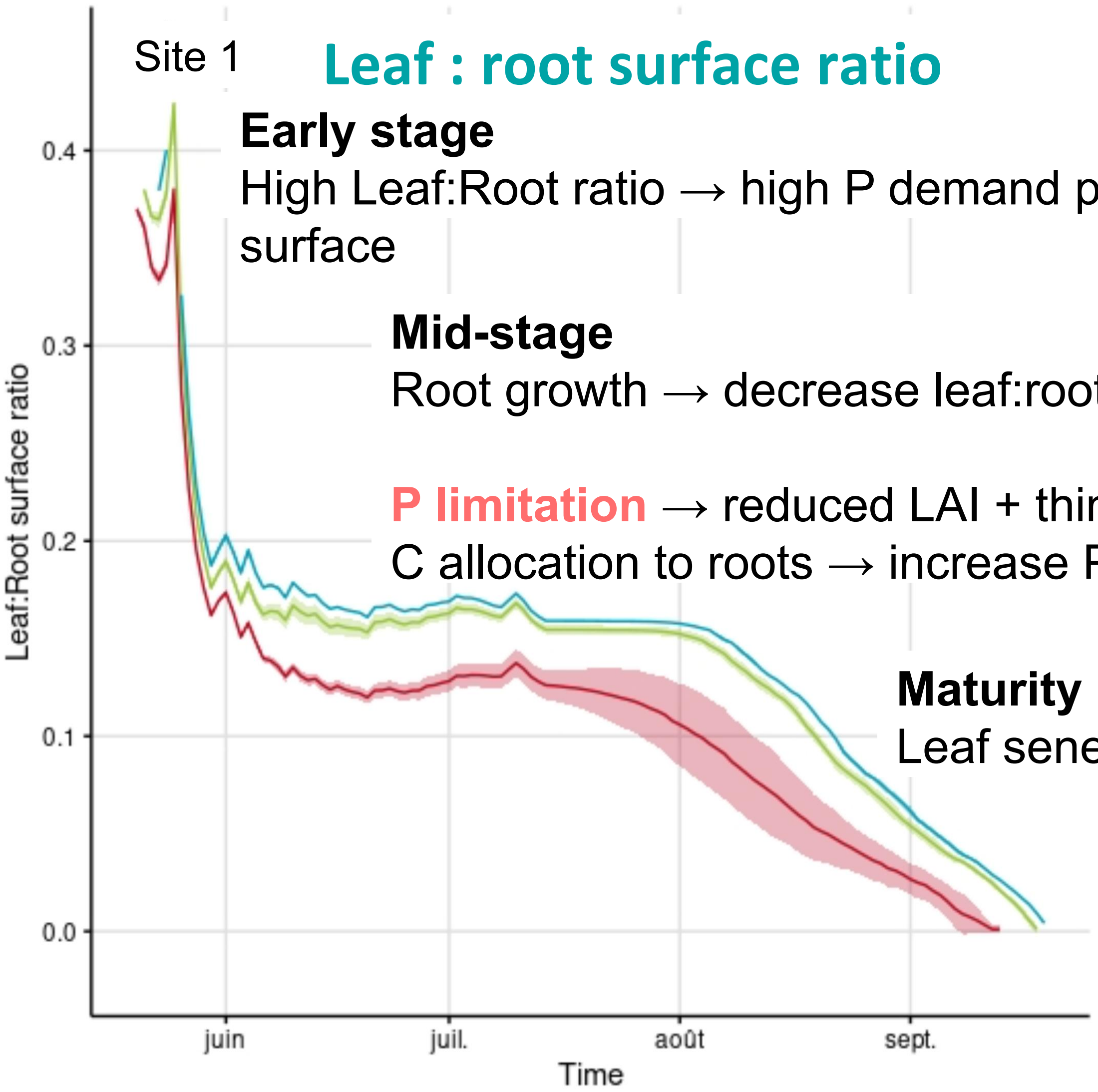
but overall good prediction of P treatments and pedoclimatic effects :

- Increasing P uptake with increasing P fertilization

- Within a site, variations in P accumulation are driven by initial C_P

Seghouani et al 2024 under review (EJA)

P stress feedback simulation



Leaf : root surface ratio

Early stage
High Leaf:Root ratio → high P demand per root surface

Mid-stage
Root growth → decrease leaf:root ratio

P limitation → reduced LAI + thinner & longer root + higher C allocation to roots → increase P uptake efficiency

Maturity
Leaf senescence → Lower Leaf:Root ratio

Seghouani et al 2024 under review (EJA)

Conclusion and further model enhancement

- The adapted STICS model for simulating P uptake and its feedback on plant growth is now available.
- First evaluations showed good performance for maize in the temperate zone under low to high P levels.
- To ensure a good simulation of the dynamics of P accumulation, particular attention must be paid to the simulation of root development, especially at the beginning of the crop cycle.

The model needs to be evaluated for other crop species and under other experimental conditions to assess both its robustness and its genericity.

Accordingly other processes will be developed and incorporated :

- organic P mineralisation
- rhizospheric processes : organic acid and phosphatase exudation
- mycorrhizal association

Thank you

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