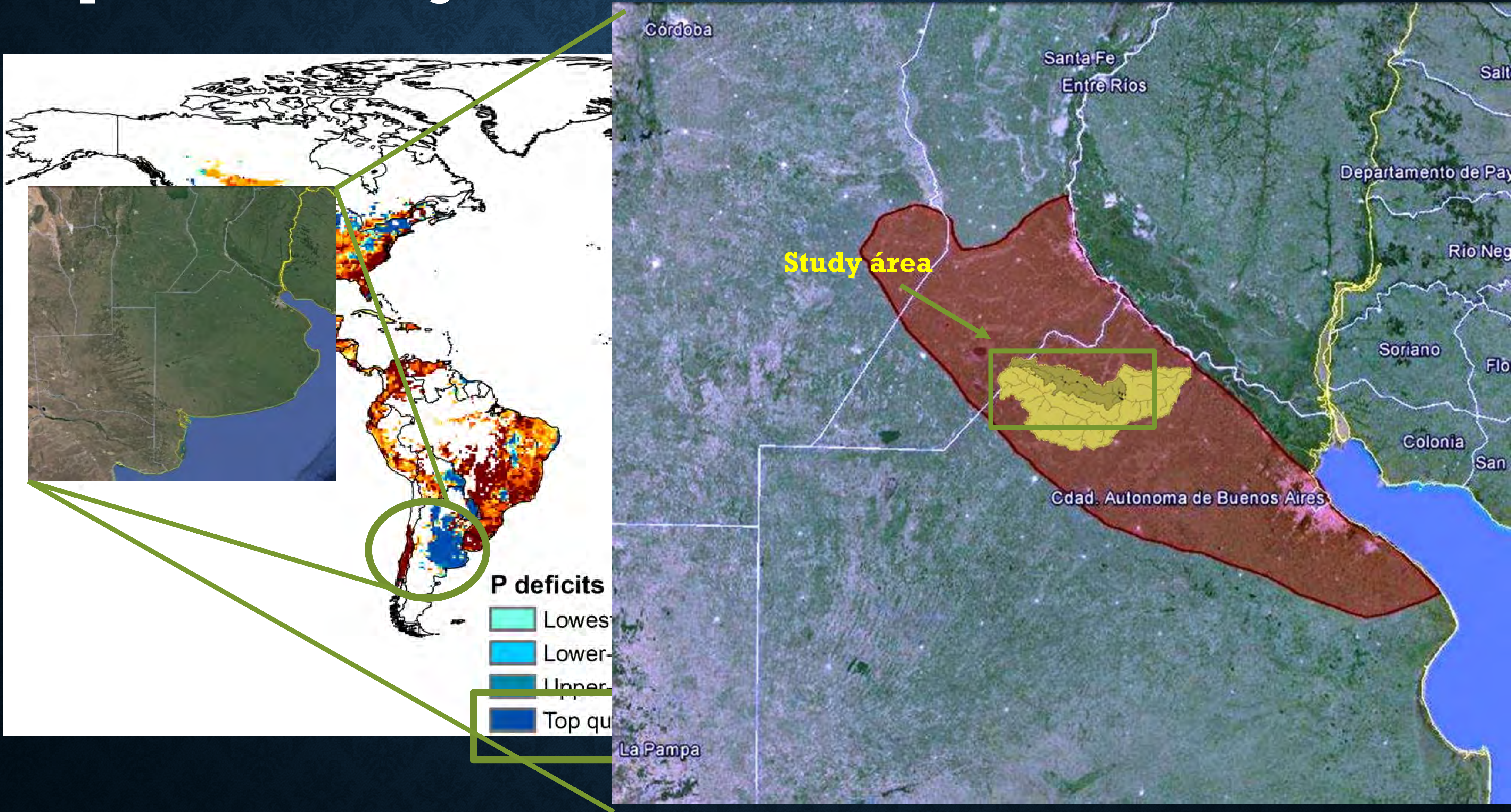
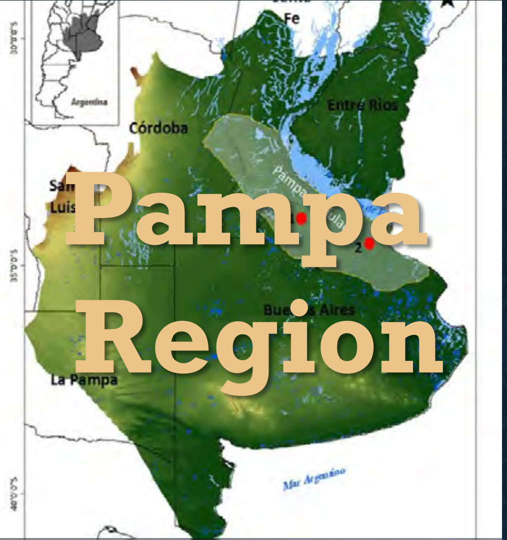
REDISTRIBUTION OF SOIL PHOSPHORUS FRACTIONS DUE TO THE USE OF COVER CROPS IN A SOYBEAN MONOCULTURE CROP SEQUENCE

INTA

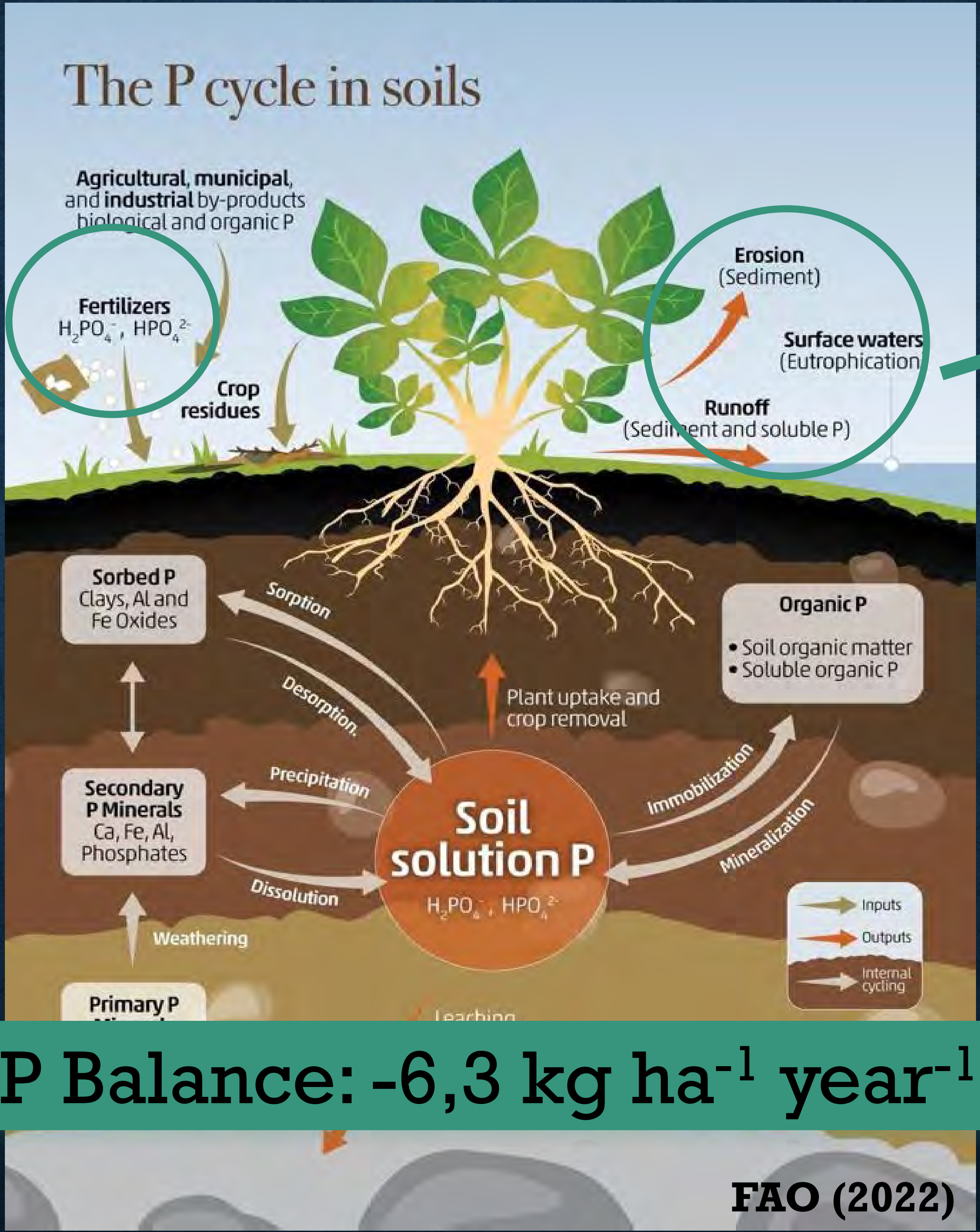
Ms. Sc. (Agr.) Ana Paula Giannini

The problem of P at global scale





Low P doses
13 kg P ha^{-1} $year^{-1}$



P Balance: -6,3 kg ha^{-1} $year^{-1}$

FAO (2022)

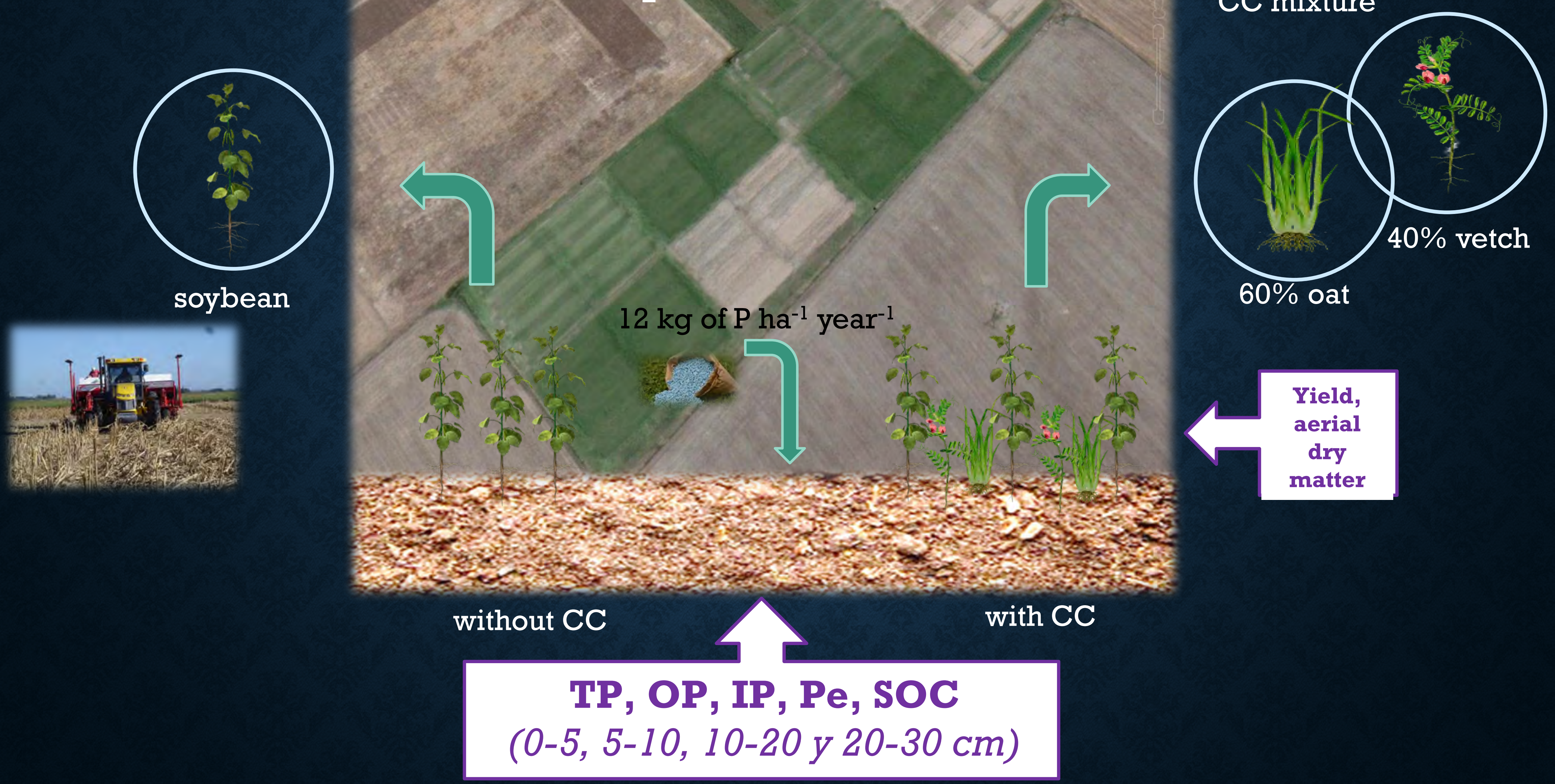
P losses
1.3±0.3 kg P ha^{-1} $year^{-1}$
Torti & Andriulo (2014)

Sustain biomass production in the future and avoid negative impacts on the environment, requires to improve current P management strategies

AIM

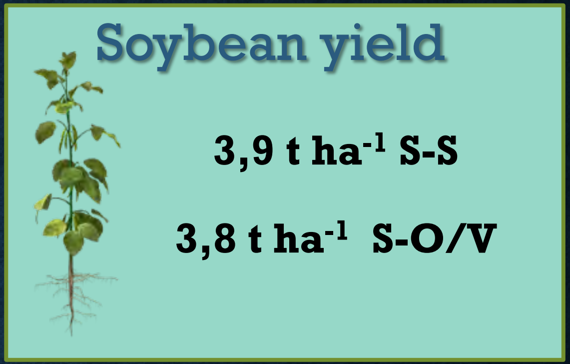
Evaluate the effect of including CC in soybean monoculture on TP, OP, IP, and Pe, SOC, yield and aerial dry matter after four and eight years in a typical Argiudol from the Argentina rolling pampa.

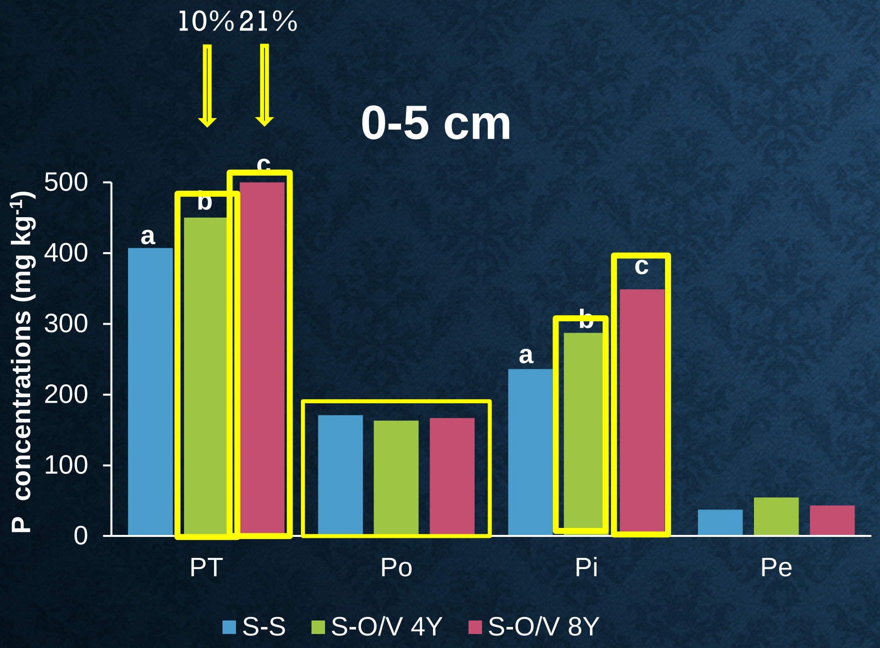
In a 31-year no-tillage soybean monoculture trial, a rotation with or without Cover Crops was evaluated

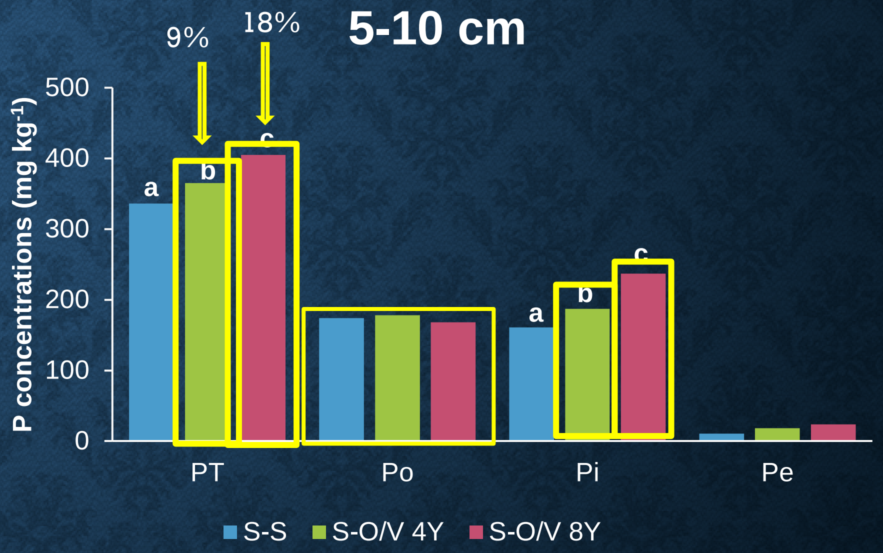



Autumn/winter period
Soybean
monoculture
Soybean-oat/vetch

Effect of the inclusion of CC on P forms



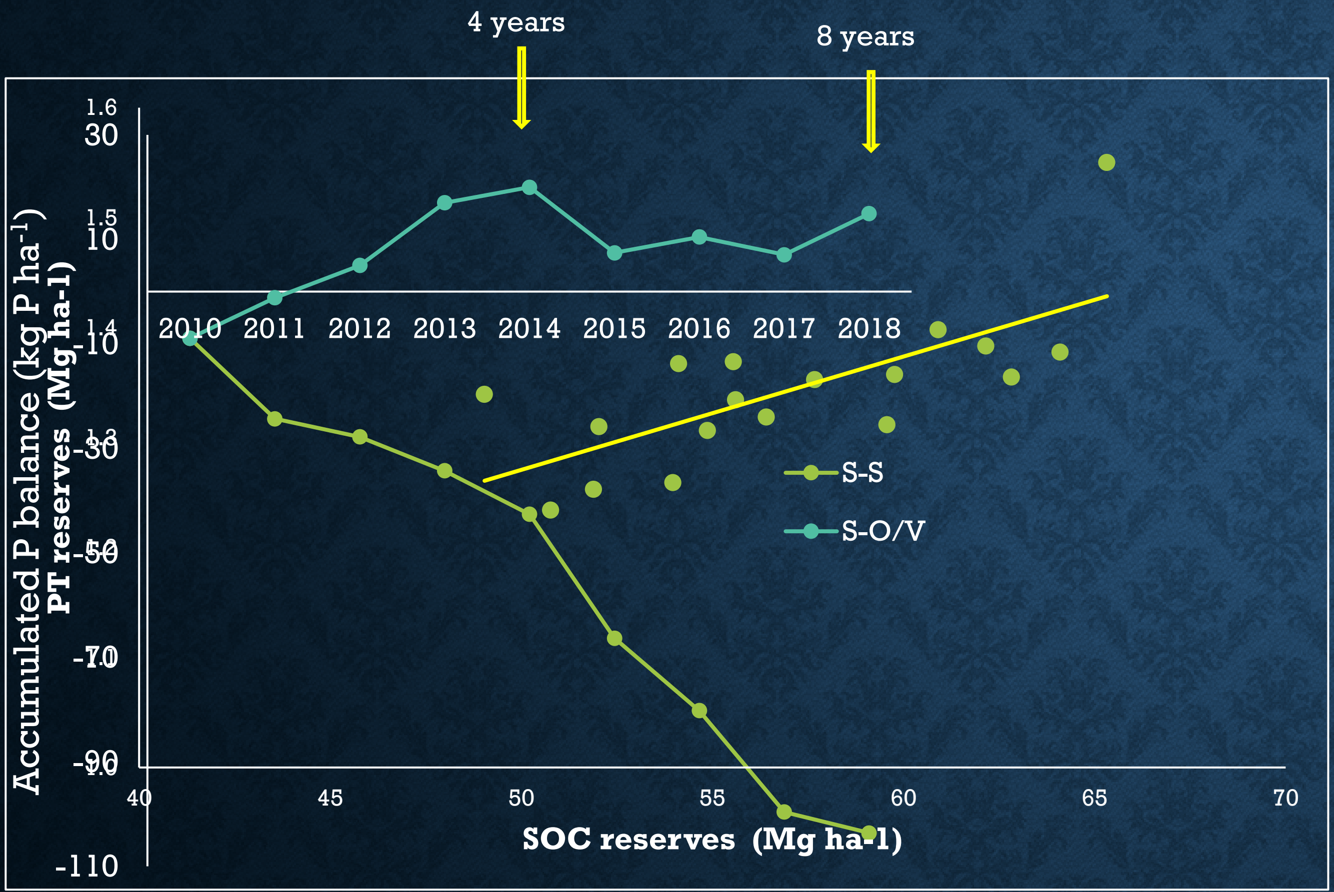




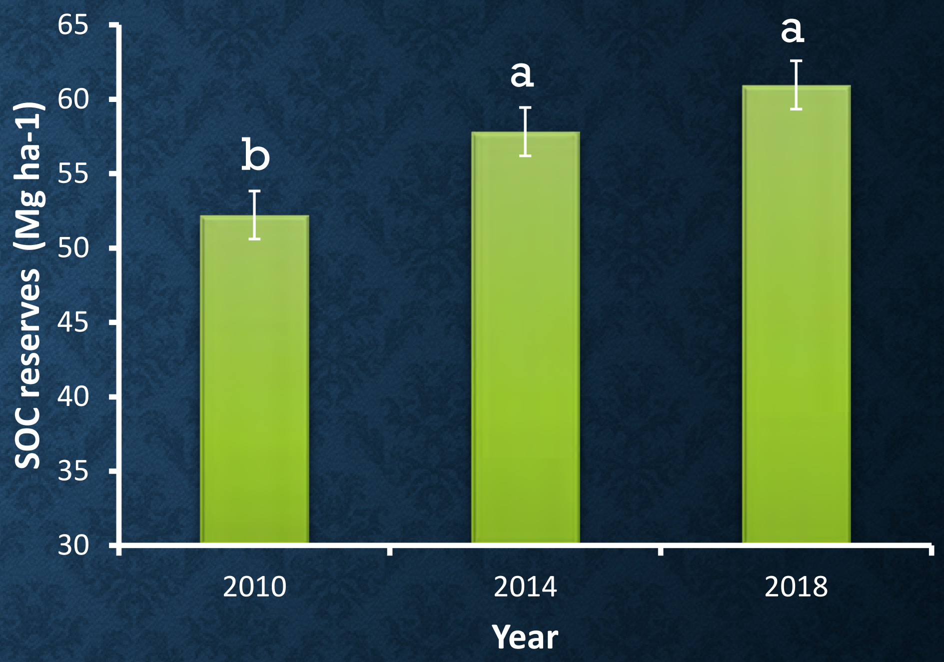
The OP issued from the CC, particularly from vetch, would provide fast recycling organic fractions to the soil, that are mineralized increasing IP, delivering it in synchrony with the requirements of the commercial crop.

The IP correlated with Pe ($p<0.01$).

Accumulated P balance



Soil Organic Carbon



SOC reserves was correlated with TP reserves at 0-30 cm (p<0.01).

P Balance: Fertilizer + O/V Mixture (0,19%) + Crop removal

input **output**

The additional carbon input from CC progressively increased the SOC reserves.

Aerial dry matter

8,1 t ha^{-1}

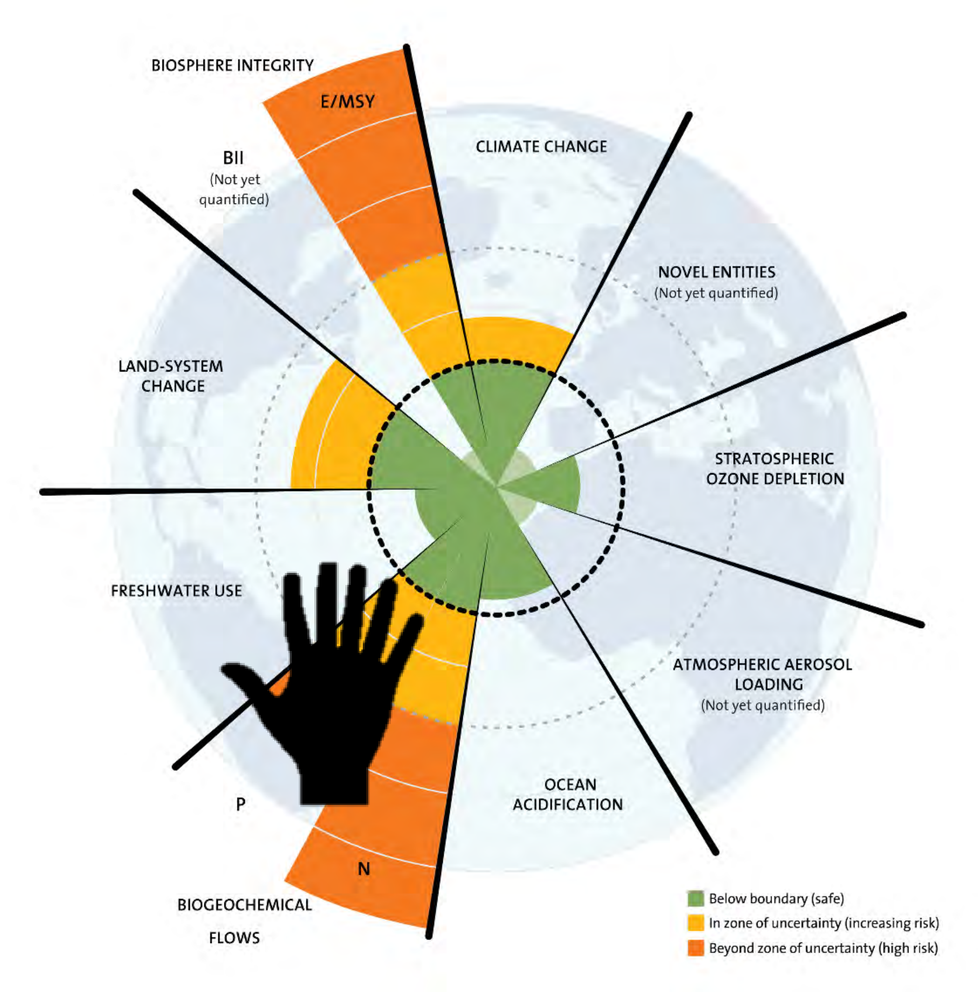
(After 4Y)

6,4 t ha^{-1}

(After 8Y)

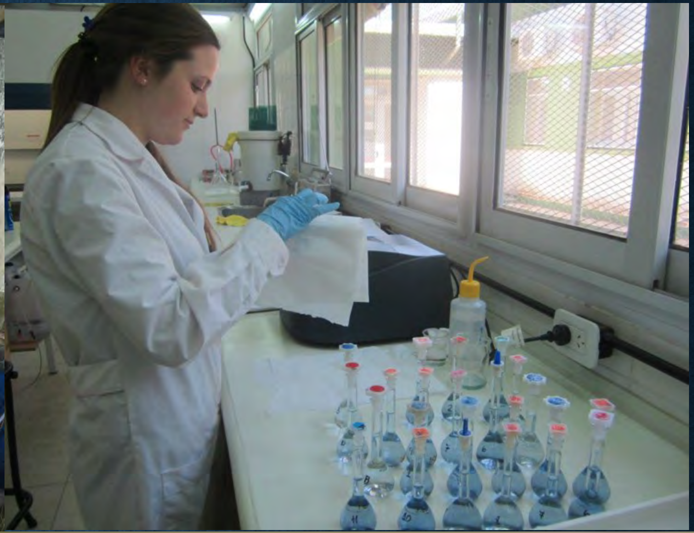
This technology leads to maintain soybean yields without resorting only to increased phosphorus fertilizer doses, improving soil and environment quality in the medium term.

At local/regional scale we would be contributing not to cross the planetary boundaries of P



Rockstrom et al. (2009).







THANK YOU

IMPACT OF LONG-TERM COVER CROP MANAGEMENT ON THE PHOSPHORUS DISTRIBUTION AT THE SOIL RUNOFF INTERACTION ZONE.

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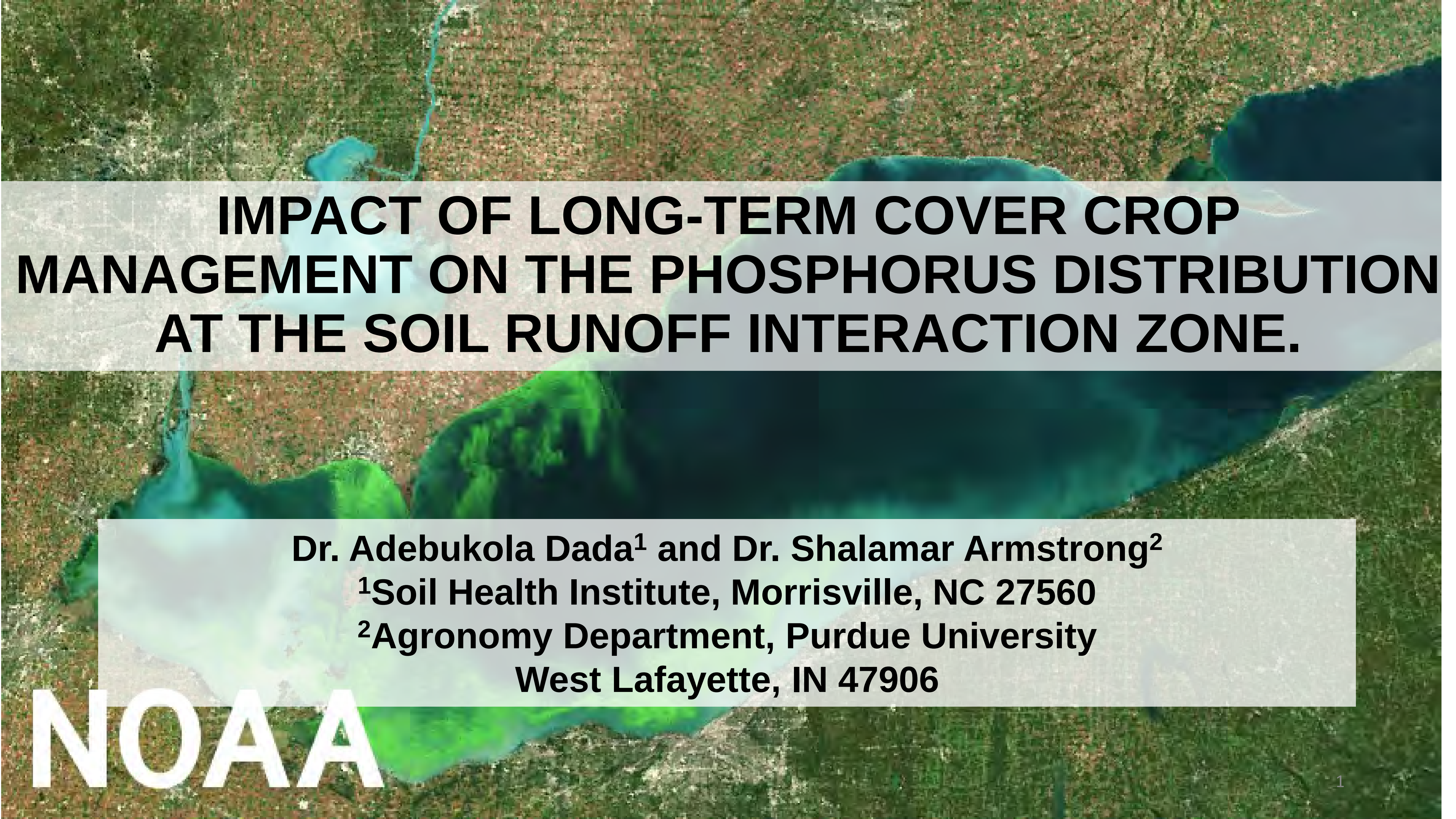
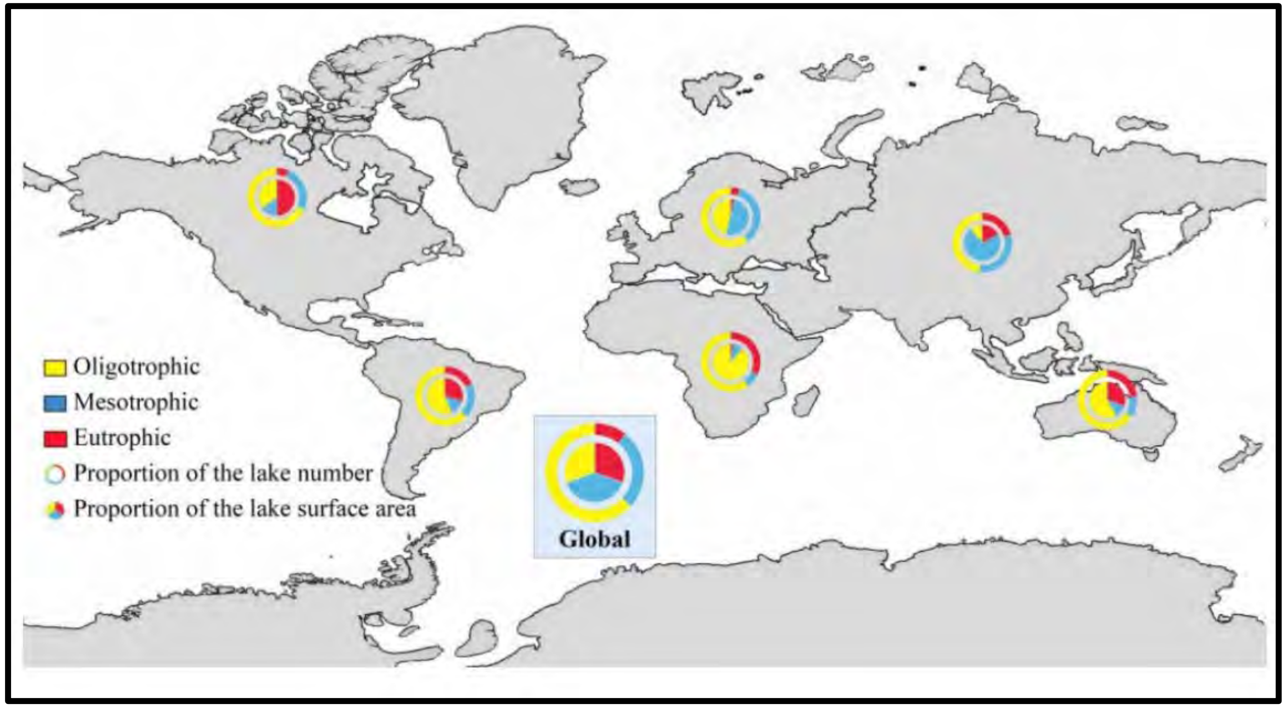
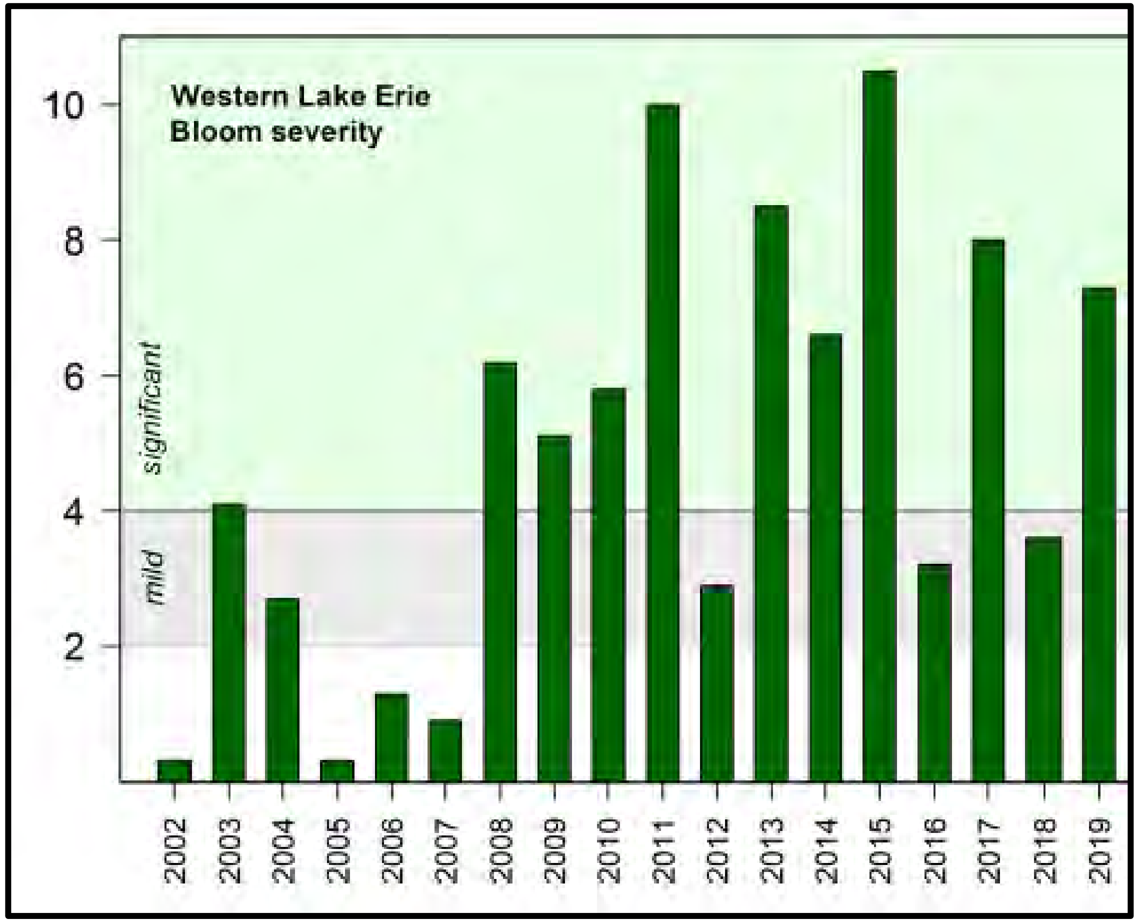


Introduction



Global distribution of water eutrophication. The pie chart of the outside circle corresponds to the proportion of the number of large lakes in each eutrophication state in the continent, and the pie chart of the inside circle corresponds to the proportion of the surface area of large lakes in each eutrophication state in the continent. (Zhang et al., 2021)



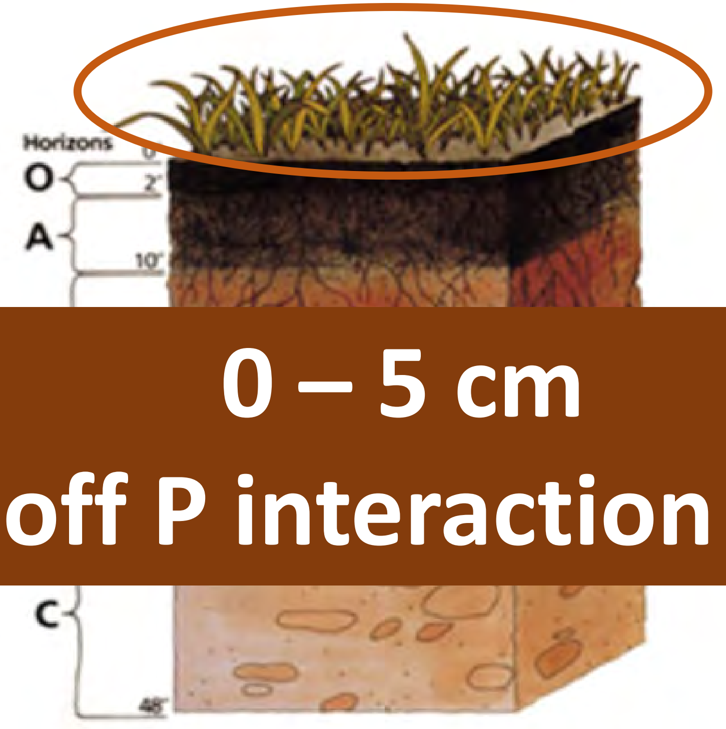
Severity index of Lake Erie harmful Algal Bloom (HAB) from 2002 - 2019. Adapted from Guo *et al*; (2021)

Introduction

- Increased Spring TP & DRP loading from agricultural watershed

  Agricultural source = 88%

- Surface runoff = **52% TP** (Smith et al., 2015)



0 – 5 cm
runoff P interaction zone

https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr7/profile/?cid=nrcs142p2_047970

Introduction

- **BMPs**

  Planting cover crops

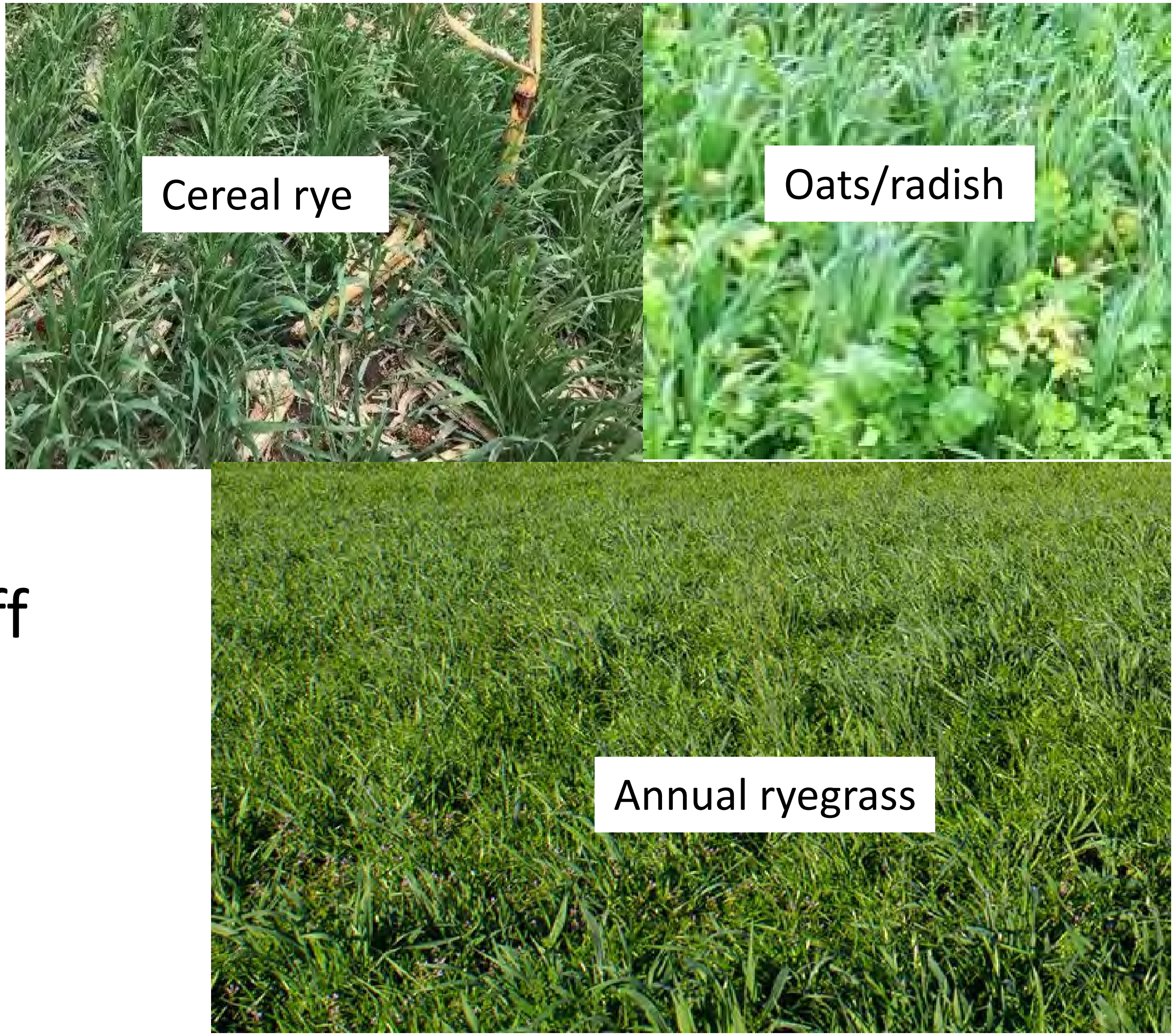
- **Benefits of planting cover crops**

  I. Increase soil organic matter

  II. Reduce Nitrate loss

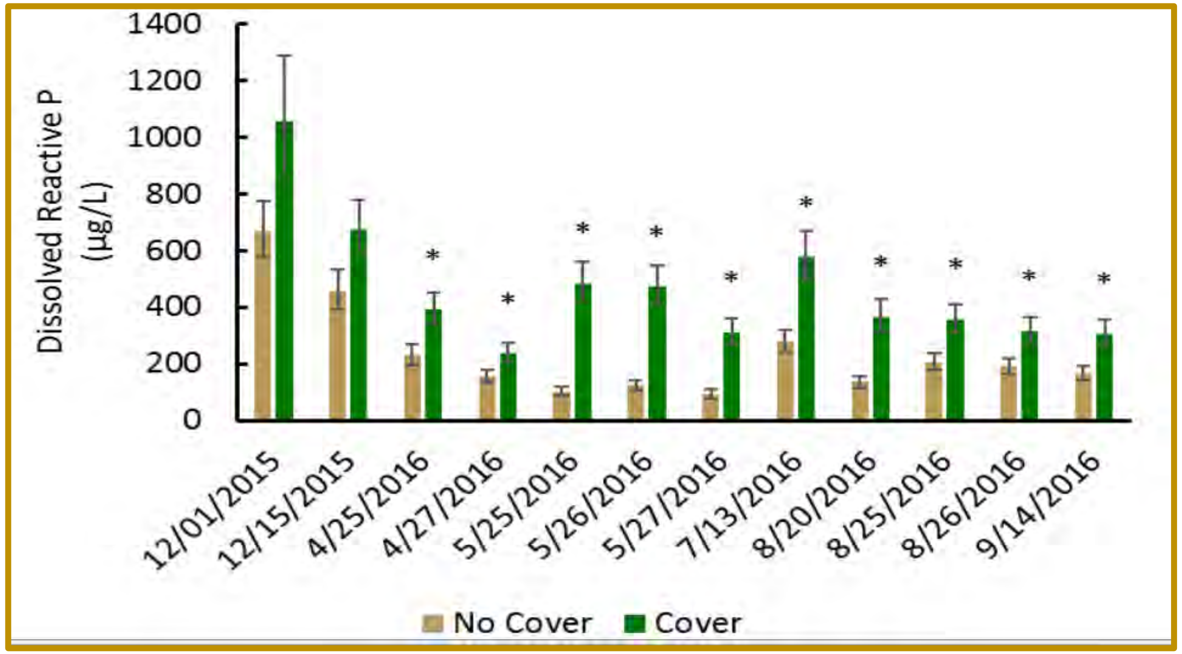
  III. Reduce soil erosion and run-off

  IV. Reduce particulate and Total P loss (Riddle and Bergstrom, 2013; Bechmann et al., 2005)

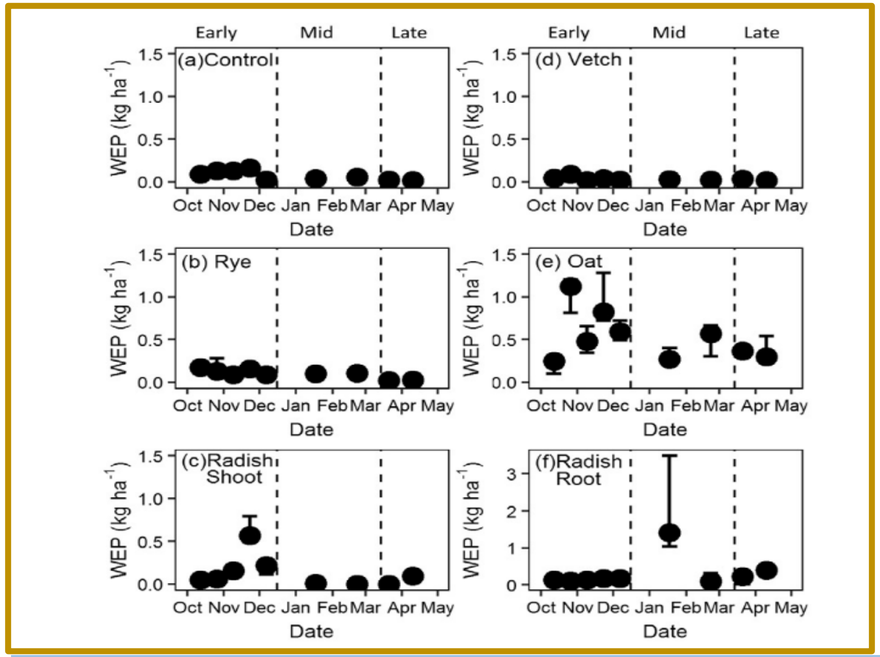


Adapted from canr.msu.edu

Introduction



Cover crop increased DRP loss. (Carver, 2018)



Differences in WEP from cover crop species (Cober et al., 2019)

- ➢ Plant different cover crop species
- ➢ Conclusions entirely based on vegetation impact rather than interaction between soil and DRP (Liu et al., 2015)
- ➢ Most of these studies are short term < 5 years less likelihood to capture chemical equilibrium from P cycling

Findings

Cover crops and Extractable P

- Long-term annual ryegrass decreased M3P and WEP at 0 - 4 cm soil depths.

- Annual ryegrass decreased DRP concentration desorbed after 1 hour at 0 – 4 cm suggesting it as potential species for decreasing P loss.

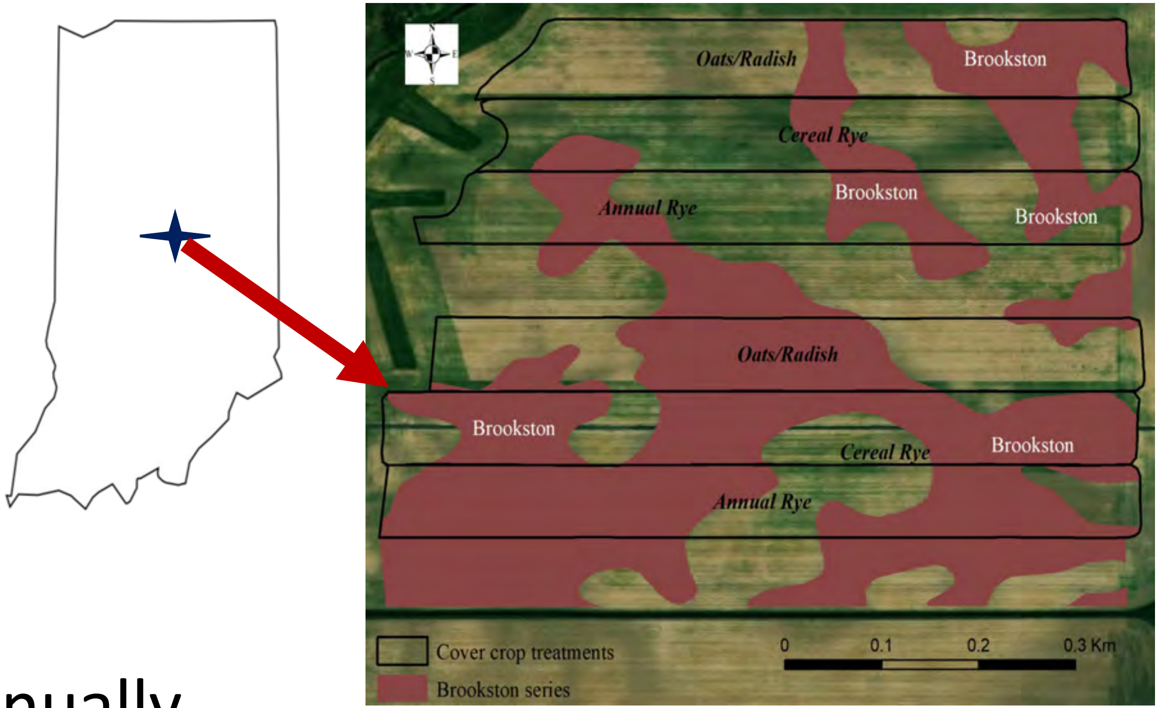
Objectives

- Determine the effect of long-term cover crop species management on the labile, moderately labile and non-labile phosphorus fractions at the soil runoff P interaction zone.

Materials and Methods

- **Field Description:**

 Indiana with 9 years CC in Corn/soybean



Field layout showing treatments

- **Soil Type**: Brookston series,
- **Slope** = 0 - 2%
- **P Management:** MAP at 145.7 kg/ha annually

In 2018, split manure applied in fall and spring at 2 tons/ha

every 4 years

- **Soil Sampling depth:** 0 – 5 cm

Materials and Methods

0.5 g soil in 50 ml centrifuge tubes

↓

30 ml deionized water, shake for 16 hours, centrifuged → H_2O - Pi

↓

30 ml 0.5 M $NaHCO_3$, shake for 16 hours, centrifuged → $NaHCO_3$-Pi

Digested with ammonium persulfate = $NaHCO_3$-P

$NaHCO_3$-Po = $NaHCO_3$-P – $NaHCO_3$-Pi

↓

30 ml 0.1 M NaOH, shake for 16 hours, centrifuged → NaOH-Pi

Digested with ammonium persulfate = NaOH-P

NaOH-Po = NaOH-P – NaOH-Pi

↓

30 ml 0.5 M HCl, shake for 16 hours, centrifuged → HCl-Pi

↓

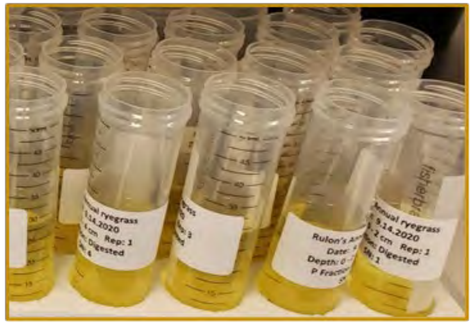
15 ml conc. HCl in hot water bath, vortex, centrifuged → CHCl-Pi

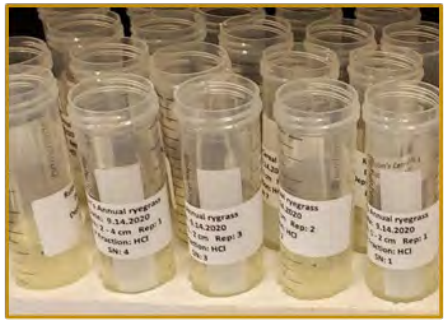
Digested with ammonium persulfate = CHCl-P

CHCl-Po = CHCl-P – CHCl-Pi

↓

Digest with Conc. H_2SO_4 and H_2O_2 → Residual-P



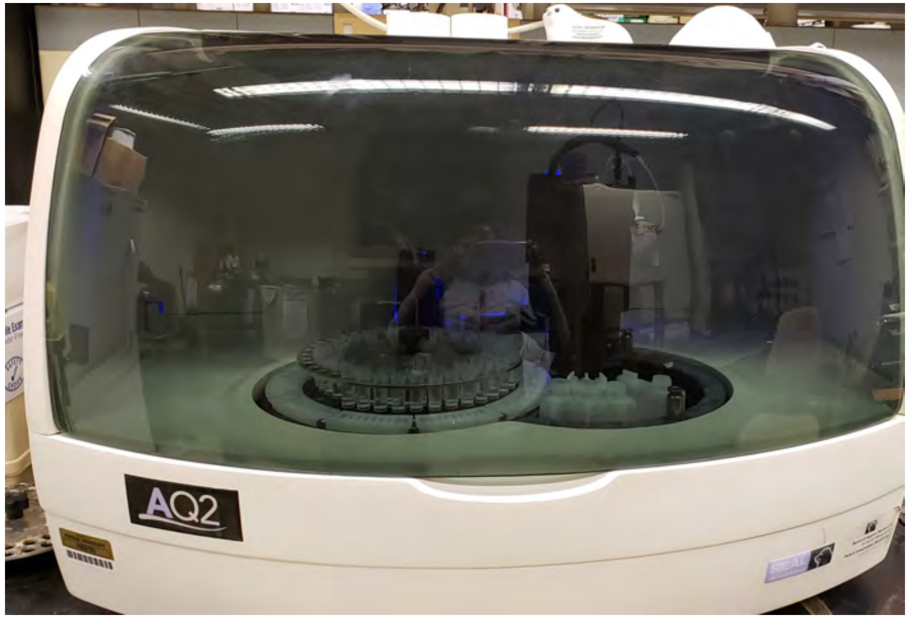


Materials and Methods

- Determination of P in samples

Pi and Po was by colorimetric analysis

Residual P was by ICP due to interference by H_2O_2



- Data Analysis

Two-way anova was used but no significant interaction between depth and treatments. Hence, P fractions were averaged across depths.

RESULTS

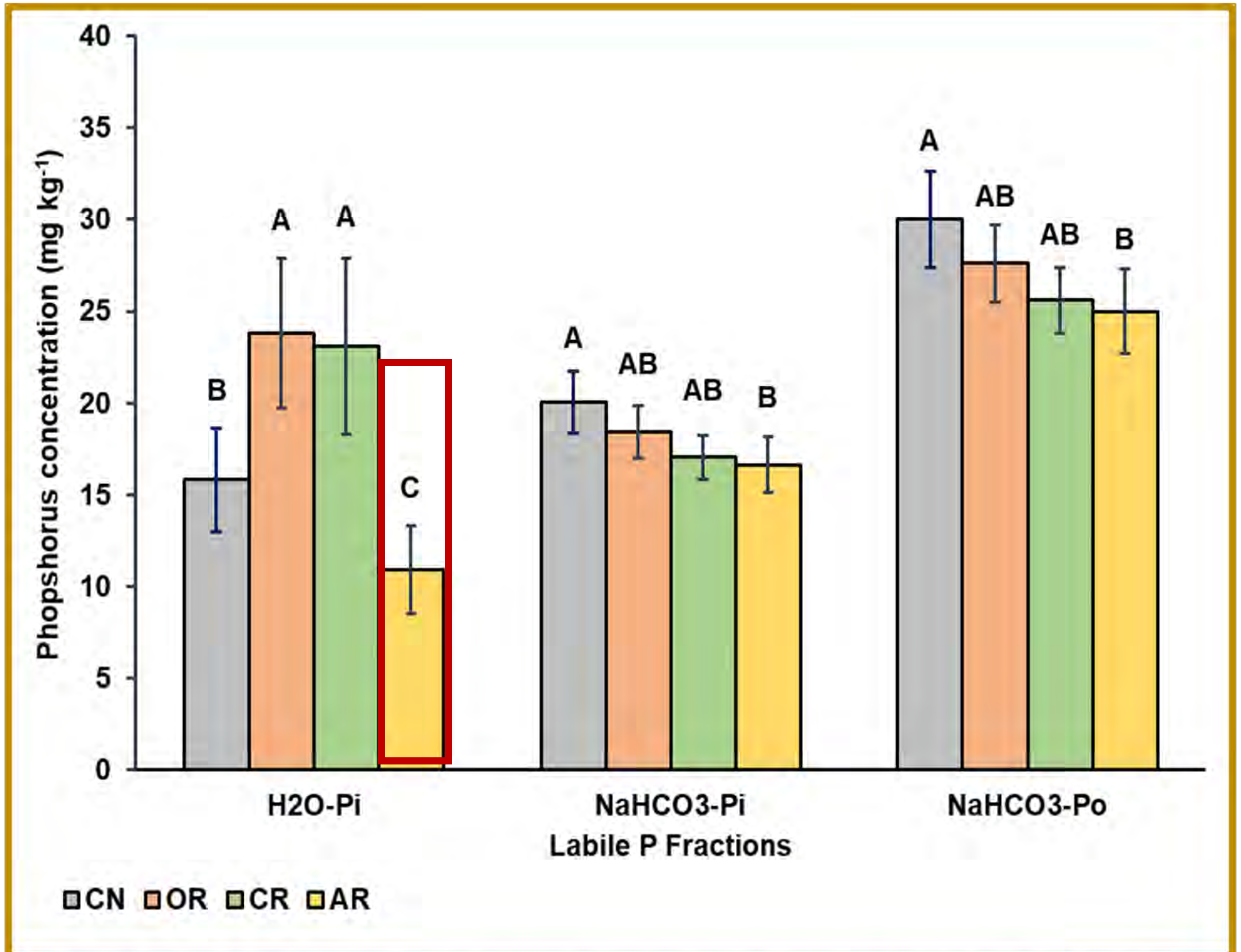


Figure 1: Labile soil P fractions after 9 years of cover crop management at 0 - 4 cm soil depth. Means followed by similar letter(s) are not significantly different at $p < 0.05$.

Oats/radish and cereal rye increased water-extractable P concentration by > 46% relative to control

Annual ryegrass decreased the water-extractable P concentration by >44% relative to all treatments

Noack et al., (2012) higher TP have a greater proportion stored as orthophosphate (25 - 75%)

RESULT

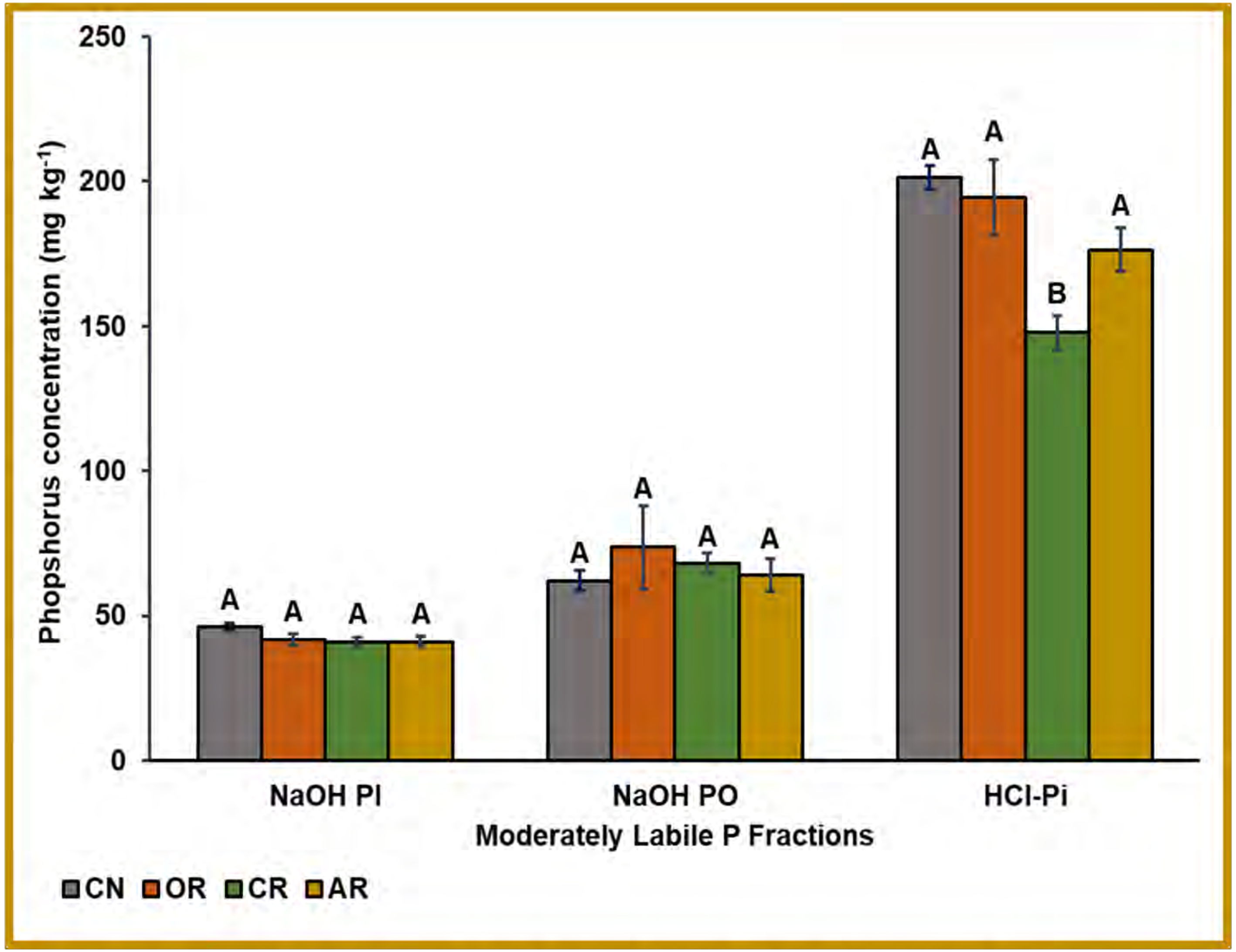


Figure 2: Moderately labile soil P fractions after 9 years of cover crop management at 0 - 4 cm soil depth. Means followed by similar letter(s) are not significantly different at $p < 0.05$.

Decrease in HCl-Pi in CR is due to dissolution of Ca bound P. (Sui et al., 1999)

Decrease in pH from 7.6 – 7.0 which may arise from production H^+

RESULT

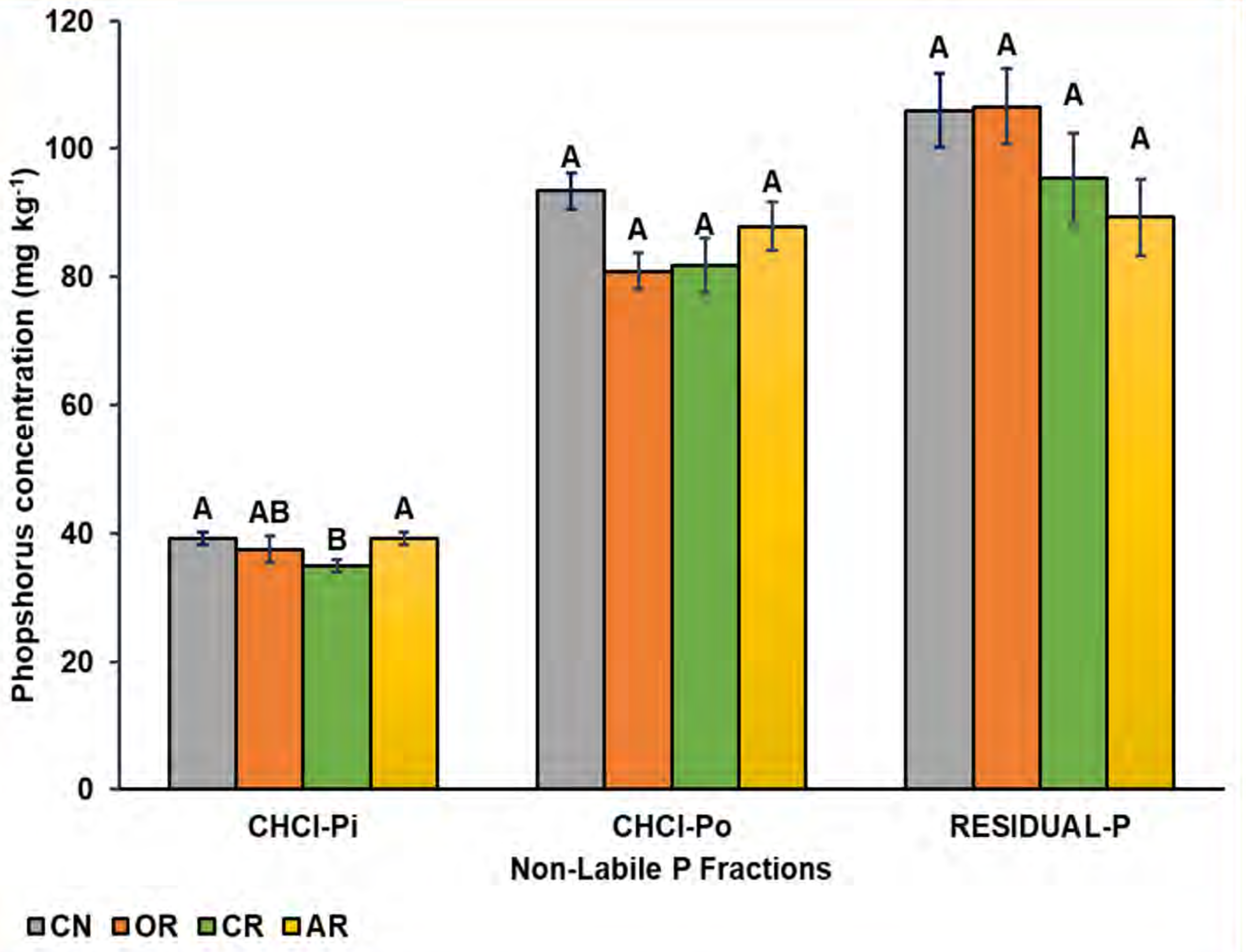


Figure 3: Non-labile soil P fractions after 9 years of cover crop management at 0 - 4 cm soil depth. Means followed by similar letter(s) are not significantly different at $p < 0.05$.

Cover crop species did not affect soil organic P concentration at 0 – 4 cm.

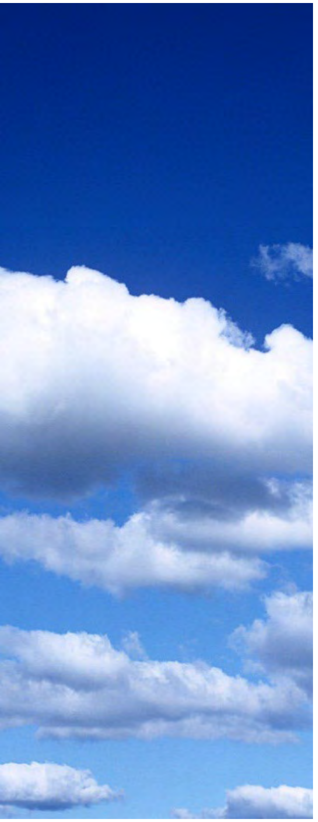
Calcium bound P is the largest P fraction in Mollisol because they have high exchangeable Ca content.

Conclusions

- All cover crop species are not created equal as it relates to P distribution in the soil runoff P interaction zone.

- Annual ryegrass should be recommended among farmers in agricultural watersheds susceptible to P loading because of its potential to accumulate less labile P over time at the runoff P interaction zone hence decreasing dissolved reactive P loading to surrounding watersheds.

Thank you



Phosphorus distribution and speciation at micro-scale in a long-term cultivated Brazilian Oxisol

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Elton Eduardo Novais Alves

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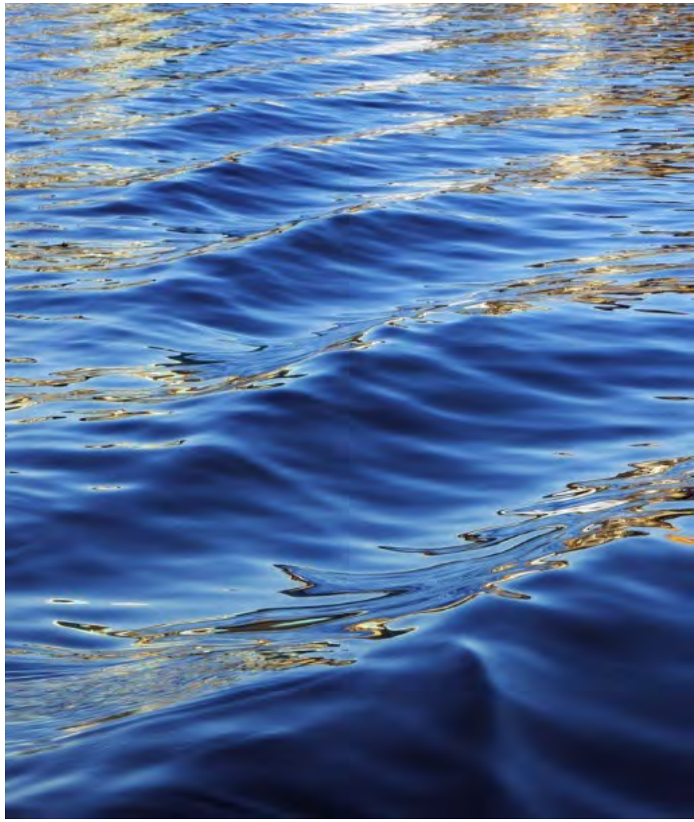


OCP

MOHAMMED VI POLYTECHNIC UNIVERSITY

Chair of Soil Science

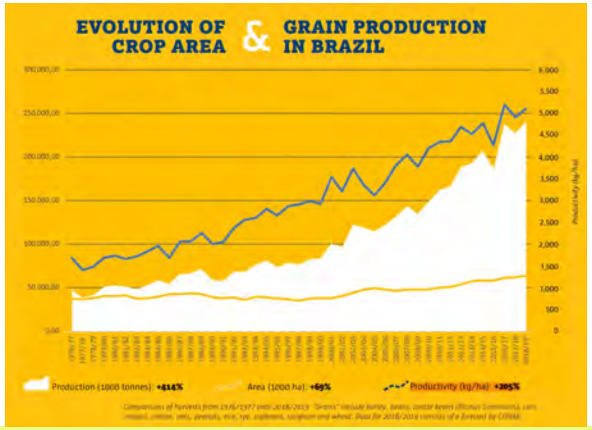
Sustainable Phosphorus Summit
November 2022, Raleigh - NC

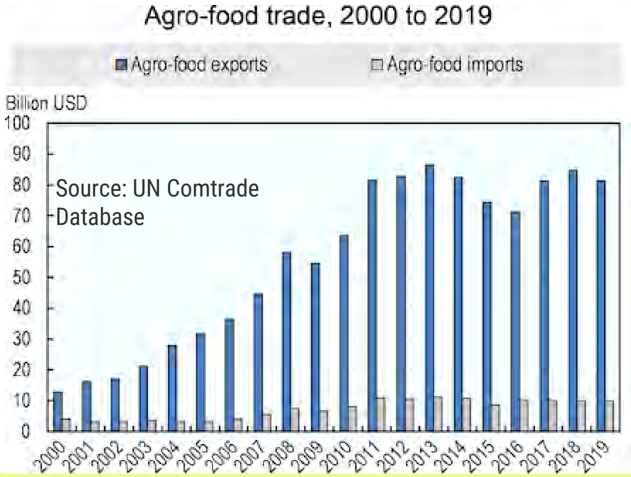
Overview

- Brazilian agriculture:
  - Brazil is the world's fourth-largest food producer
  - Cerrado (Brazilian Savanna) represents 60% of Brazilian agricultural production
  - Cerrado has highly weathered soils and Fe- and Al-(hydr)oxides clays

P fixation!

- Soil fertilization
  - Phosphate rock contains calcium-phosphorus species (e.g., hydroxyapatite - P-HAp) that are a source of P to crops after their solubilization and diffusion in the soil
  - However, the phosphate anion can be fixed on Fe and Al clay mineral surfaces and become unavailable to plants
  - This process decreases P fertilization efficiency
- Synchrotron-based techniques
  - µXRF & P K-edge µXANES – To Understand the mechanisms controlling the fate of P from the fertilizers in tropical soils
    - By assessing elemental distribution and P species in the fertosphere





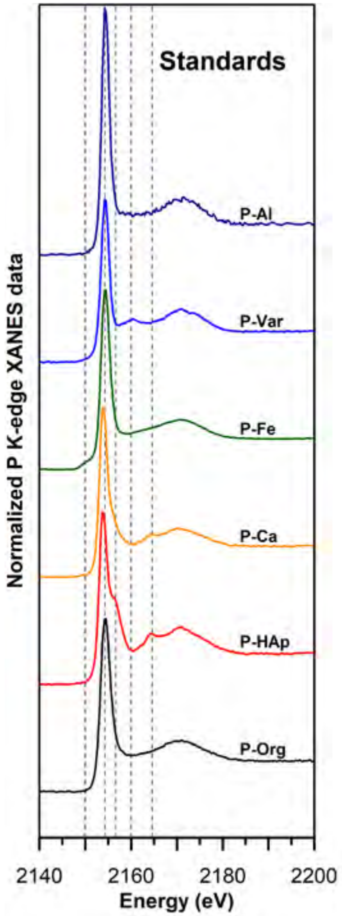
Objectives

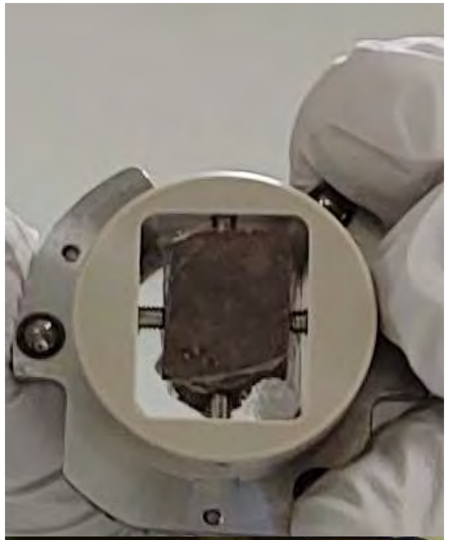
- General
  - To improve P fertilizer efficiency in highly weathered soil by understanding spatial changes at the micro-scale level based on the molecular environmental science approach
- Specific objectives
  - To assess P distribution and speciation in the fertosphere in a Brazilian Cerrado Oxisol, under a long-term field experiment using synchrotron-based microprobe techniques
  - Elucidate the mechanisms related to the transformation of P from fertilizer in the P at the soil interface

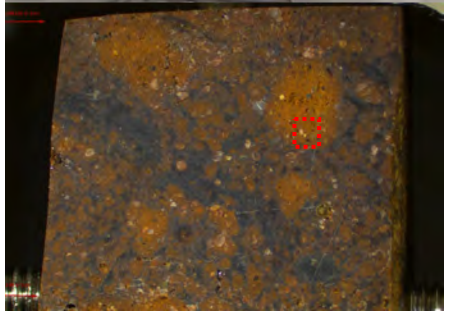
Material & Methods

- 21 yrs field experiment, Planaltina-DF, Brazil: NT vs CT, TSP vs PR, F vs B
  - Undisturbed soil sample 0-5 cm from one trial, sampled in 2021
  - Soil 21 yrs cropped with maize and fertilized with phosphate rock (100 kg ha^{-1} yr^{-1} of P_2O_5) applied broadcast

- Synchrotron-based spectroscopy (XANES and XRF)
  - The sample was fixed in a P-free organic resin and mapped by µXRF to assess the distribution of Al, P, and Si
  - P K-edge µXANES spectroscopy to assess the phosphorus species
  - P K-edge µXANES spectra were collected in a transect from P hotspots (fertilizer) to the bulk soil.







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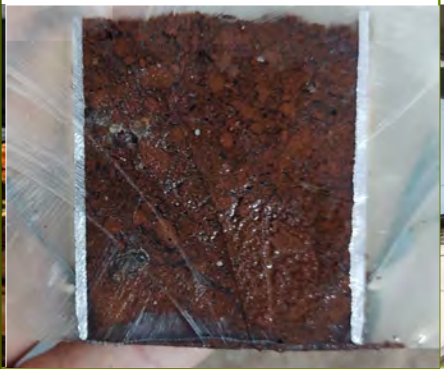
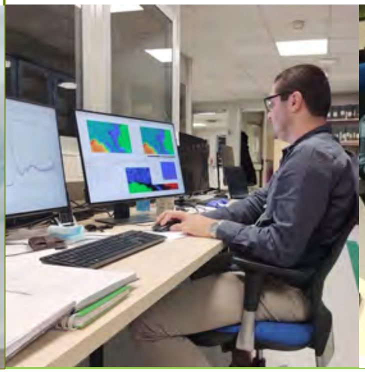
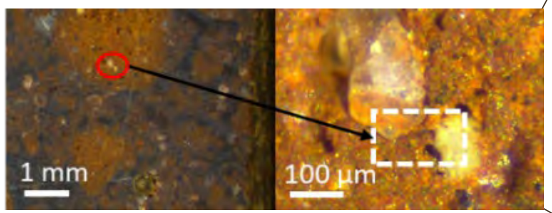
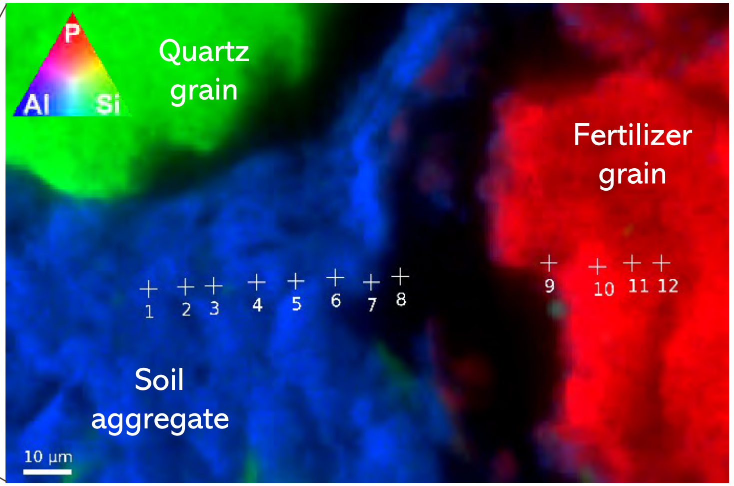
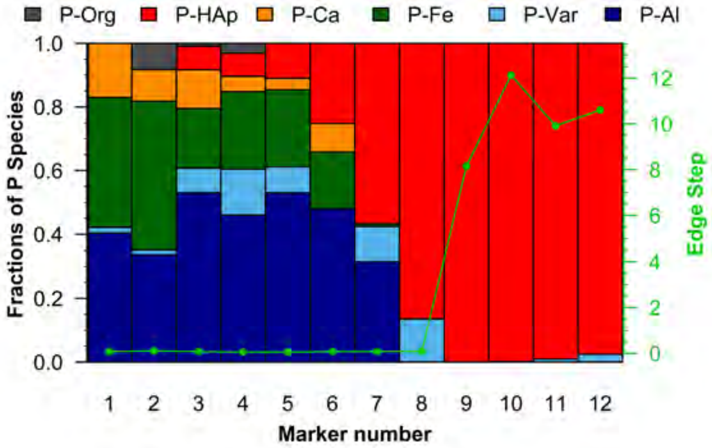
 		 

Results

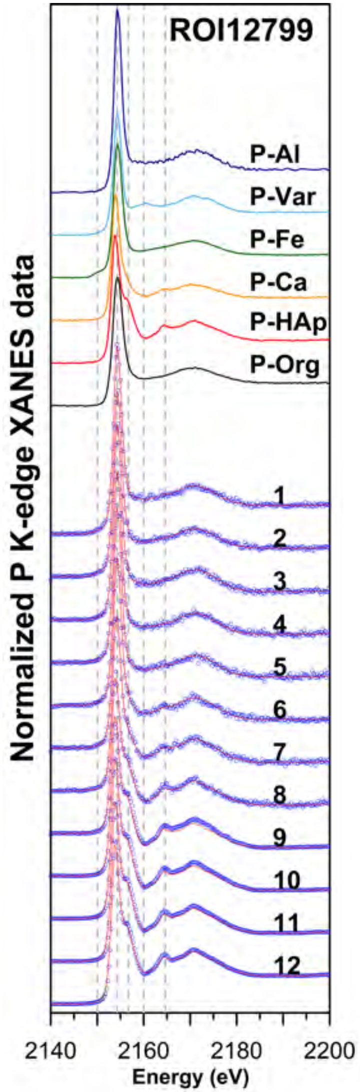




- In the P hotspots, P-HAp confirmed the location of the fertilizer grain (high edge step)
- In the soil/fertilizer interface we found P-HAp transforming to dicalcium phosphate (P-Ca, 4-17%) and P adsorbed on gibbsite (P-Al, 32-44%)
- Inside the soil aggregate, further from the fertilizer, P adsorbed on ferrihydrite (P-Fe) was also found (18-47%).



Marker	P-Al	P-Var	P-Fe	P-Ca	P-HAp	P-Org	R.fac
1	40%	2%	41%	17%	0%	0%	0.0020
2	34%	2%	47%	10%	0%	8%	0.0025
3	53%	8%	19%	12%	7%	1%	0.0029
4	46%	14%	24%	5%	7%	3%	0.0047
5	53%	8%	24%	4%	11%	0%	0.0029
6	48%	0%	18%	9%	25%	0%	0.0018
7	32%	11%	1%	0%	57%	0%	0.0017
8	0%	14%	0%	0%	86%	0%	0.0019
9	0%	0%	0%	0%	100%	0%	0.0014
10	0%	0%	0%	0%	100%	0%	0.0013
11	0%	1%	0%	0%	99%	0%	0.0012
12	0%	2%	0%	0%	98%	0%	0.0015



Conclusions

- µXRF & P K-edge µXANES was able to assess the P distribution and speciation in the fertosphere
- P transform in less bioavailable (P-Al and P-Fe) forms in a short-range space (fertilizer/soil aggregate interface)
- These technique is useful to assess new Technologies to improve P fertilization efficiency for crops

Acknowledgment

OCP MOHAMMED VI POLYTECHNIC UNIVERSITY Chair of Soil Science

ESALQ Luiz de Queiroz College of Agriculture University of São Paulo

Embrapa Cerrados

ESRF The European Synchrotron

CAPES

FAPESP

ESALQ
Luiz de Queiroz College of Agriculture
University of São Paulo

Microbial activity and P uptake by cover crops exploring the long-term Legacy P in Brazil

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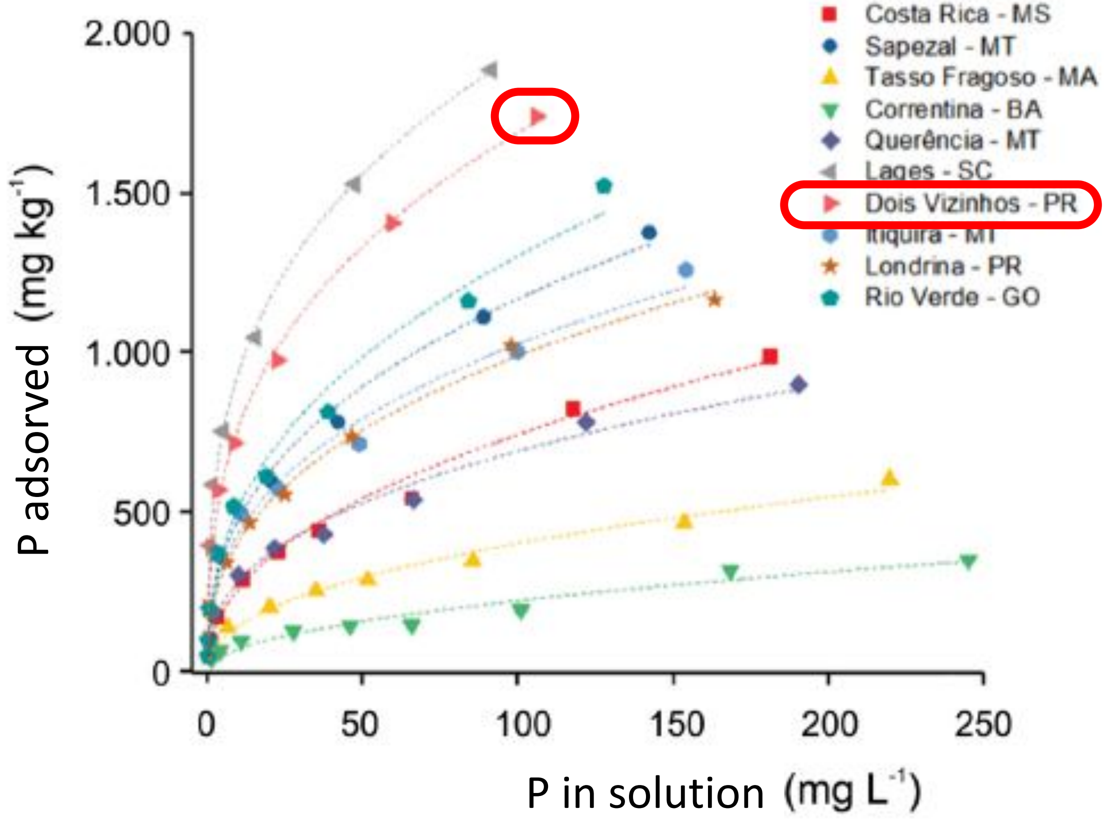
FAPESP
UTFPR
UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ

Introdution

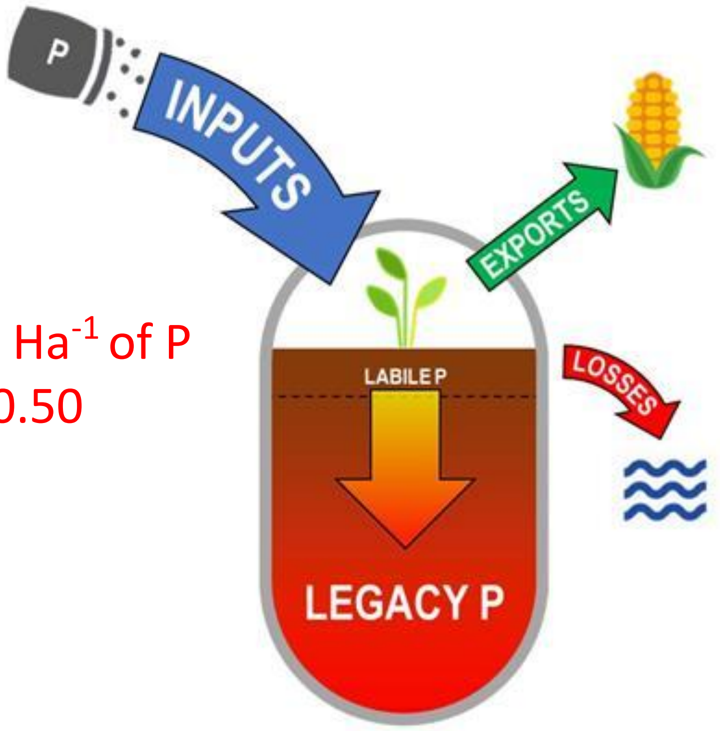
Brazilian soils

MPAC



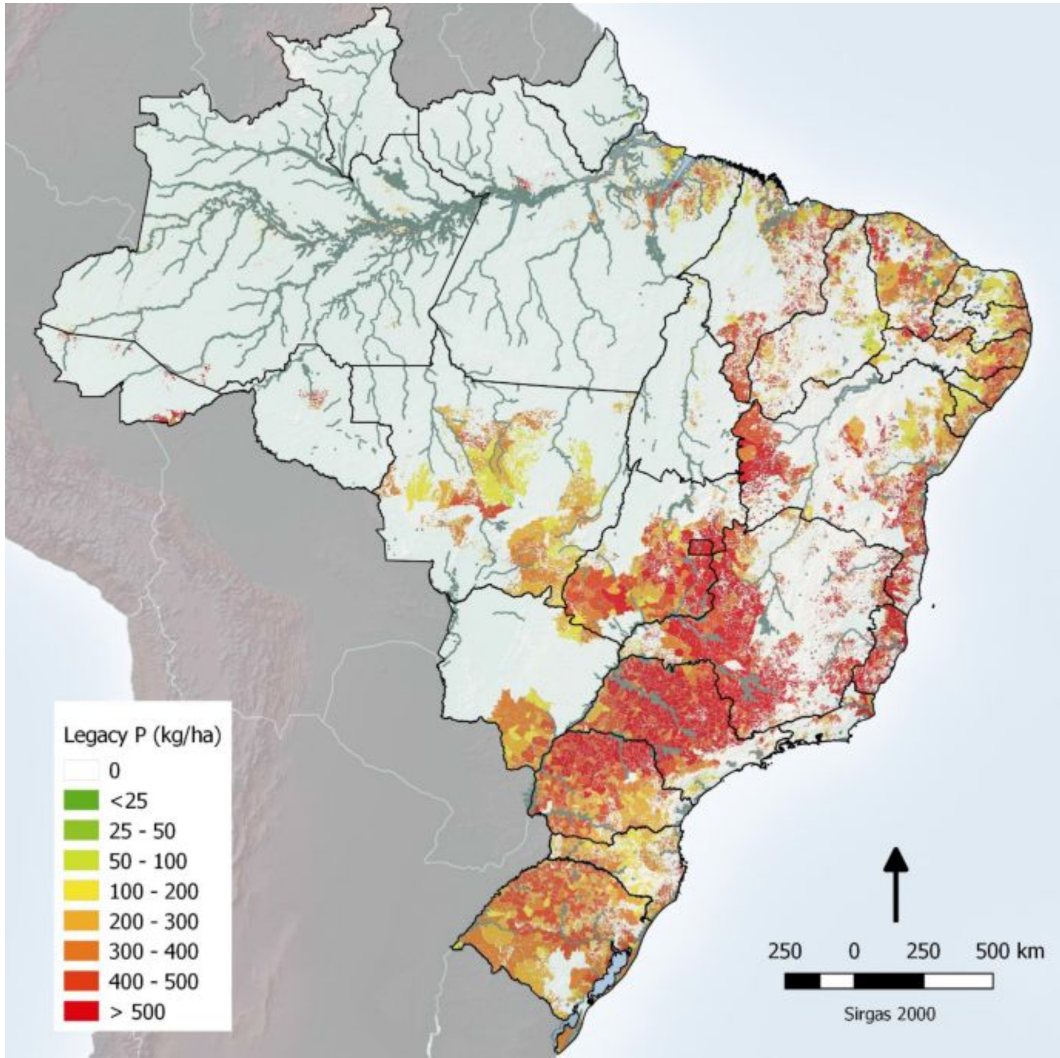
P TAX

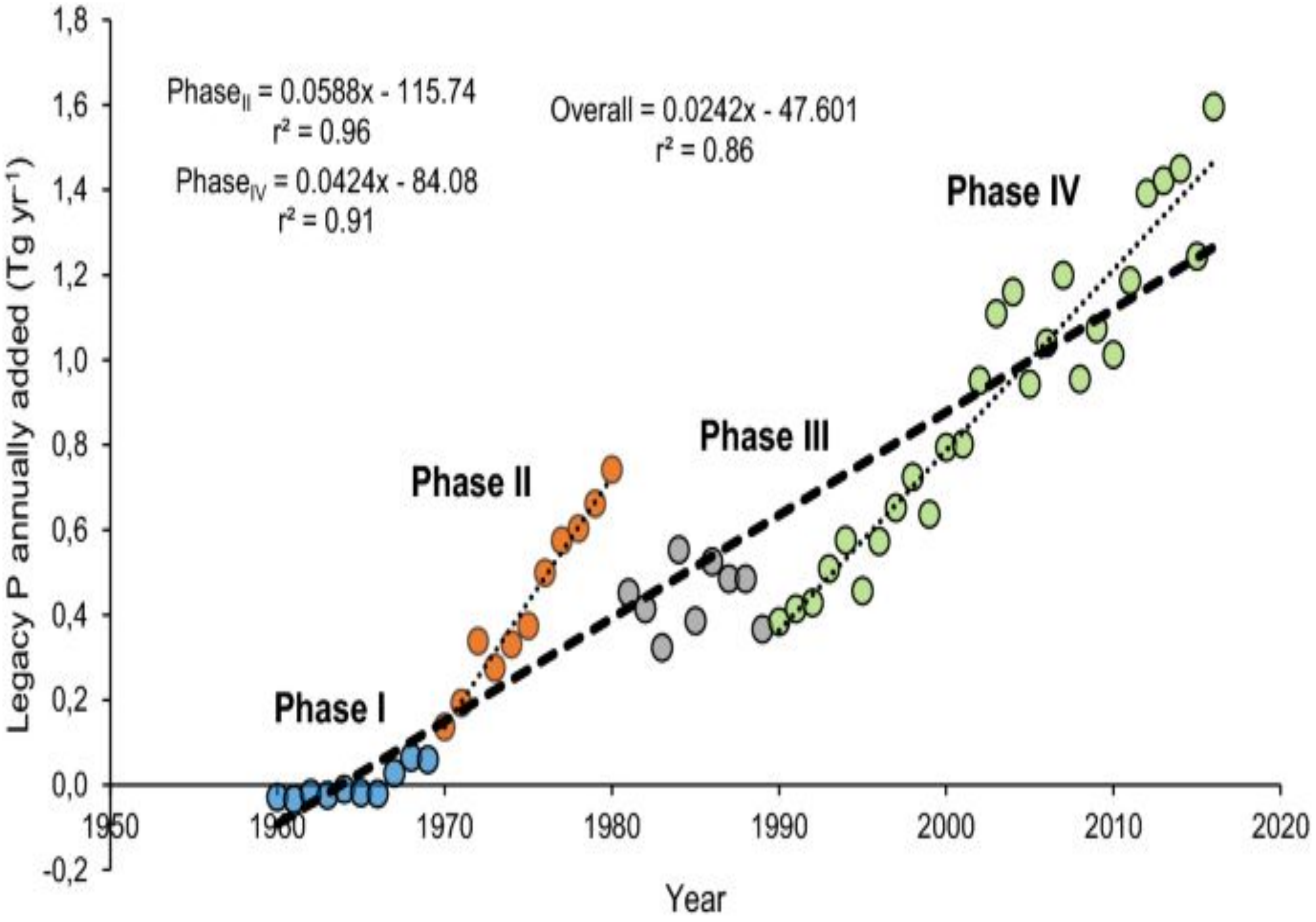
- **EXTRA RATE:** 35 Kg Ha^{-1} of P
- **P Effiency index:** ~0.50



Introdution

Legacy P accumulated 1960s - 2016

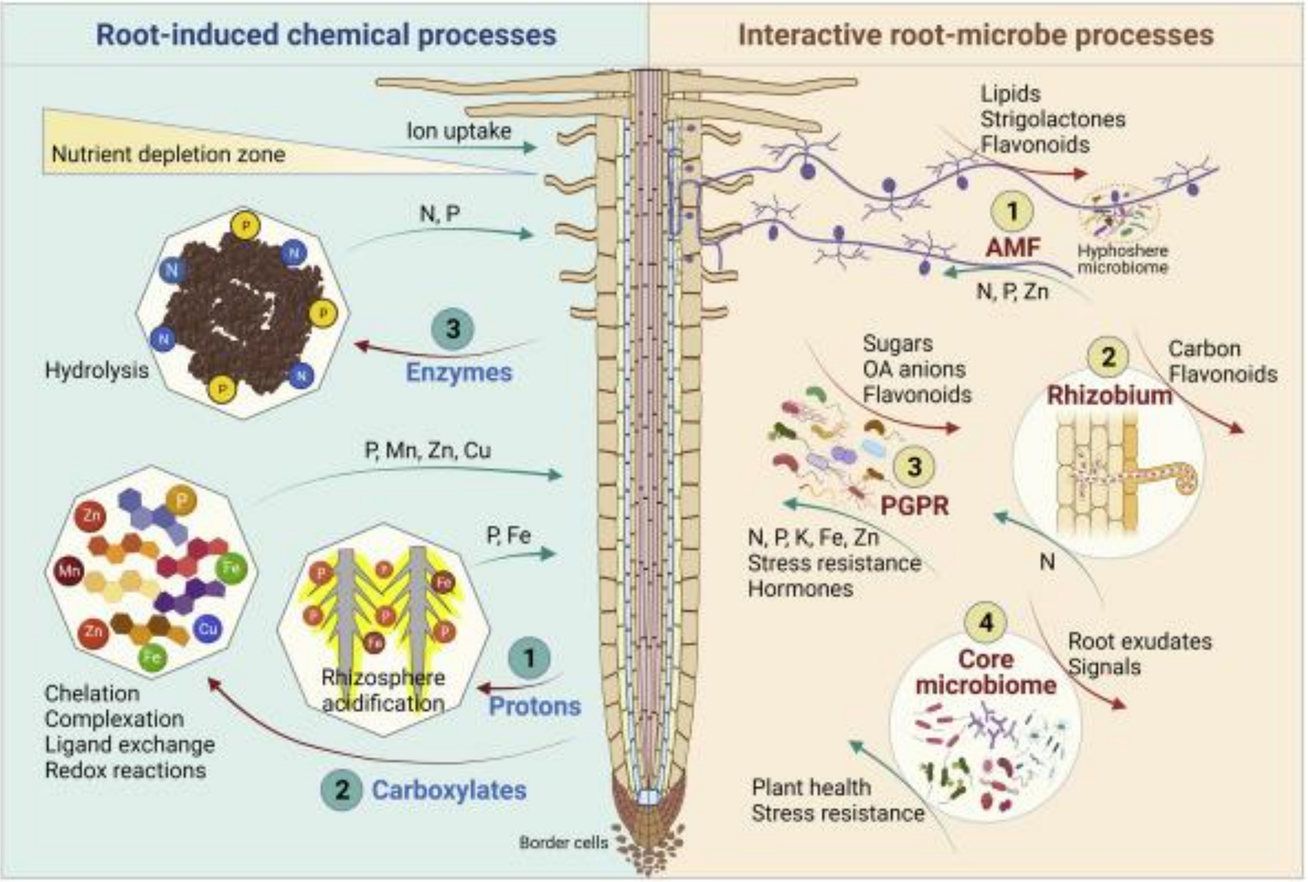


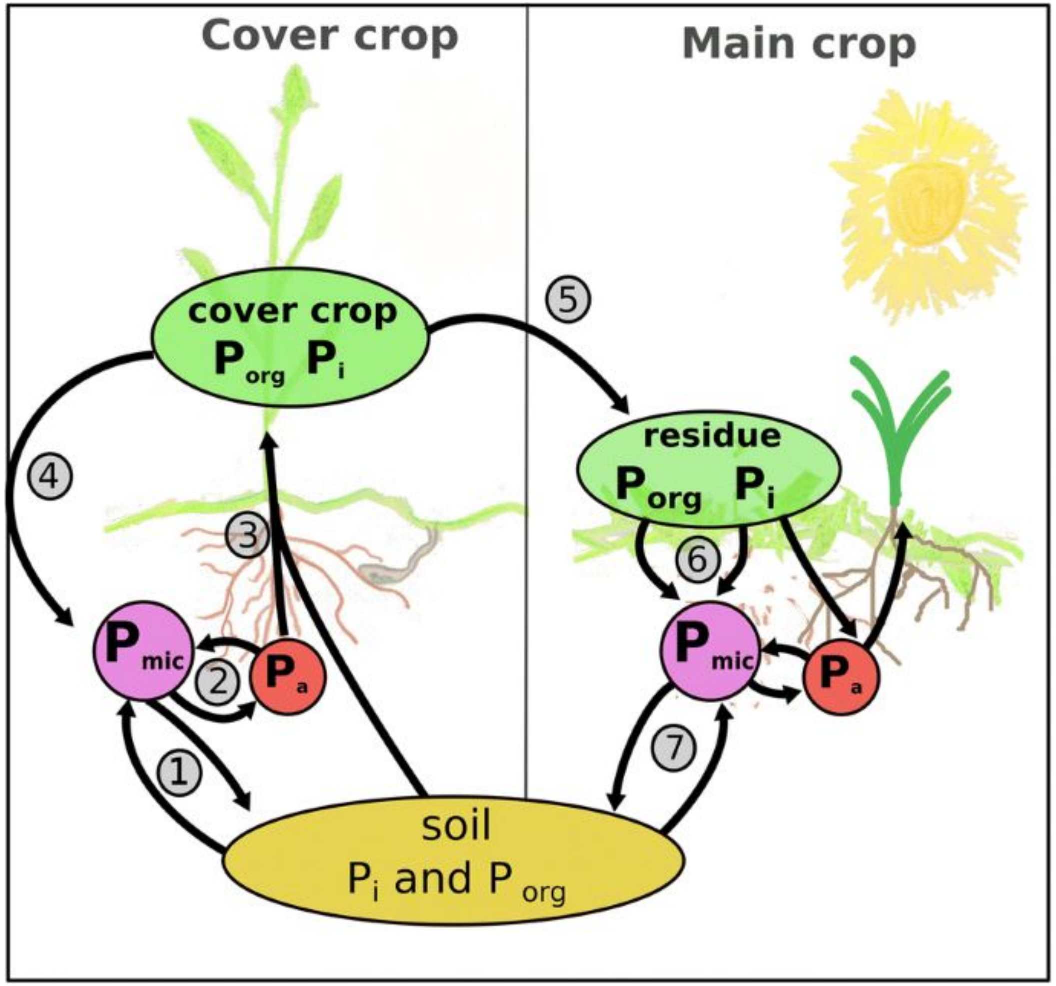


(Pavinato et al., Scientific Reports, 2020)

Introdution

Mechanism to access Legacy P

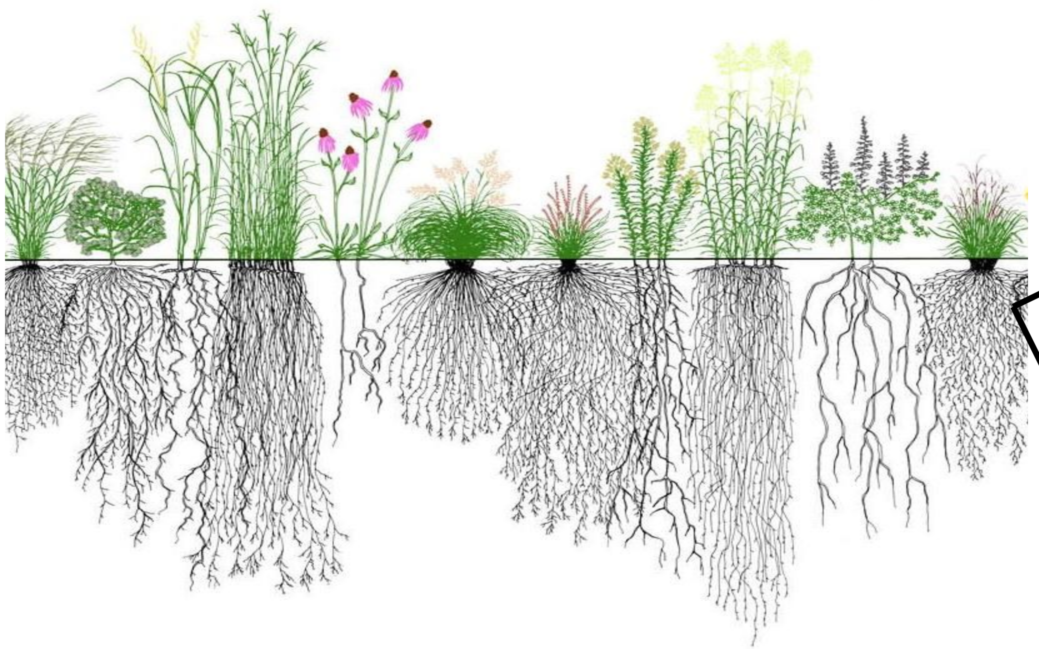


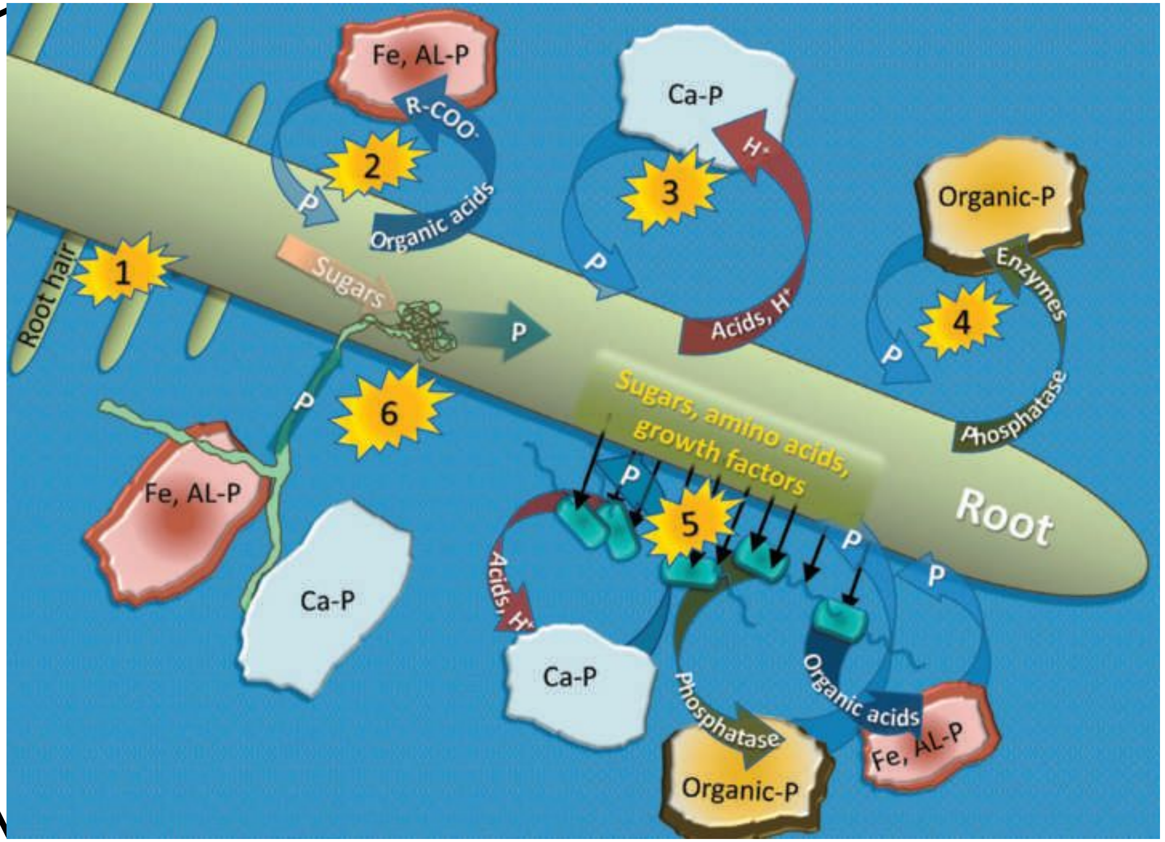


(Hallama et al., Plant and Soil, 2019; Whang et al., iScience, 2022,)

Introdution

Cover crops





(Brady & Weil, 2009)

Objetive

To check the relationship of microbial activity with P cycling by cover crops in three conditions, exploring long-term soil legacy P in south Brazil.

Materials & Methods

LTE in GLTEN

SCAN ME

Local: Dois Vizinhos, Paraná, South Brazil.

Establishment: 2009 in clayey Rhodic Hapludox (WRB/FAO).

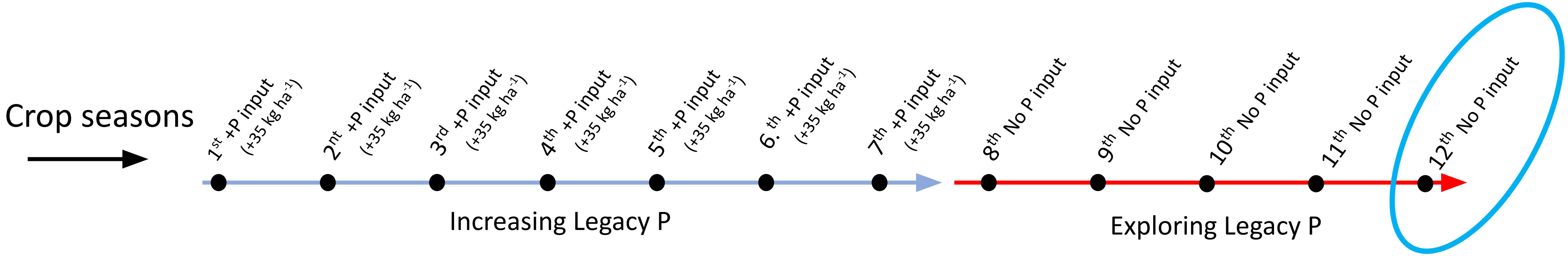
Design: factorial 3x6 in randomized blocks, with three replications - Plots: 5x5 m.

Source P X Cover crops

- **Control (Nil-P)**
- **Single superphosphate (18% soluble P_2O_5 – SSP)**
- **Rock phosphate (9% soluble - RP)**

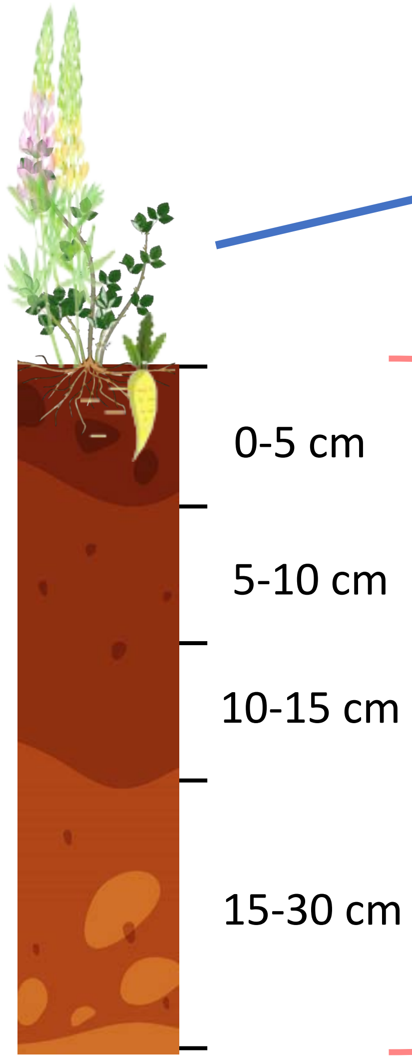
Fallow | **Common vetch** | **White lupin** | **Fodder radish** | **Ryegrass** | **Black oat**

Materials & Methods



Materials & Methods

Analyzes:



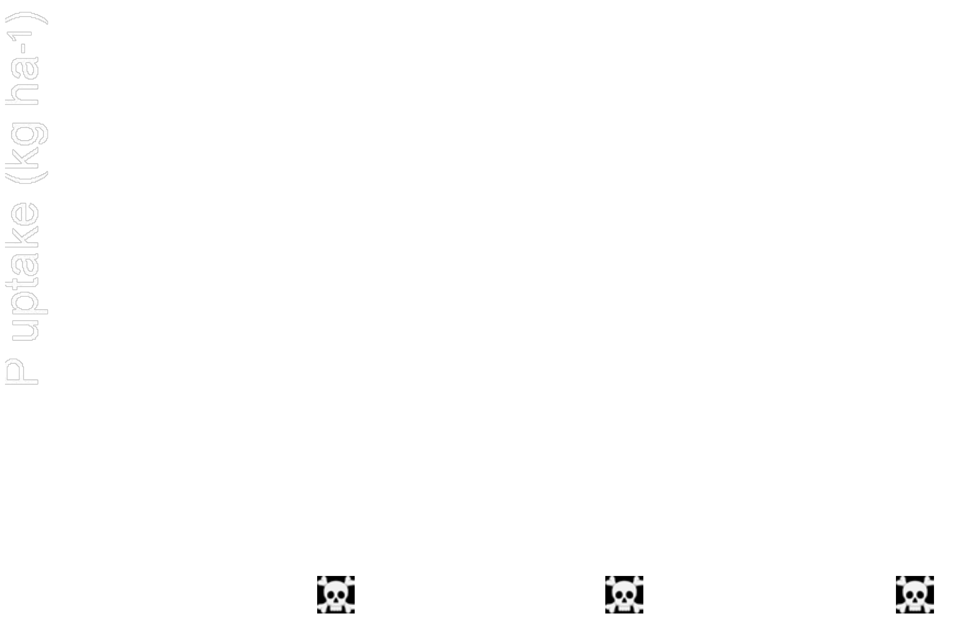
Cover crops:
- P uptake

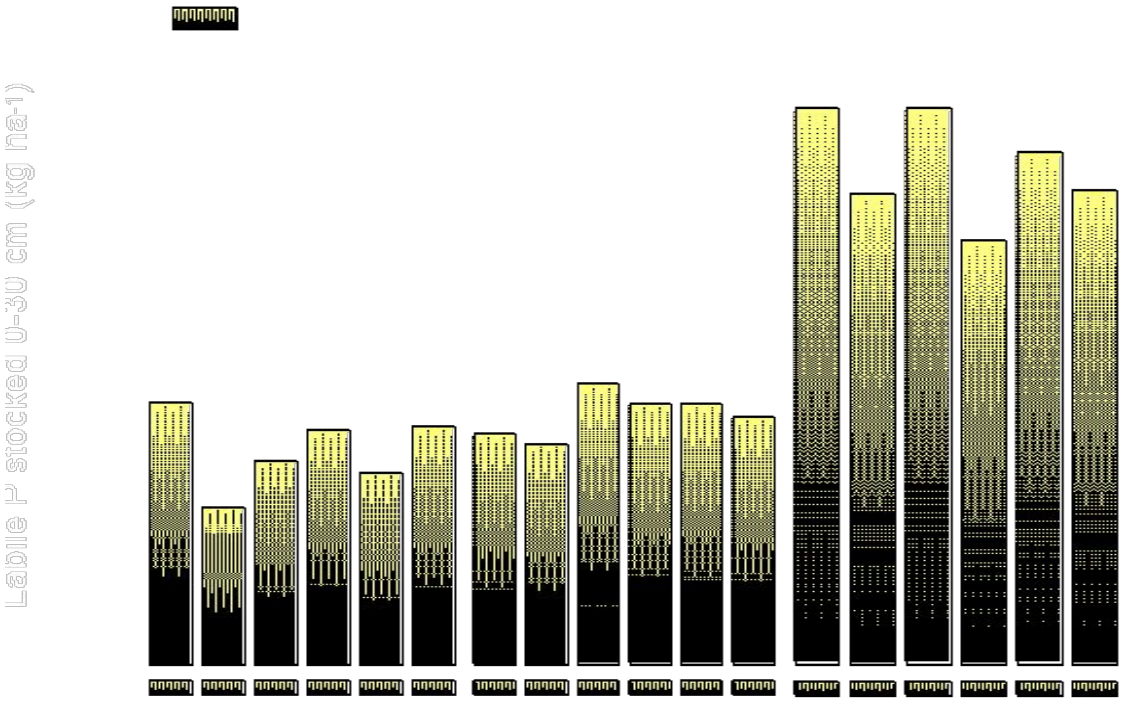
Microbial activity:
- C and P of microbial biomass (MBC and MBP);
- Acid phosphatase and β-glucosidase.

Soil P pools:
- Chemical P fractionation (Hedley et al., 1982)

Statistics: ANOVA, LSD test and pearson's correlation ($p \leq 0.05$)

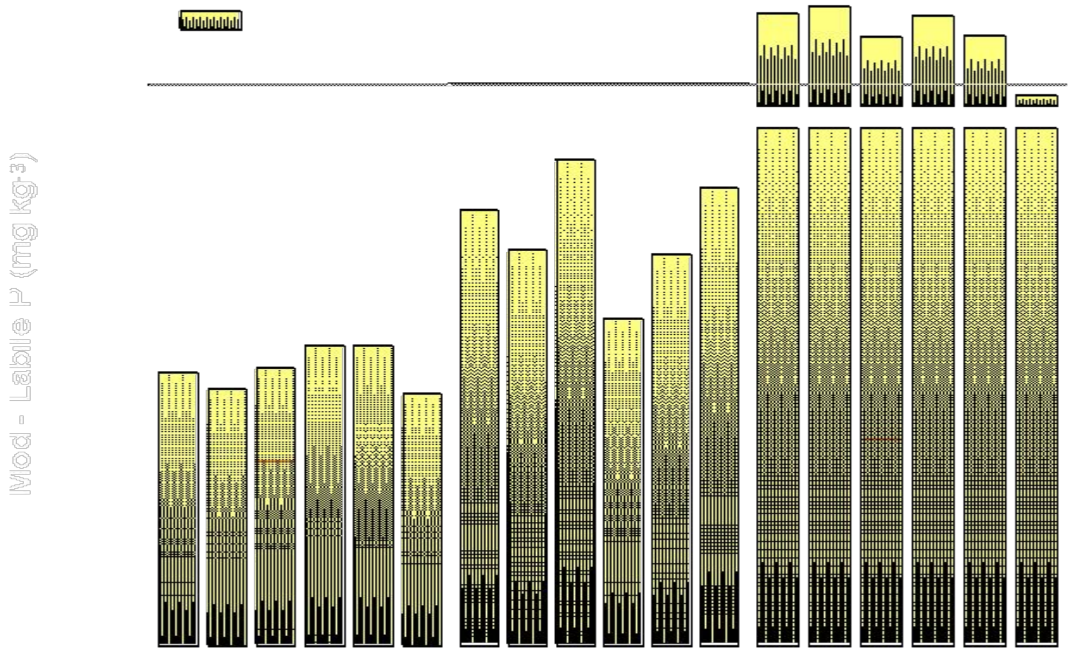
Results

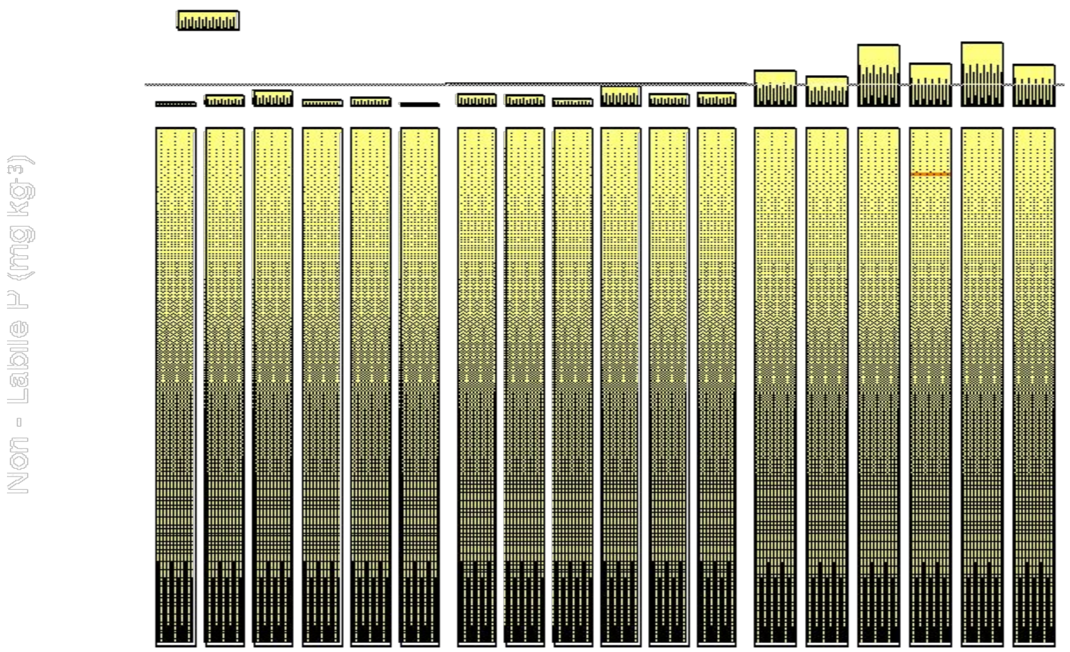




☠ Frost killed fodder radish

Results





Microbial biomass C (MBC)

MBC (mg kg-1)

β-glucosidase activity

β-glucosidase (µg PNG g-1 h-1)

Microbial biomass P (MBP)

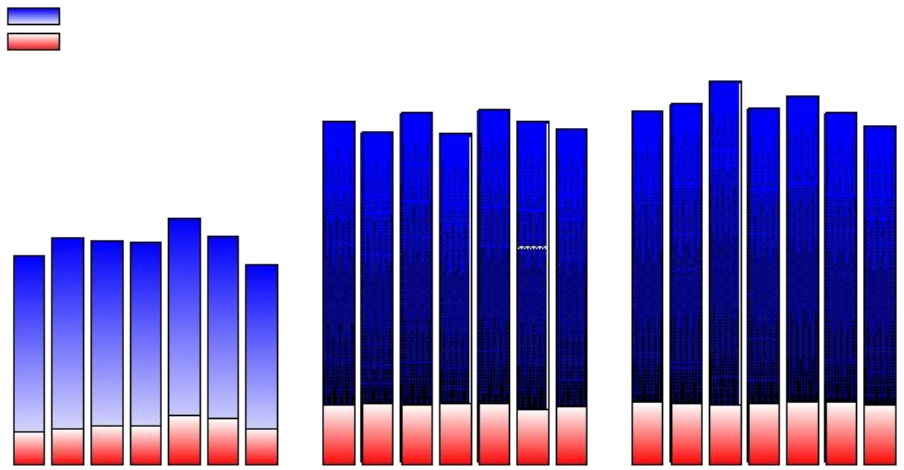
MBP (mg kg-1)

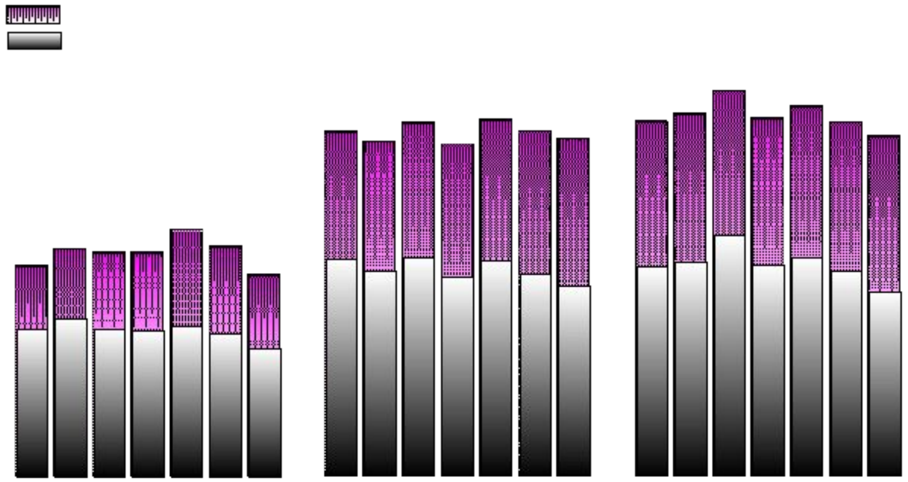
Acid phosphatase activity

Acid phosphatase (µg PNF g-1 h-1)

13

Crop accumulated yield after 12 yrs (7 yrs fertilized + 5 yrs without)





Conclusions

A great legacy P was observed under RP application, what persisted for long time (more than 5 years)

Legacy P may allowed great cash crop yield when well-managed the whole production system (crop rotation, cover crops, etc...)

More MBC and MPC were observed under the residual effect of RP, irrespective the cover crop species (high MPC under legumes)

Acid phosphatase activity was a bit higher under Nil-P and SSP, specially for legumes as cover crops, compared to RP

ESALQ

Luiz de Queiroz College of Agriculture
University of São Paulo

Thank you

Paulo S. Pavinato & Joao H. Luz
E-mail: pavinato@usp.br

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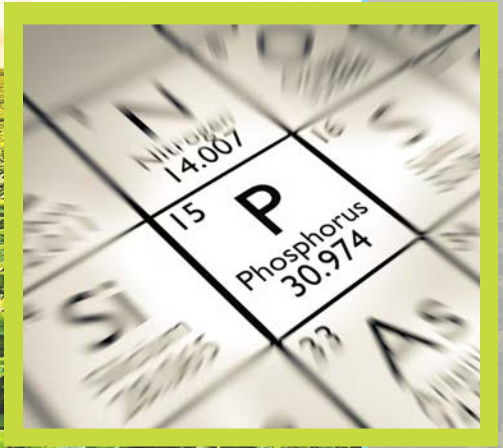


Global Phosphorus fertilizer price trends and future volatility

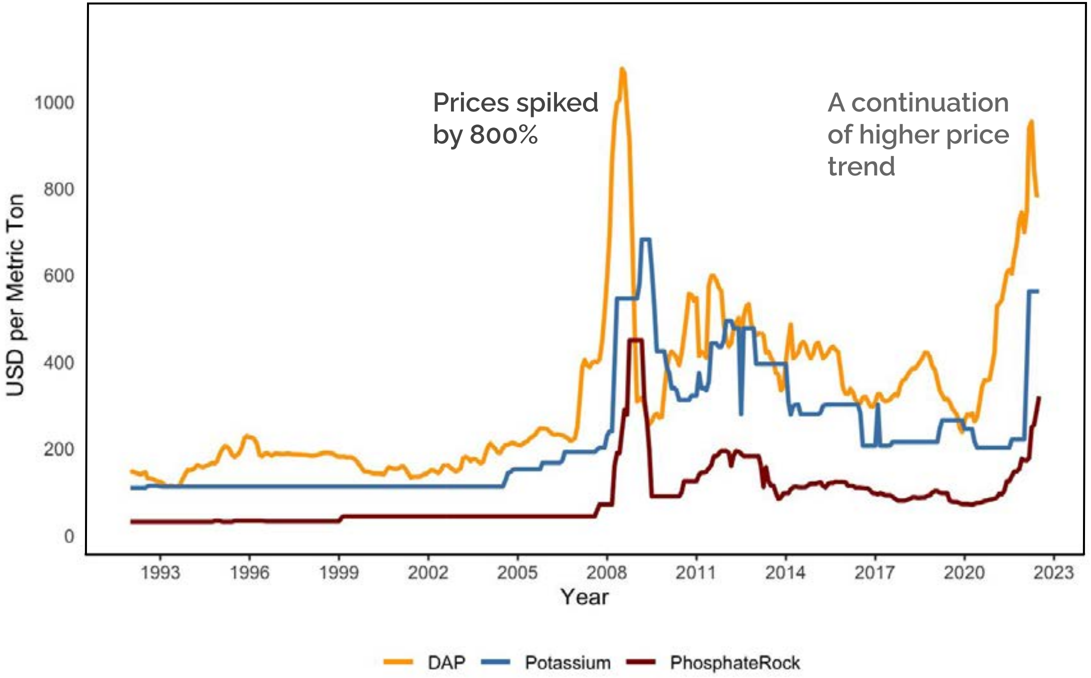
Thu Ho, Dr. Justin Baker
Department of Forestry and Environmental Resources
NC State University

Motivation

Fertilizer prices have risen **46%** since the start of 2021, reaching levels unseen since the 2008 global financial crisis

(World Bank, 2022)

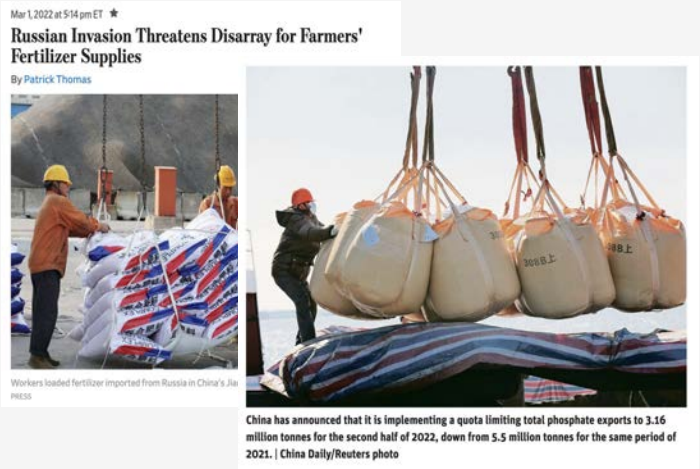
Monthly prices of DAP, Potassium, and Phosphate Rock 1993 - 2022



Remained reasonably stable

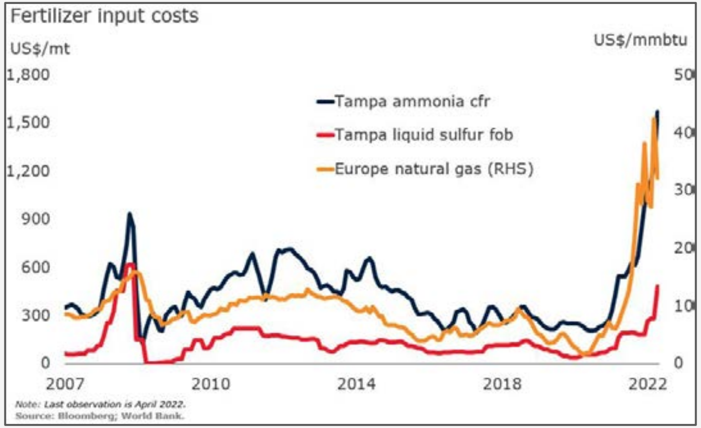
Doubled the baseline preceding the price spike

Supply disruptions



- ➢ Russia is the **third-largest phosphate exporter** and a **major supplier of key raw materials** for fertilizer production.
- ➢ **China - the world's largest P exporters -** imposed a quota for phosphate exports.

Surging input costs



- ➢ **Rising prices of natural gas and coal** led to widespread cutbacks of ammonia and sulfur, driving up fertilizer prices.

The continuation of **higher-price trends in global fertilizer** markets has escalated near- and long-term **global food security concerns**

Objectives

- Develop **an econometric approach** to examine price trends of Phosphate Rock and DAP fertilizer.
- Understand **drivers of past structural changes** in the market and generate **short-run price volatility forecasts.**

METHODOLOGY

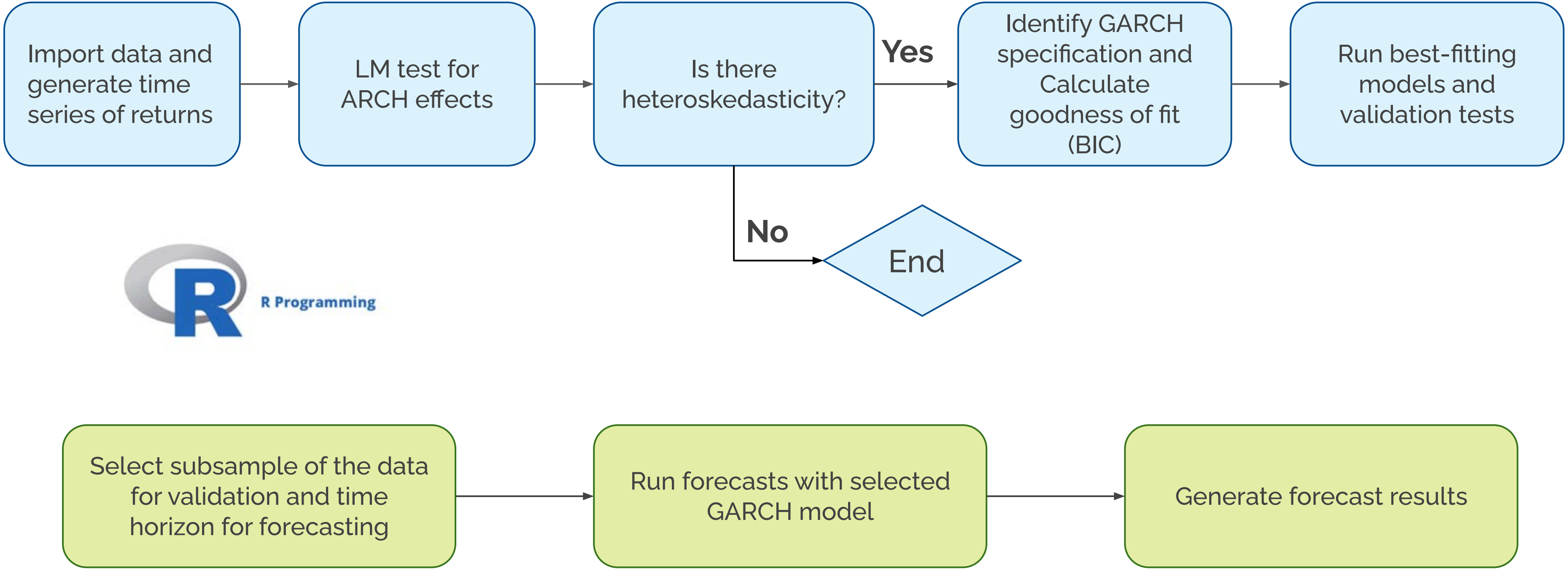
World Bank monthly commodity price data (1992/01 - 2022/07) → Structural Break Test (Bai & Perron Test 1998,2003) → GARCH model identification and forecasting

Generalized AutoRegressive Conditional Heteroskedasticity (GARCH)

- Depends on previous value of time series
- Variance depends on past information
- Variance of the error term is not constant

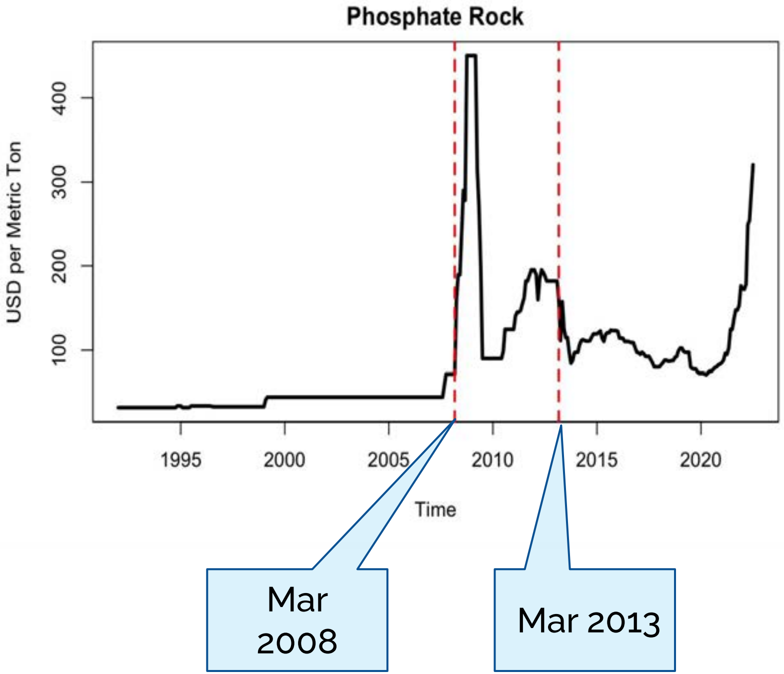
GARCH (p,q)	$R = \sigma_t \epsilon_t, \sigma_t^2 = \alpha_0 + \Sigma_{i=1}^{q} \alpha_i R_{t-i}^2 + \Sigma_{j=1}^{p} \beta_j \sigma_{t-q}^2$
EGARCH (p,q)	$R_t = \sigma_t \epsilon_t, ln(\sigma \vert t^2) = \alpha_0 + \Sigma_{i=1}^{q} \frac{\vert R_{t-i} \vert + \delta_i R_{t-i}}{\sigma_{t-i}} + \Sigma_{j=1}^{p} \beta_j ln(\sigma_{t-j}^2)$
GJR-GARCH (p,q)	$R_t = \sigma_t \epsilon_t, \sigma_t^2 = \alpha_0 + \Sigma_{i=1}^{q} (\alpha_i + \gamma_i N_{t-i}) R_{t-i}^2 + \Sigma_{j=1}^{p} \beta_j \sigma_{t-j}^2$

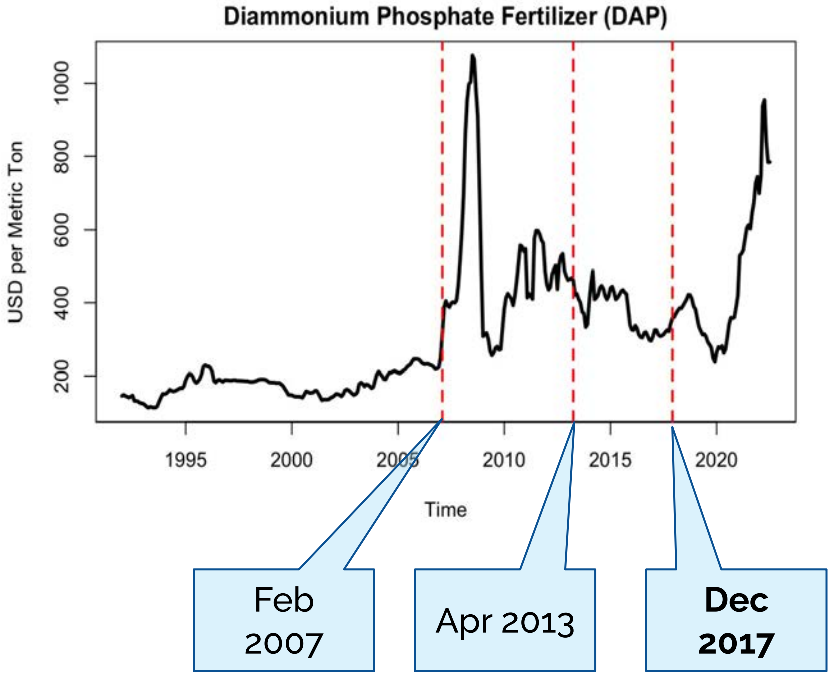
Flowchart of fitting GARCH model



RESULTS

Structural Break Test

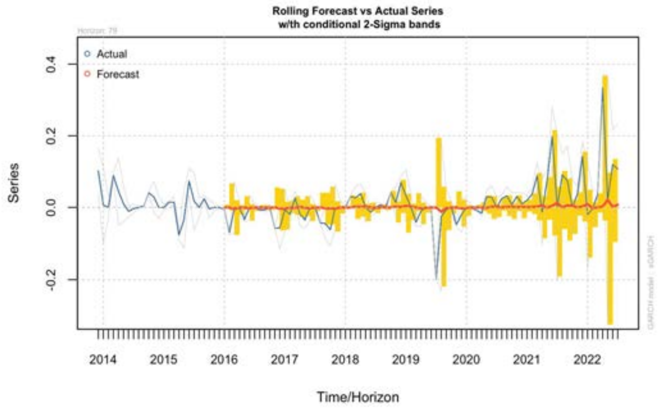


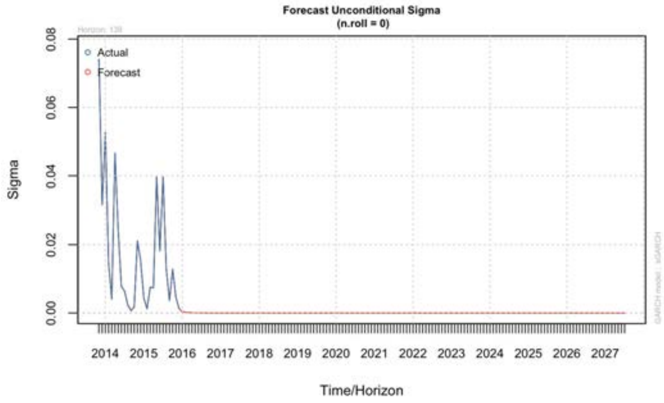


RESULTS

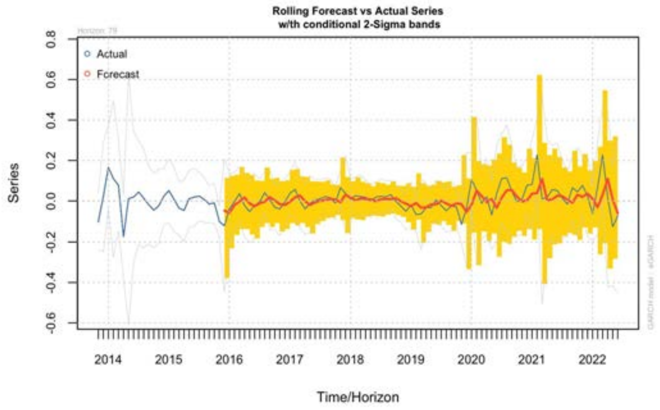
GARCH volatility forecasts

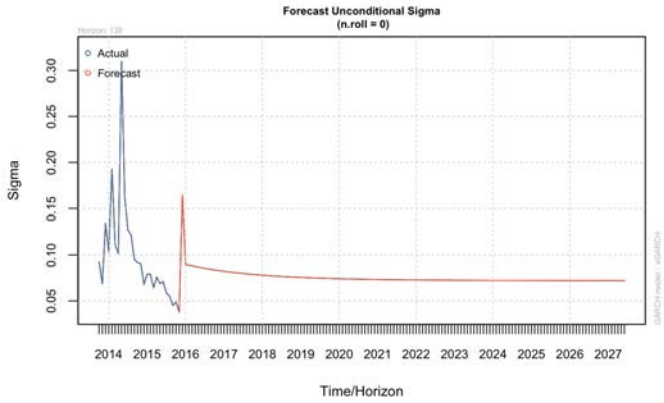
P Rock





DAP





Key Takeaways

GARCH methodology is promising for characterizing the dynamic behavior of price series data as it reflects asymmetric volatility clustering.

All commodities exhibited significant structural breakpoints over the past 30 years, inferring that the **fertilizer markets had historically experienced multiple periods of high volatility**.

Price volatility of DAP and Phosphate Rock is predicted to **subside in the next 5 years**.

Empirical results can help vulnerable agricultural producer groups and policy-makers **develop near-term risk mitigation strategies**, recognizing that high fertilizer price trends could subside within a few years.

THANK YOU
Q&A

ACKNOWLEDGEMENTS

NC STATE UNIVERSITY

STEPS
Science and Technologies for Phosphorus Sustainability

NSF

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Sustainable Phosphorus Alliance

Sustainable Phosphorus Summit

Raleigh, North Carolina, USA November 1 & 2, 2022

Improving phosphorus use efficiency by chickpea crop using electromagnetic induction, soil properties, and crop yield data under semi-arid conditions

Mohamed Chtouki[1,2], Frédéric Nguyen[3], Sarah Garré[2], and Abdallah Oukarroum[1]

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[2] University of Liege - Gembloux Agro-Bio Tech Faculty, Water, Soil & Plant Exchanges Biosystem Engineering, Gembloux B-5030, Belgium
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Corresponding : mohamed.chtouki@um6p.ma

Context of the study

- **Phosphorus: important macronutrient for crop growth and development**
  - Energy transfer
  - Photosynthesis
  - Root growth
- **Low P use efficiency (< 20%)**
  - Low P mobility and availability particularly in calcareous soil
  - P precipitation and adsorption processes, low soil OM content, etc
  - Dry conditions (**water stress**)
- **Climate change: water scarcity, longer and frequent drought episodes**

Context of the study

- **Strong pressure on natural resources**

- **Chickpea is an important crop for Mediterranean agriculture**
  - Chickpea is the second most important food legume worldwide
  - Good source of carbohydrates and protein for human and animals
  - Important legume in Mediterranean cropping systems (rotation)

- **P use efficiency improvement strategies**
  - Development of **new P fertilizer formulas** (WSF, SRF (Poly-P), CRF,…)
  - Use of additives (Humic Substances, seaweed extracts) and beneficial microorganisms (PSB, AMF, …) ..
  - **Development of new P application methods (P fertigation, variable P fertilizer application, …)**

Background

Orthophosphate VS Polyphosphate

Journal of Plant Nutrition and Soil Science

IUSS – UISS – IBU

RESEARCH ARTICLE | Full Access

Phosphorus fertilizer form and application frequency affect soil P availability, chickpea yield, and P use efficiency under drip fertigation

Mohamed Chtouki, Rachida Naciri, Sarah Garré, Frederic Nguyen, Youssef Zeroual, Abdallah Oukarroum

First published: 01 September 2022 | https://doi.org/10.1002/jpln.202100439

TABLE 3 Effect of phosphorus (P)-fertilizer form and fertigation frequency (F_{sow}: P-fertilizer applied at sowing, F_{week}: once a week, and F_{3days}: every 3 days) on nutrients acquisition and P use efficiency of chickpea

Fertilizer	Fertigation frequency	Nutrient acquisition (mg pot^{-1}) P	Nutrient acquisition (mg pot^{-1}) N	P use efficiency (%)
Control		74.9 ± 9^{c}	463.2 ± 53^{c}	
Ortho-P	F_{sow}	104.8 ± 14^{b}	832.2 ± 29^{ab}	24.5 ± 3.6^{bc}
	F_{week}	112.5 ± 7^{ab}	868.8 ± 113^{ab}	30.7 ± 3.2^{b}
	F_{3days}	100.5 ± 15^{b}	757.5 ± 96^{b}	20.9 ± 3.1^{c}
Poly-53	F_{sow}	111.8 ± 8^{ab}	855.3 ± 72^{ab}	30.2 ± 3.8^{b}
	F_{week}	118.6 ± 11^{a}	933.2 ± 88^{a}	35.8 ± 1.3^{a}
	F_{3days}	114.5 ± 3^{ab}	868.1 ± 37^{ab}	32.4 ± 2.2^{ab}
Poly-100	F_{sow}	114.3 ± 11^{ab}	853.3 ± 125^{ab}	32.2 ± 2.9^{ab}
	F_{week}	120.5 ± 7^{a}	878.3 ± 16^{ab}	37.3 ± 3.4^{a}
	F_{3days}	109.2 ± 10^{ab}	816.5 ± 147^{ab}	28.1 ± 3.2^{b}
Mean values				
Control		74.9 ± 9^{C}	463.2 ± 53^{C}	
Ortho-P		105.9 ± 4^{B}	819.5 ± 27^{B}	25.4 ± 3.1^{B}
Poly-53		114.9 ± 3^{A}	885.5 ± 39^{A}	32.8 ± 2.9^{A}
Poly-100		114.6 ± 3^{A}	849.4 ± 35^{AB}	32.5 ± 3.1^{A}
p-Values				
Fert		0.000***	0.000***	0.022*
Freq		0.000***	0.000***	0.047*
Fert × Freq		0.046*	0.021*	0.039*

Note: Data are mean values ± SD ($n = 3$). Dissimilar letters within the same column indicate significant differences at $p < 0.05$ according to Tukey's test for both lowercase and uppercase superscript letters, and ns: not significant, *, **, and *** indicate differences at $p \geq 0.05$, $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Background

Orthophosphate VS Polyphosphate

scientific reports

Check for updates

OPEN

Interactive effect of soil moisture content and phosphorus fertilizer form on chickpea growth, photosynthesis, and nutrient uptake

Mohamed Chtouki[1,2], Fatima Laaziz[1], Rachida Naciri[1], Sarah Garré[2], Frederic Nguyen[3] & Abdallah Oukarroum[1,4]

Water shortage and soil nutrient depletion are considered the main factors limiting crops productivity in the Mediterranean region characterized by longer and frequent drought episodes. In this study, we investigated the interactive effects of P fertilizer form and soil moisture conditions on chickpea photosynthetic activity, water and nutrient uptake, and their consequent effects on biomass accumulation and nutrient use efficiency. Two P fertilizer formulas based on orthophosphates (Ortho-P) and polyphosphates (Poly-P) were evaluated under three irrigation regimes (I1: 75% of field capacity, I2: 50% FC and I3: 25% FC), simulating three probable scenarios of soil water content in the Mediterranean climate (adequate water supply, medium, and severe drought stress), and compared to an unfertilized treatment. The experiment was conducted in a spilt-plot design under a drip fertigation system. The results showed significant changes in chickpea phenotypic and physiological traits in response to different P and water supply regimes. Compared with the unfertilized treatment, the stomata density and conductance, chlorophyll content, photosynthesis efficiency, biomass accumulation, and plant nutrient uptake were significantly improved under P drip fertigation. The obtained results suggested that the P fertilizer form and irrigation regime providing chickpea plants with enough P and water, at the early growth stage, increased the stomatal density and conductance, which significantly improved the photosynthetic performance index (PI_{ABS}) and P use efficiency (PUE), and consequently biomass accumulation and nutrient uptake. The significant correlations established between leaf stomatal density, PI_{ABS}, and PUE supported the above hypothesis. We concluded that the Poly-P fertilizers applied in well-watered conditions (I1) performed the best in terms of chickpea growth improvement, nutrient uptake and use efficiency. However, their effectiveness was greatly reduced under water stress conditions, unlike the Ortho-P form which kept stable positive effects on the studied parameters.

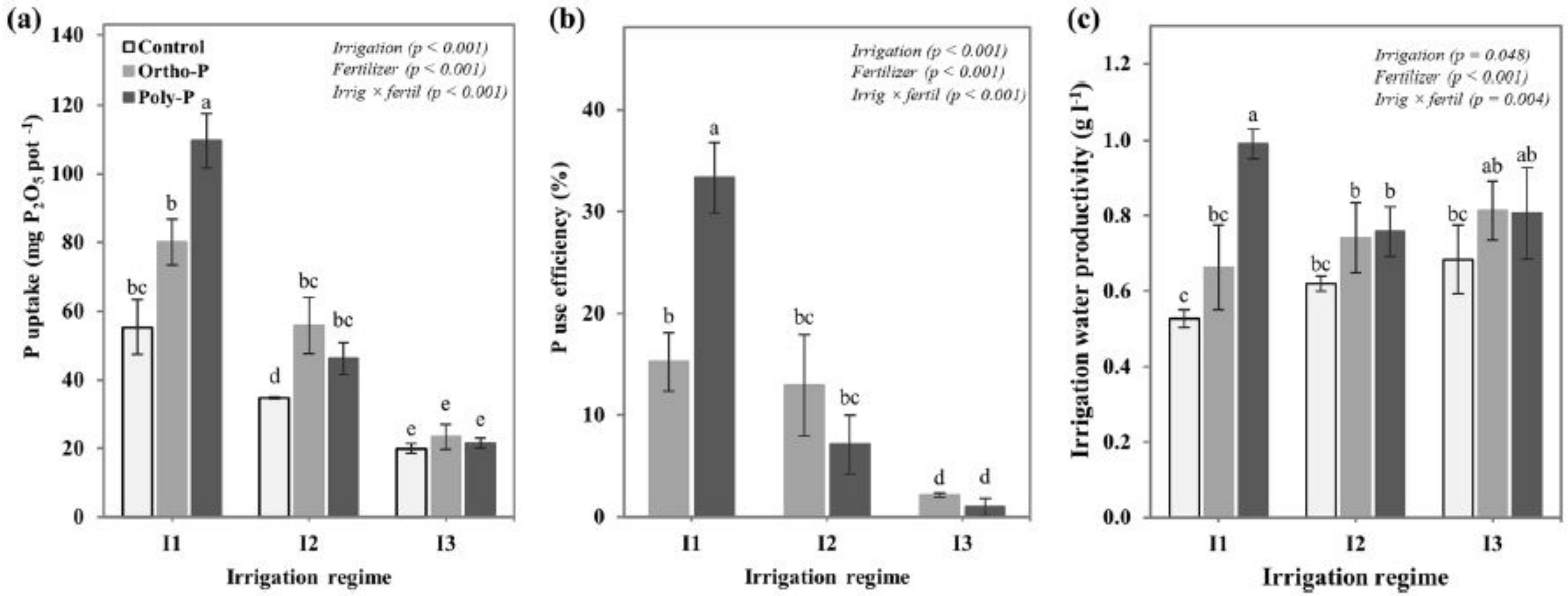


Figure 5. Interactive effects of P fertilizer form and irrigation regime on (a) phosphorus uptake, (b) phosphorus use efficiency, and (c) irrigation water productivity of chickpea (*Cicer arietinum*). Values are means of 6 replicates ± SE, dissimilar letters indicate significant differences at $p < 0.05$, according to Duncan's new multiple range test.

Objective of the study

High spatial variability of soil properties can greatly affect fertilizer use efficiency and crop productivity !!

1) Assess the spatial variability of soil properties using electromagnetic induction (EMI) technique

2) Modeling chickpea yield using EMI, soil properties, and historical crop yield data

3) Improving P use efficiency through variable rate P application strategy under drip fertigation system

Methods

Experimental site description

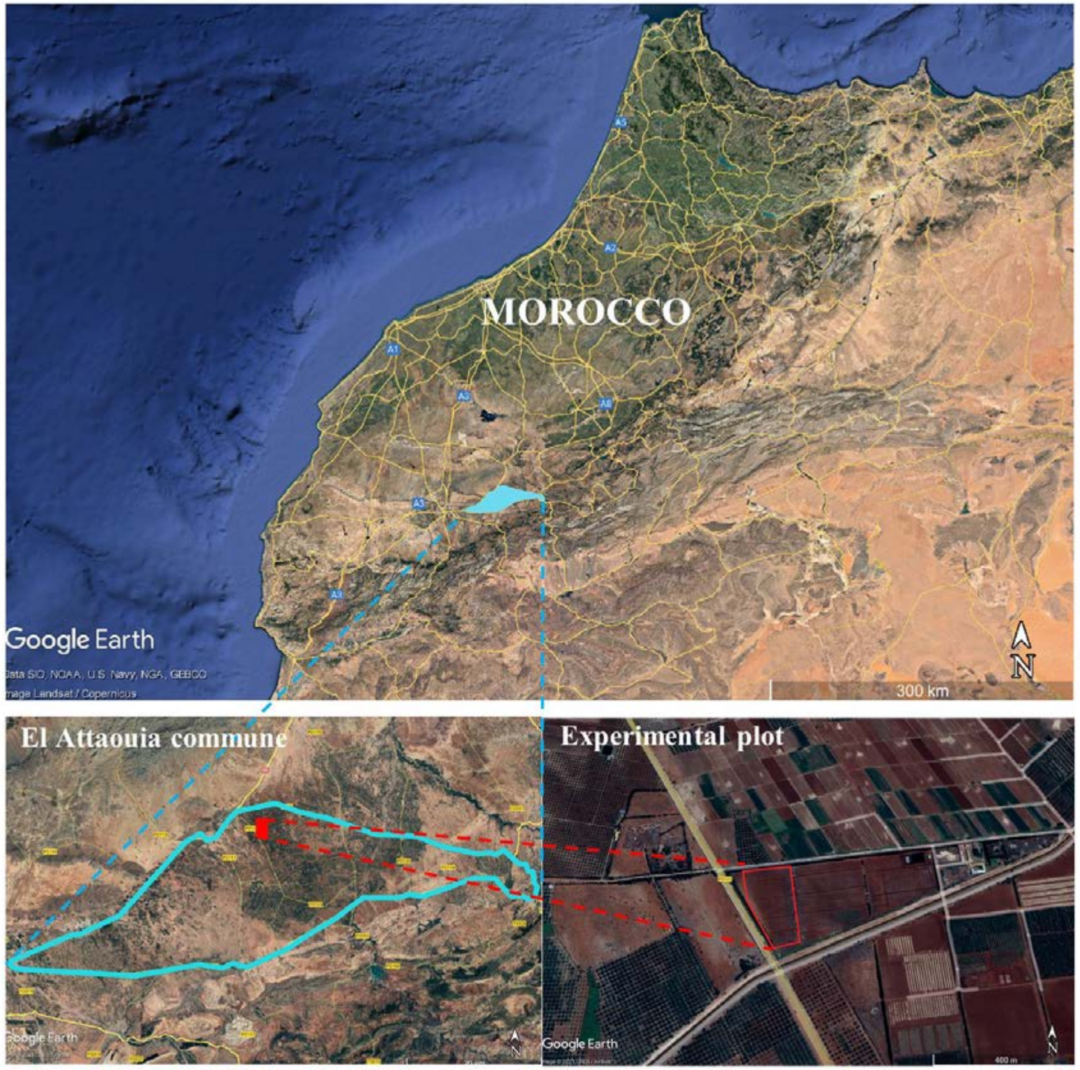


Figure . Location of the experimental site in El Attaouia, Kelâa des Sraghna, Morocco

- Clayey calcareous soil
- Mean daily temperature: 19.7 °C
- Annual rainfall (100 to 250 mm)
- More than 80% of precipitation occurring between December and March.

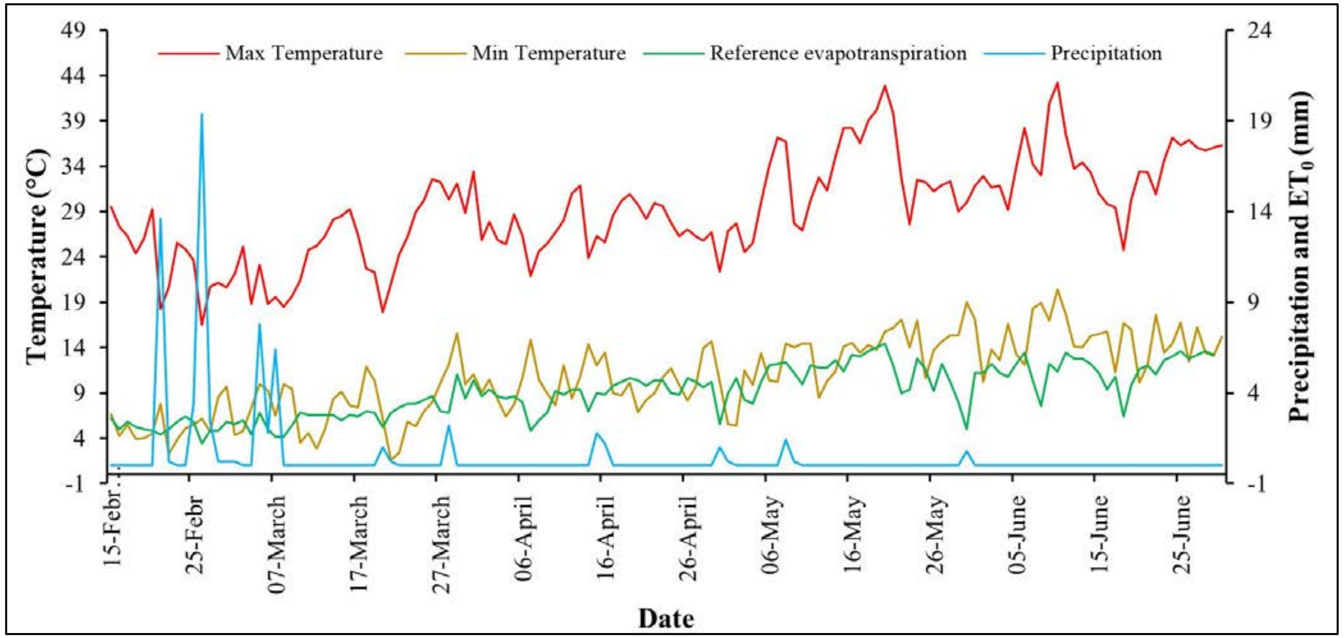
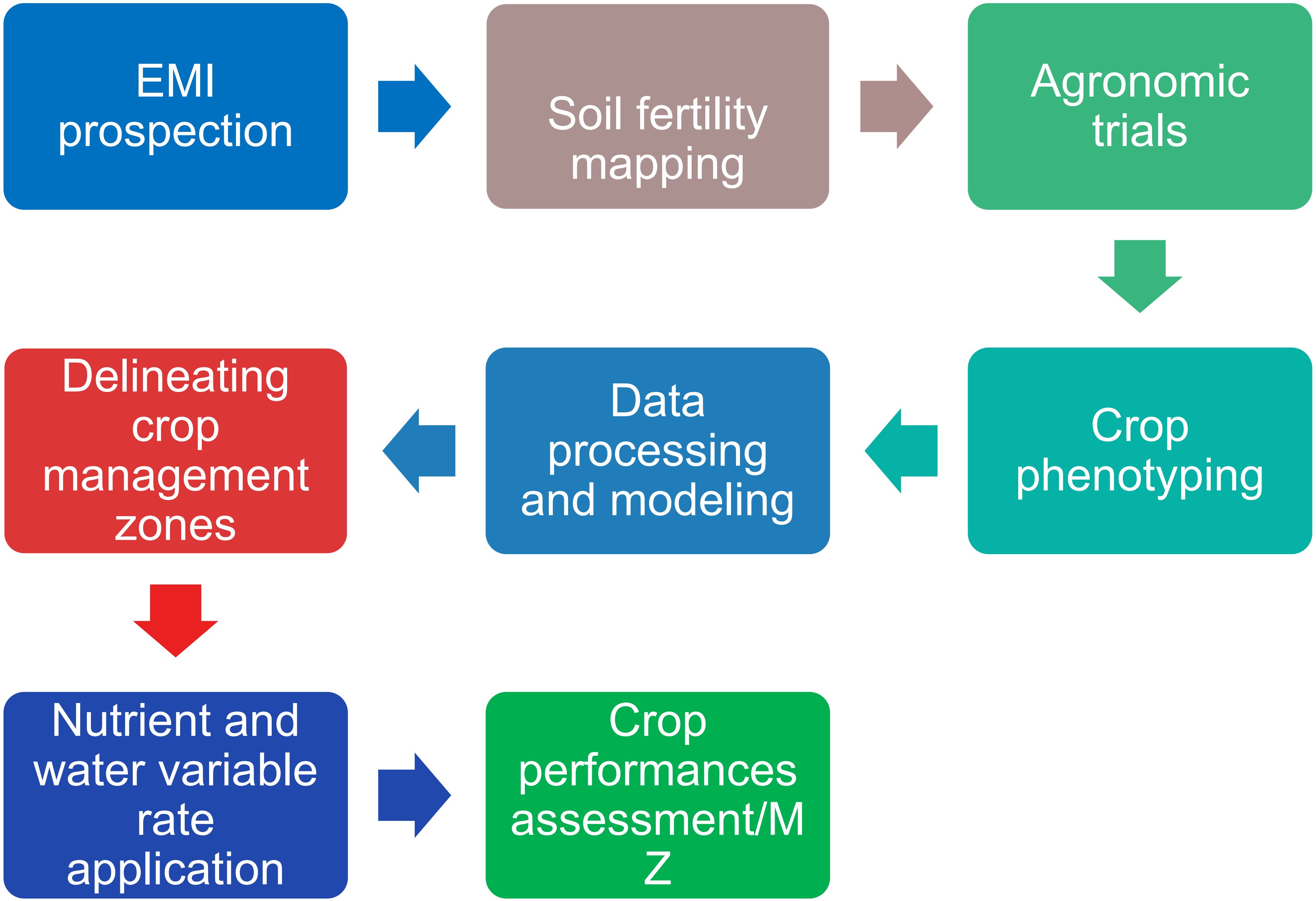


Figure. Agrometeorological data of the studied site: minimal and maximal temperature, precipitation, and reference evapotranspiration (ET_0).

Methods

Study design



Methods

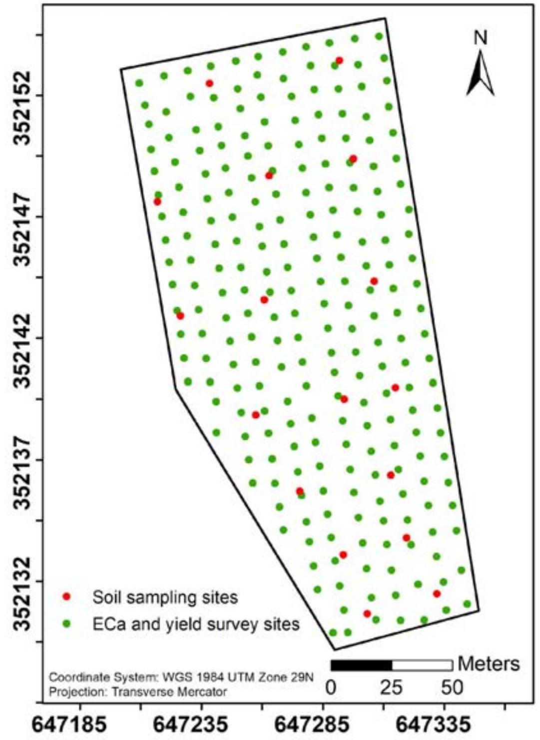
Electromagnetic induction-based soil maps and soil sampling

- Soil spatial variability was firstly assessed by the measurement of soil apparent electrical conductivity (ECa) in December 2020 using the CMD Mini-Explorer 6L

- The ECa measurements were taken using a georeferenced manual mode at a grid of 10 × 10 m for a total of 246 sites across the study area.

- The CMD Mini-Explorer conductivity meter was connected to a global navigation satellite system receiver (GNSS R10, Trimble, USA)

- 17 soil sampling sites were selected based on the ECa maps (at 15, 25, 40, and 50 cm depths) for soil analysis



Methods

Agronomic field experiment (March-June)

Chickpea drip fertigation trials in 2.5 hectare, with homogeneous treatment of the studied plot

- 120 kg ha^{-1} of chickpea seeds sown at 80 cm × 10 cm spacing (row × plant) and irrigated with a dripper of 4 l h^{-1} per plant

- 30 kg ha^{-1} of N, 46 kg ha^{-1} of P_2O_5 (Ortho-P form), and 25 kg ha^{-1} of K_2O were homogeneously applied

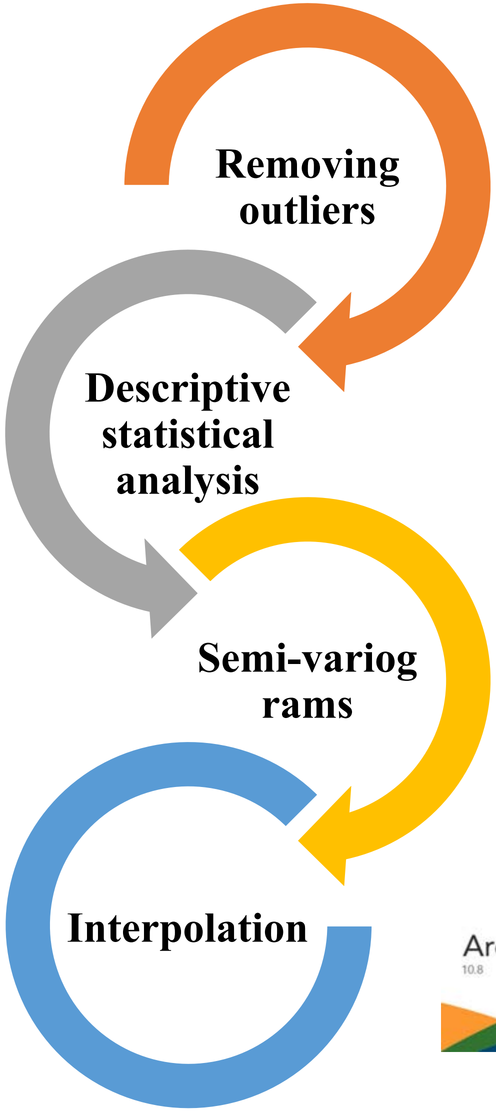
Harvest: Biological and grain yield maps

- Physiological maturity (25 June 2021)

- Yield assessed in 246 small plots of 1.6 m^2 (two sowing lines spaced 80 cm × 1 m long) applying a systematic sampling design (10 m × 10 m).

Methods

Statistical and geostatistical analyses



Tukey method

pandas

Spatial models fitting with **GS+**
Criteria: smallest RSS, highest R^2)

ArcGIS ArcMap 10.8

Interpolation methods: **ordinary kriging or inverse-distance weighting (IDW)**

Methods

Relationship between soil attributes, ECa, and chickpea yield

- **Correlation matrices** performed with “Pandas” and “Seaborn” packages in Python 3.9 (15 cm, 25 cm, 40 cm, and 50 cm) and depth increments (0-15 cm, 0-25 cm, 0-40 cm, and 0-50 cm).
- **Multilinear regression (MLR) models**
- 70% and 30% of the collected data set used as training set and validation set respectively.
- The **NRMSE** was calculated according to the following equation:

$$NRMSE = \frac{\sum_{i=1}^{n}\left(Y_{obs} - Y_{pred}\right)^2}{n \times \bar{Y}_{obs}}$$

Y_{obs} and Y_{pred} : observed and predicted values of the chickpea grain yield respectively,

$\bar{Y}_{obs}$: average grain yield of the total dataset (n = 246).

Methods

Chickpea management zones delineation

- Cluster analysis: GY maps and the explanatory-variables maps (ECa, pH, P, Ca)
- **Unsupervised classification: fuzzy c-means algorithm**
- **Fuzziness Performance Index (FPI) & Normalized Classification Entropy Index (NCE)**

$$\mathrm{FPI} = 1 - \frac{c}{(c-1)}\left[1 - \frac{1}{n}\sum_{k=1}^{n}\sum_{i=1}^{c}(u_{ik})^2\right]$$

$$\mathrm{NCE} = \frac{c}{(n-c)}\left[-\frac{1}{n}\sum_{k=1}^{n}\sum_{i=1}^{c} u_{ik}\, \log_a\, (u_{ik})\right]$$

C reprensents the centroid values in the cluster; uik, the values for each observation K in cluster I; $\log_a$, any positive integer, and n, the number of data analyzed

- Evaluation of the proposed clusters by the comparison of means using **one-way ANOVA in SPSS**

Results

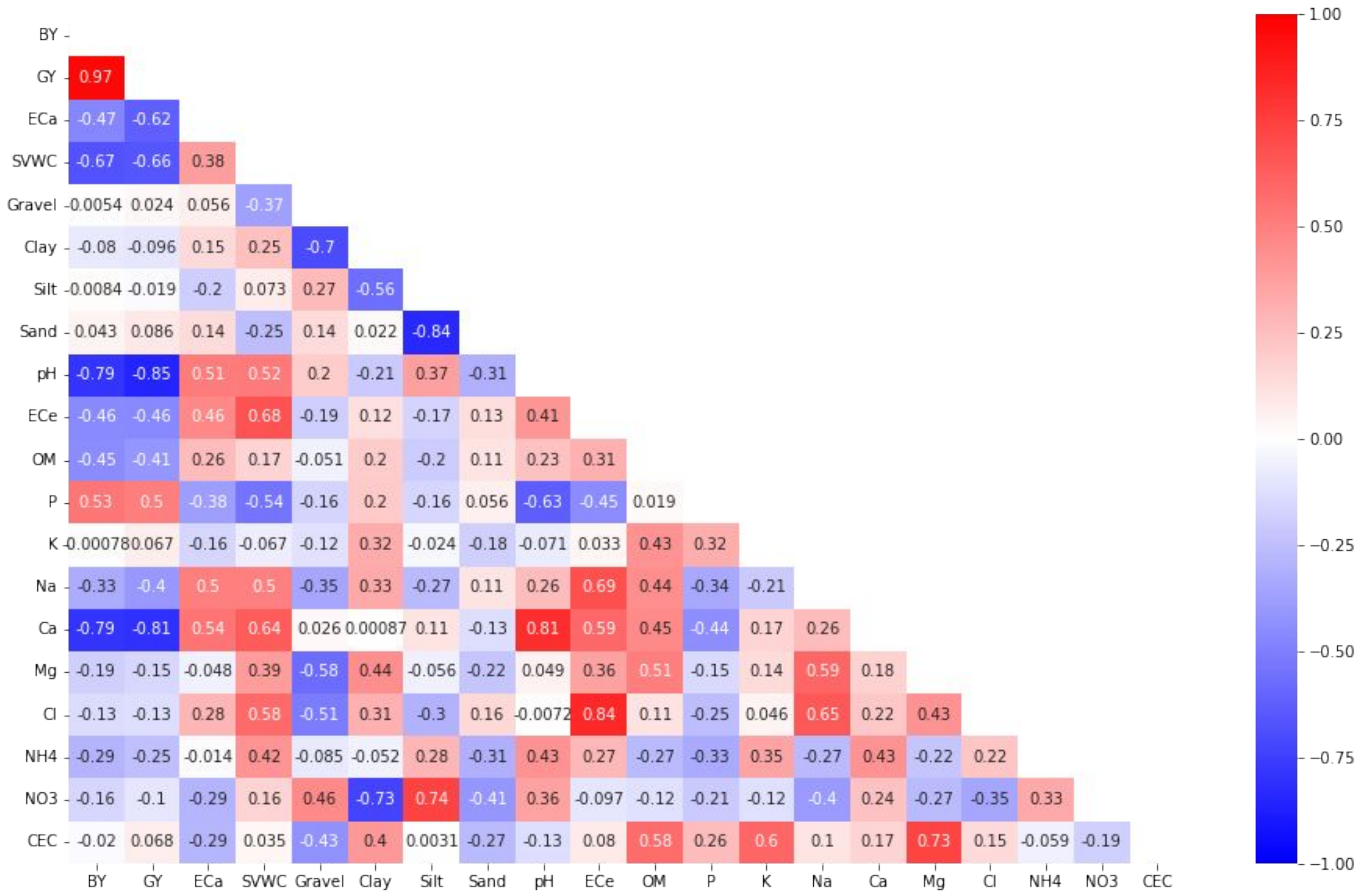
Descriptive statistics of soil attributes and chickpea yield

- Clayey soil (40% clay)
- High levels of calcium carbonates
- High pH (8.2)
- Medium organic matter content
- Medium to relatively high salinity
- High variation in chickpea grain yield (CV = 37.8)

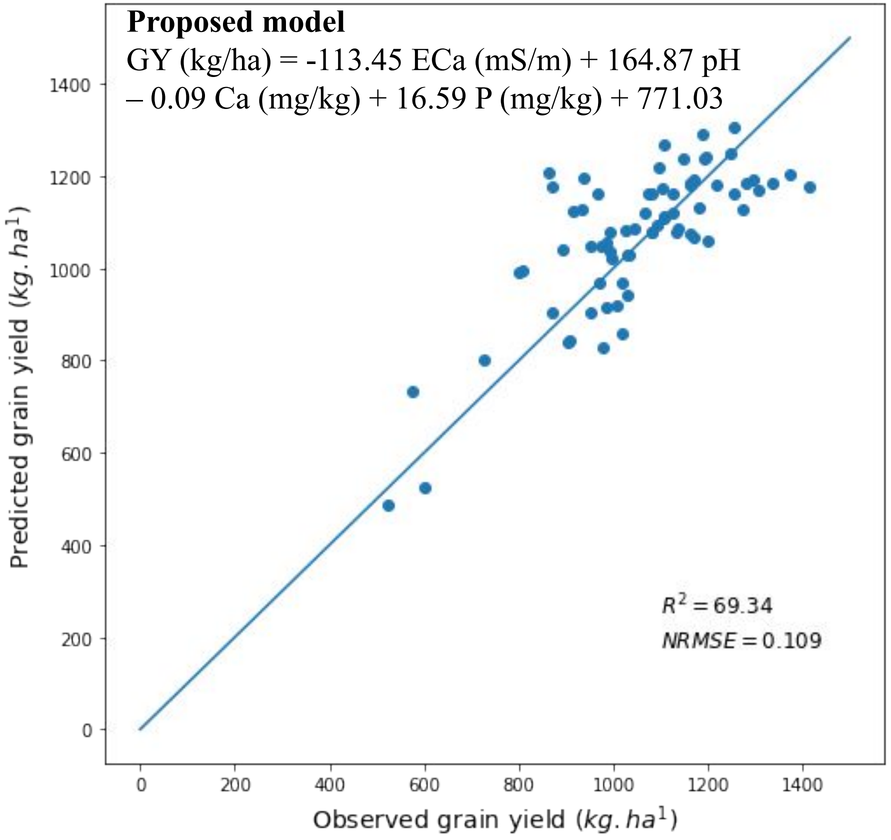
Soil depth	Paramter	Mean	Min	Max	SD	CV	A	K	SW
25 cm	ECa	7.4	4.7	11.4	1.1	14.8	0.41	0.84	0.98*
	SVWC (%)	11.2	6.0	18.40	3.8	34.2	0.59	-0.57	0.93^{ns}
	Gravel (%)	160.3	72.0	250.0	47.8	29.8	-0.26	-0.33	0.97^{ns}
	Clay (%)	380.0	340.0	420.0	27.4	7.21	-0.50	-1.33	0.82*
	Silt (%)	244.7	140.0	340.0	50.3	20.5	-0.25	-0.09	0.96^{ns}
	Sand ($g\ kg^{-1}$)	375.3	280.0	460.0	41.5	11.1	-0.26	1.06	0.96^{ns}
	pH	8.2	7.8	8.5	0.2	2.4	0.05	-0.76	0.96^{ns}
	ECe ($mS\ cm^{-1}$)	0.2	0.2	0.3	0.1	25.0	0.46	-0.61	0.95^{ns}
	OM (%)	1.5	0.7	2.3	0.35	23.3	0.07	1.47	0.96^{ns}
	P ($mg\ kg^{-1}$)	16.2	6.11	30.6	7.3	44.8	0.24	-0.87	0.95^{ns}
	K ($mg\ kg^{-1}$)	347.3	223.4	477.3	80.6	23.2	-0.15	-0.94	0.94^{ns}
	Na ($mg\ kg^{-1}$)	234.3	148.1	341.5	54.6	23.3	0.05	-0.36	0.96^{ns}
	Ca ($mg\ kg^{-1}$)	4060.5	3143.4	7152.1	1151.6	28.3	1.54	1.92	0.78**
	Mg ($mg\ kg^{-1}$)	518.0	430.9	590.2	50.4	9.7	-0.51	-0.72	0.92^{ns}
	Cl ($mg\ kg^{-1}$)	89.5	25.4	189.7	50.5	56.4	0.63	-0.85	0.91^{ns}
	NH_4 ($mg\ kg^{-1}$)	1.5	0.1	3.5	1.2	80.0	0.43	-1.41	0.89^{ns}
	NO_3 ($mg\ kg^{-1}$)	29.5	13.3	49.4	11.0	37.2	0.30	-0.79	0.88*
	CEC ($meq\ 100g^{-1}$)	17.2	11.1	19.7	2.4	13.9	-1.32	1.45	0.86*
	BY ($kg\ ha^{-1}$)	3505.6	587.5	6950.0	1171.8	33.4	0.02	0.08	0.99*
	GY ($kg\ ha^{-1}$)	1042.5	226.8	2089.4	394.5	37.8	0.40	-0.10	0.98*

Results

Relationship between chickpea yield and soil properties (25 cm)



Relationship between chickpea yield and soil properties

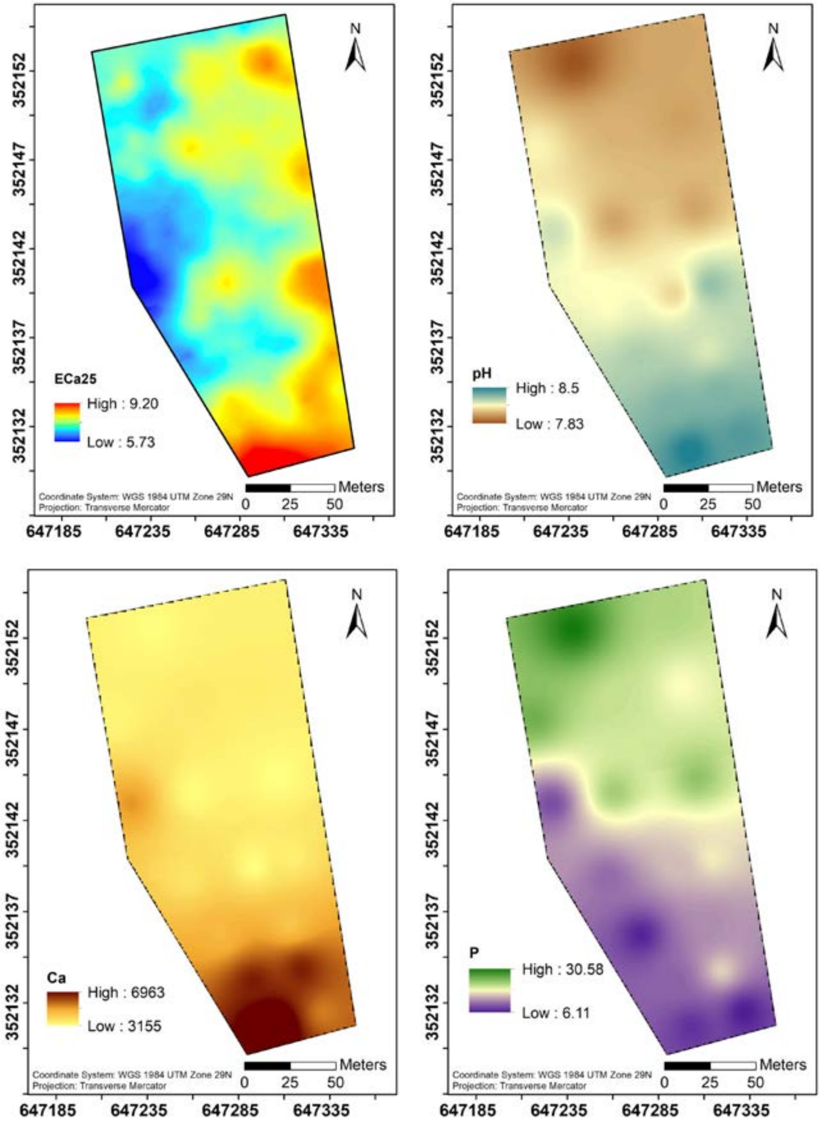


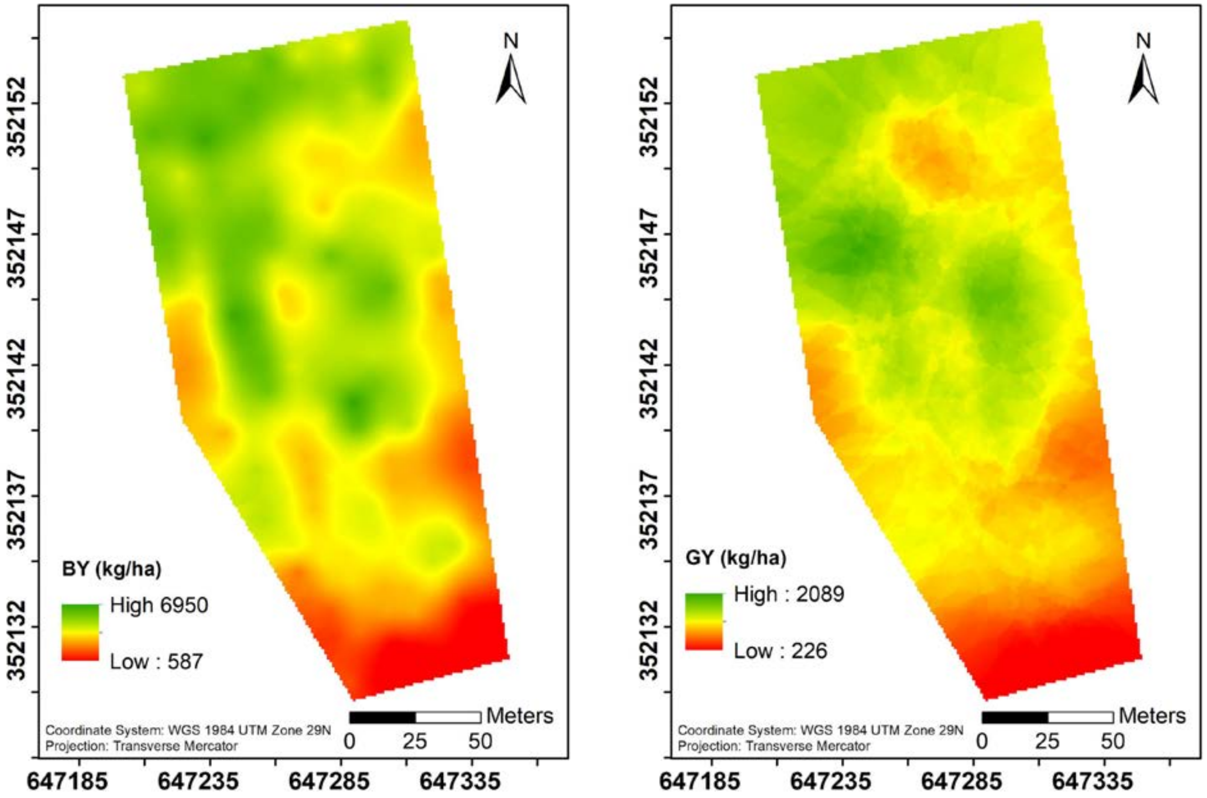
Model parameters

R squared: 69.34
Mean Absolute Error: 89.91
Mean Square Error: 13528.75
Root Mean Square Error: 116.31
Normalized Root Mean Square Error: 0.109

Results

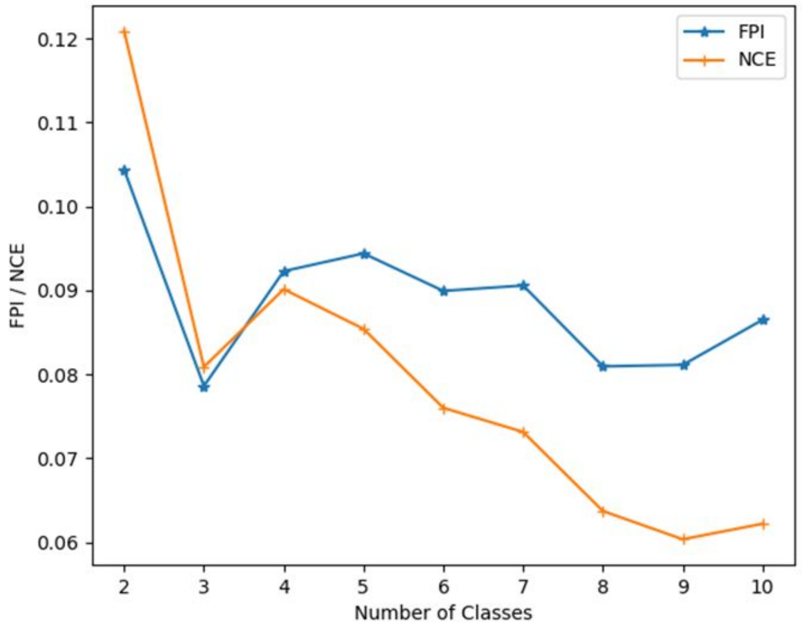
Spatial variability of soil Eca, soil physical-chemical properties, and crop yield

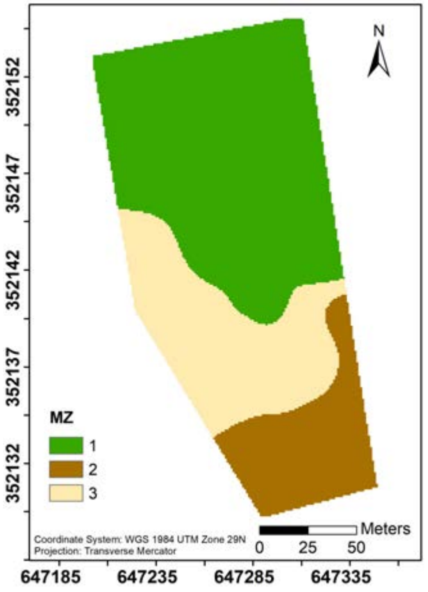




Results

Delineation of drip fertigation management zones (MZs)





- **MZ 1: high yield potential (+54% than MZ2)**, adequate P content, low pH and Ca than other MZ
- **MZ 3: medium yield (+33% than MZ2)**, low P, medium salinity, medium Ca content
- **MZ 2: lower yield potential**, low P, very high pH and Ca, high risk of P and micronutrient availability, relatively high salinity

Table . Comparison of the average chickpea biological and grain yields and soil attributes used in the multiple regression model, in different delineated MZs.

Management zone	Sampling sites (n)	ECa25 ($mS\ m^{-1}$)	pH	Ca ($mg\ kg^{-1}$)	P ($mg\ kg^{-1}$)	Biologgical yield ($kg\ ha^{-1}$)	Grain yield ($kg\ ha^{-1}$)
MZ1	137	7.35 ± 0.04^b	8.03 ± 0.01^c	3371 ± 30^c	21.41 ± 0.2^a	3977 ± 49^a	1165 ± 10^a
MZ2	38	8.17 ± 0.07^a	8.36 ± 0.01^a	5272 ± 57^a	11.09 ± 0.4^c	2281 ± 94^c	752 ± 19^c
MZ3	61	7.03 ± 0.06^c	8.21 ± 0.01^b	3955 ± 45^b	12.66 ± 0.3^b	3300 ± 74^b	1003 ± 15^b

Results

Practical recommendations from MZs delineation

- Rationalize the P fertilizer rates considering the P content in each MZ
- MZs with a high salinity level should receive more irrigation water to limit the salt flow to the surface and promote leaching
- Avoid the use of P fertilizers rich in calcium (like TSP) and favor sulphate forms for N and K fertilizers (ammonium sulphate, potassium sulphate, etc) to decrease soil pH
- Micronutrient supply (Spray application) may be necessary in case of appearance of nutritional deficiency on plants

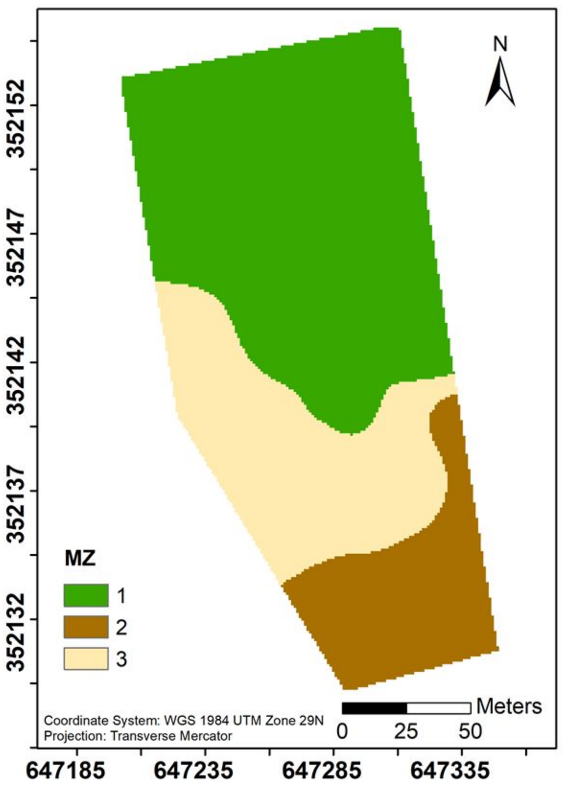
2^{nd} Field experiment: variable rate P application via drip fertigation

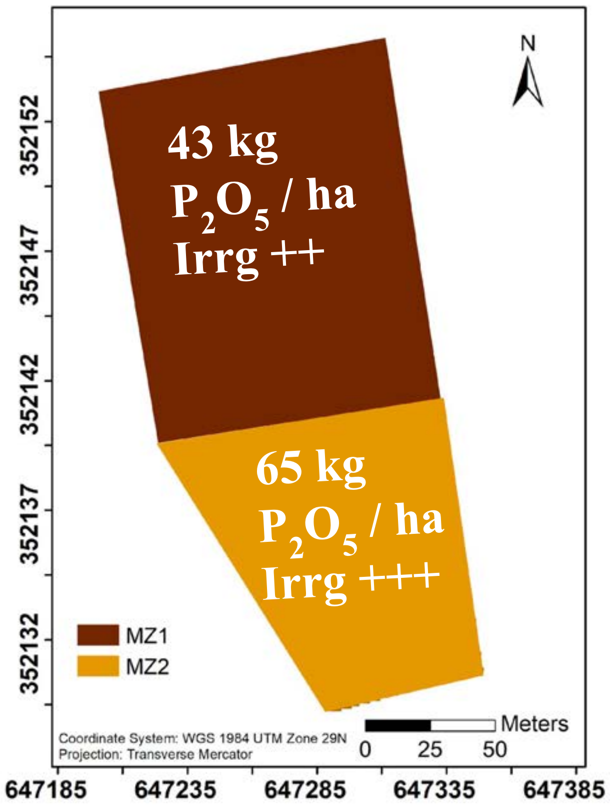
Methodology

Variable rate application of water and P

MAP (Ortho-P form): water soluble P fertilizer, weekly application

P rates calculated from the results of pot experiments

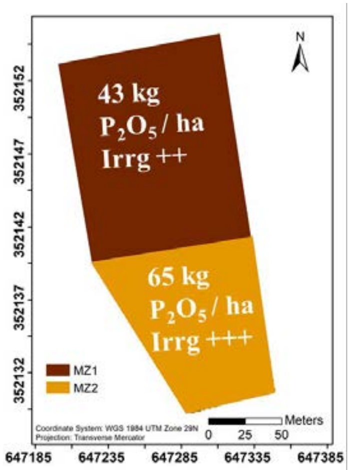




2nd Field experiment: variable rate P application via drip fertigation

Results

Treatment	MZ	GY (kg/ha)	Shoot P (%)	Seed P (%)	PUE (%)
Conventional treatment	MZ1	1135 + 15	0.09 ± 0.01	0.44 ± 0.02	18.41
	MZ2	898 + 18	0.08 ± 0.01	0.39 ± 0.01	15.32
	Avg	1040 ± 50	0.086 ± 0.01	0.42 ± 0.02	**17.17**
Variable rate P fertigation	MZ1	1886 + 35	0.12 ± 0.01	0.46 ± 0.01	39.17
	MZ2	1568 + 41	0.11 ± 0.02	0.46 ± 0.01	20.52
	Avg	1758 ± 50	0.096 ± 0.01	0.432 ± 0.02	**31.71**



PUE 17.17%

Variable rate P fertigation

PUE 31.71%

Conclusions

- Poly-P fertilizers applied in well-watered conditions performed the best in terms of chickpea growth improvement, nutrient uptake and use efficiency

- However, the effectiveness of Poly-P was greatly reduced under water stress conditions, unlike the Ortho-P form which kept stable positive effects on the studied parameters

- Water availability remains an important point to be considered for any eventual integration of the Poly-P fertilizer forms in the crop fertilization programs under Mediterranean conditions

- P management practices (frequency, P from, and rate) had a great impact on chickpea productivity in calcareous soils

Conclusions

- The EMI technique presents a high opportunity to assess soil spatial heterogeneity rapidly, costly, and at large scale

- Soil fertility maybe assessed by soil-oriented sampling scheme using EMI data as first clusters

- Modeling crop yield using soil and crop data may help to carefully chose the explicative variables of the spatial heterogeneity of crops yields, which increase the quality of crop management zones (MZs) delineated

- In addition to chose of P form and rate, P application using variable rate application (VRA) contribute greatly to improve PUE and crops yield at plot and regional scale

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Agro-Bio Tech

MOHAMMED VI
POLYTECHNIC
UNIVERSITY

ESAFE
SCHOOL OF AGRICULTURE,
FERTILIZATION AND
ENVIRONMENTAL SCIENCES

Thanks

Biodegradable polymer nanocomposites for controlled release and targeted delivery of phosphorus during crop growth

Jason C. White[1], Howard Fairbrother[2], Leslie Sigmon[2], Shital Vaidya[1], Jaya Borgatta[1], Corey Thrasher[2], Christian Dimkpa[1], Wade Elmer[1]

[1]CT Agricultural Experiment Station (CAES); [2]Johns Hopkins University (JHU)

by Nubia Zuverza-Mena

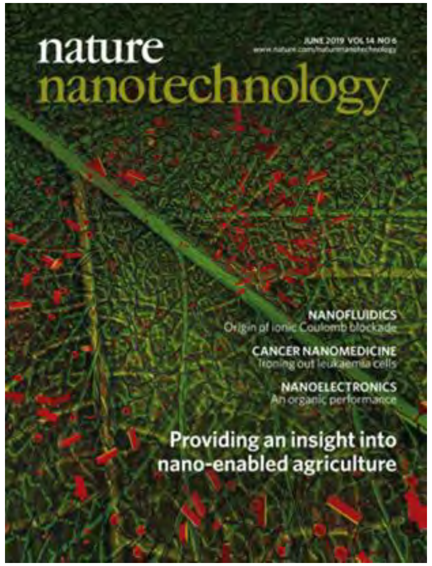
Assistant Scientist - Analytical Chemistry

CAES

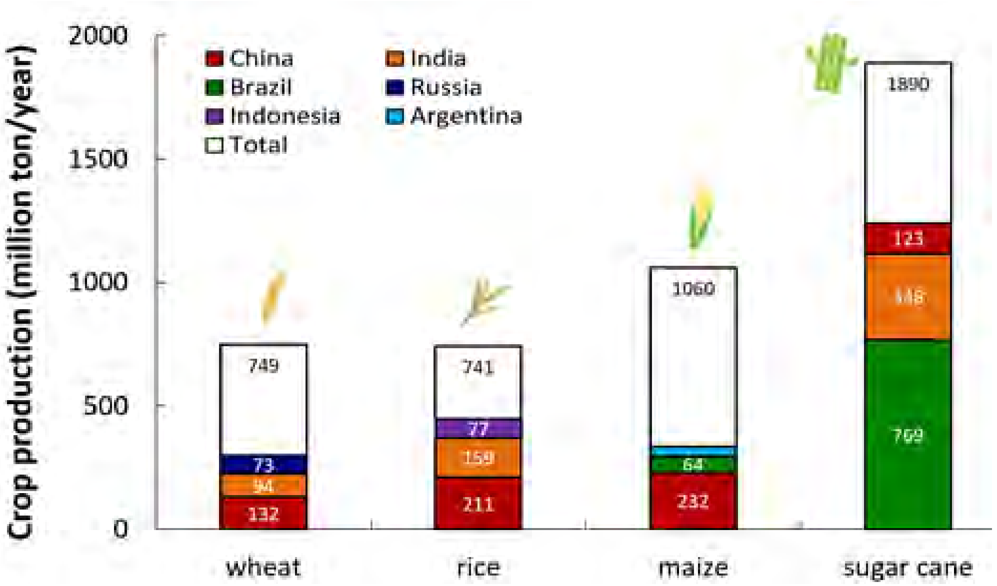
Sustainable Phosphorus Summit – November, 2022

Agriculture: Current perspective

- Agricultural productivity has increased dramatically in the last 50 years (irrigation, agrichemicals) However, global agriculture is dominated by a small number of crops in a few countries.
- The rate of crop yield increase has declined since the 1980s.
- Poverty and hunger have decreased globally, but 800 million are chronically hungry; 2 billion suffer micronutrient deficiencies.
- Agricultural systems in the much of the world have plateaued at 20-80% of yield potential
- Agrichemical delivery efficiency is often only 1-25% (Nanotechnology!)



Kah et al. 2019 *Nature Nano* 14:532-540.



www.ct.gov/caes

Why nano-agriculture?
Declining global food security!!!

- Current estimates are that food production will need to increase by 70-100% by 2050 to sustain the population
- Negative pressure from a changing climate and a loss of arable soil
- And then there is COVID…
- Novel strategies and technologies are needed from "farm to fork" (and beyond) to sustainably solve the grand challenge of global food security
- Nanotechnology **<u>can and will</u>** play a significant role in this effort; **<u>particularly with the inefficiencies</u>**!!!

FOOD SECURITY: COVID-19

COVID-19 risks to global food security

Economic fallout and food supply chain disruptions require attention from policy-makers

PNAS January 2019

Decline in climate resilience of European wheat

Helena Kahiluoto[a,1], Janne Kaseva[b], Jan Balek[c,d], Jørgen E. Olesen[e], Margarita Ruiz-Ramos[f], Anne Gobin[g], Kurt Christian Kersebaum[h], Jozef Takáč[i], Francoise Ruget[j], Roberto Ferrise[k], Pavol Bezak[l], Gemma Capellades[l], Camilla Dibari[k], Hanna Mäkinen[a], Claas Nendel[h], Domenico Ventrella[m], Alfredo Rodríguez[f,n], Marco Bindi[k], and Mirek Trnka[c,d]

CLIMATE CHANGE

Increase in crop losses to insect pests in a warming climate

Curtis A. Deutsch[1,2*†], Joshua J. Tewksbury[3,4,5†], Michelle Tigchelaar[6], David S. Battisti[6], Scott C. Merrill[7], Raymond B. Huey[2], Rosamond L. Naylor[8]

ACS NANO www.acsnano.org EDITORIAL

At the Nexus of Food Security and Safety: Opportunities for Nanoscience and Nanotechnology

In a 2009 report, the United Nations Food and Agriculture Organization (UNFAO) presented the grand challenge "How to Feed the World in 2050", as the number of people worldwide is estimated to grow to 9.1 billion.[1] This increase in social policies and economic investment and, notably, new technologies.[1] Technologies are needed to enable sustainable and intelligent farming practices as the increased food production is forecasted to be achievable by increasing crop

PNAS

Opinion: To feed the world in 2050 will require a global revolution

Paul R. Ehrlich[a,1] and John Harte[b,1]

[a]Department of Biology, Stanford University, Stanford, CA 94305; and [b]Energy and Resources Group, University of California, Berkeley, CA 94720

Achieving universal food security is a staggering challenge, especially in a world with an (and especially in combination) impede attempts to achieve progressive and effective policies

feed humanity makes the prospects seem slim for making the projected 9.7 billion population food-secure and healthy in 2050, and perhaps billions more beyond that (5).

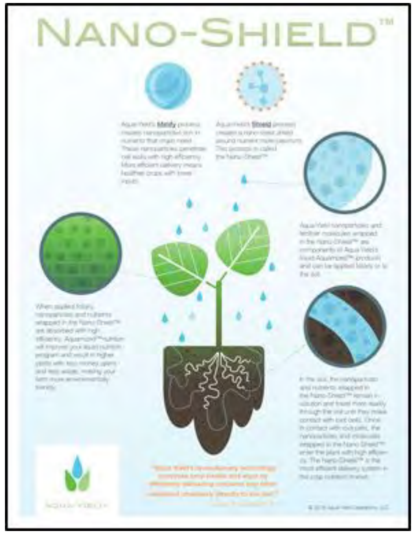
Major Challenges

Humanity now faces severe biophysical con-

Nanotechnology and agriculture

- There has been significant interest in using nanotechnology in agriculture to:
  - Increase production rates and yield
  - Increase efficiency of resource utilization
  - Minimize waste production
- Specific applications include:
  - Nano-fertilizers, Nano-pesticides
  - Nano-based treatment of agric. waste
  - Nanosensors

2018



nature nanotechnology — ARTICLES — 2020

Advanced material modulation of nutritional and phytohormone status alleviates damage from soybean sudden death syndrome

Chuanxin Ma, Jaya Borgatta, Blake Geoffrey Hudson, Ali Abbaspour Tamijani, Roberto De La Torre-Roche, Nubia Zuverza-Mena, Yu Shen, Wade Elmer, Baoshan Xing, Sara Elizabeth Mason, Robert John Hamers and Jason Christopher White

Environmental Science Nano — 2017 — TUTORIAL REVIEW

Nanotechnology for sustainable food production: promising opportunities and scientific challenges

Sónia M. Rodrigues, Philip Demokritou, Nick Dokoozlian, Christine Ogilvie Hendren, Barbara Karn, Meagan S. Mauter, Omowunmi A. Sadik, Maximilian Safarpour, Jason M. Unrine, Josh Viers, Paul Welle, Jason C. White, Mark R. Wiesner and Gregory V. Lowry

Environmental Science Nano — 2018 — PAPER

Environmental fate of nanopesticides: durability, sorption and photodegradation of nanoformulated clothianidin†

Melanie Kah, Helene Walch and Thilo Hofmann

REVIEW ARTICLE | INSIGHT — nature nanotechnology — 2019

Nano-enabled strategies to enhance crop nutrition and protection

Melanie Kah, Nathalie Tufenkji and Jason C. White

Various nano-enabled strategies are proposed to improve crop production and meet the growing global demands for food, feed and fuel while practising sustainable agriculture. After providing a brief overview of the challenges faced in the sector of crop nutrition and protection, this Review presents the possible applications of nanotechnology in this area. We also consider performance data from patents and unpublished sources so as to define the scope of what can be realistically achieved. In addition to being an industry with a narrow profit margin, agricultural businesses have inherent constraints that must be carefully considered and that include existing (or future) regulations, as well as public perception and acceptance. Directions are also identified to guide future research and establish objectives that promote the responsible and sustainable development of nanotechnology in the agri-business sector.

Environmental Science Nano — 2019 — CRITICAL REVIEW

Recent advances in nano-enabled fertilizers and pesticides: a critical review of mechanisms of action

Ishaq O. Adisa, Venkata L. Reddy Pullagurala, Jose R. Peralta-Videa, Christian O. Dimkpa, Wade H. Elmer, Jorge L. Gardea-Torresdey and Jason C. White

NANOTECHNOLOGY AND AGRICULTURE

Achieving food security through the very small

Nanotechnology could make agriculture more efficient and more sustainable, but more systematic understanding of the mechanisms involved is necessary to prove the potential of nano-enabled agrochemicals.

Jason C. White and Jorge Gardea-Torresdey

REVIEW ARTICLE — nature food — 2020

Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture

Thilo Hofmann, Gregory Victor Lowry, Subhasis Ghoshal, Nathalie Tufenkji, Davide Brambilla, John Robert Dutcher, Leanne M. Gilbertson, Juan Pablo Giraldo, Joseph Matthew Kinsella, Markita Patricia Landry, Wess Lovell, Rafik Naccache, Mathews Paret, Joel Alexander Pedersen, Jason Michael Unrine, Jason Christopher White and Kevin James Wilkinson

ACS NANO — 2021

Nanotechnology and Plant Viruses: An Emerging Disease Management Approach for Resistant Pathogens

Tahir Farooq, Muhammad Adeel, Zifu He, Muhammad Umar, Noman Shakoor, Washington da Silva, Wade Elmer, Jason C. White, and Yukui Rui

“Nano” research at the CAES

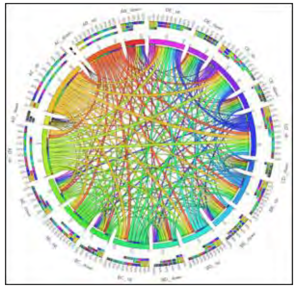
The Center for Sustainable Nanotechnology

Nanyang Technological University – Harvard T.H. Chan School of Public Health
Initiative for Sustainable Nanotechnology

USDA
National Institute of Food and Agriculture

1. Applications: Nano-enabled agriculture

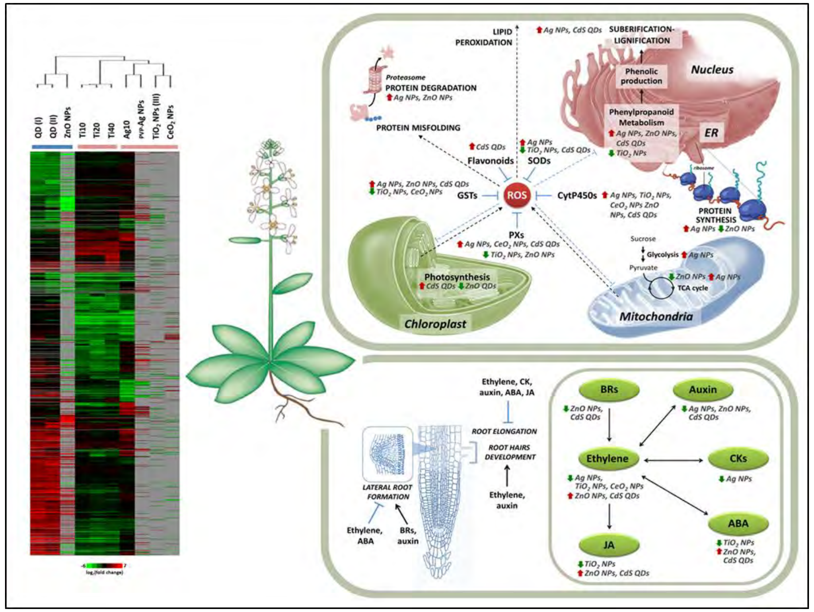
- Nano-enabled micro/macronutrient delivery platforms
- Nanoscale micronutrients to modulate crop nutrition for disease suppression
- Nanoscale materials to enhance stress tolerance, photosynthesis, induce RNA interference



Ruotolo et al. 2018. *Environ. Sci. Technol.* 52:2451-2467.

2. Implications: Nanotoxicology

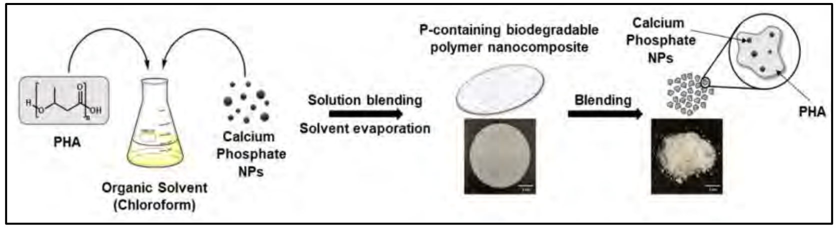
- Fate and effects of nanomaterials (NM) on plants and related biota
- Investigating the molecular basis of plant response; to ensure accurate risk assessment and safe use
- NM trophic transfer and transgenerational

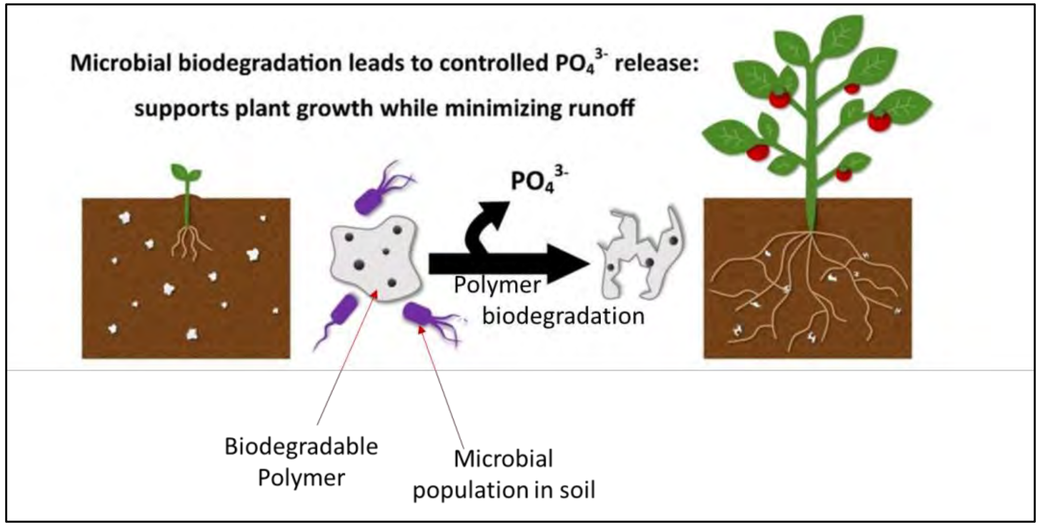


Polymer nanocomposites - P delivery

- We propose to make a **tunable suite** of biodegradable polymer nanocomposite fertilizers that will release P to plants as desired rates.
- Polyhydroxyalkanoate (PHA) is a highly biodegradable polymer made by bacteria.
- We used solution blending to make composites of PHA and calcium phosphate (CaP) nanoparticles (NPs); then we mix that composite into soil with plants.
- As native bacteria in soil biodegrade the PHA, CaP is released from the polymer matrix and becomes available to plants.
- There is little or no P run-off because CaP is retained in the PHA until it is biodegraded and released.
- This responsive platform is tunable (changing polymers or co-polymer ratios).

Sigmon et al. 2021 *ACS Agric. Sci. Technol*. DOI: 10.1021/acsagscitech.1c00149





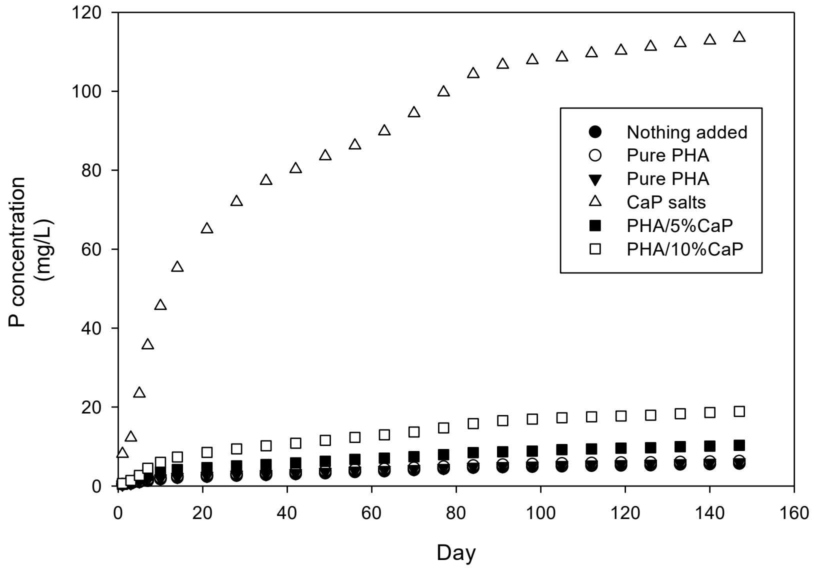
The Center for Sustainable Nanotechnology

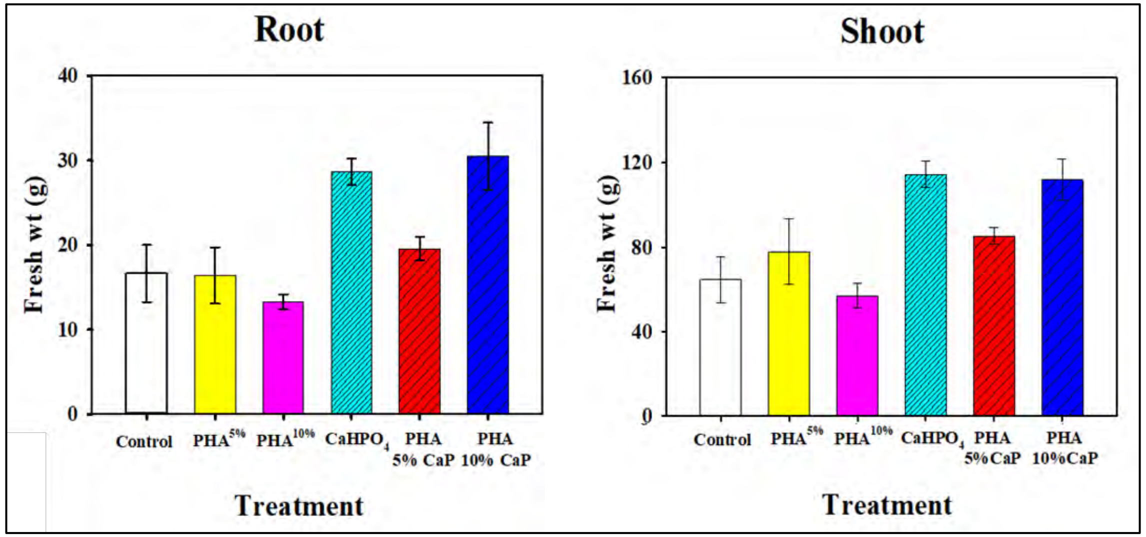
USDA National Institute of Food and Agriculture

NSF

Polymer nanocomposites - P delivery

- Polymer nanocomposites added to soil with tomato plants; compared to CaP salts that mimic traditional fertilizers for 150 days (full life cycle).
- Leachate (i.e., runoff) was collected periodically and P in runoff was measured with ICP-OES
- The nanoscale polymers **reduced P "run-off" by 10-fold**!
- Plant biomass, chlorophyll, fruit yield, nutritional content, total protein, and lycopene content were all statistically equivalent between conventional P and the nanocomposite P materials.





Sigmon et al. 2021 *ACS Agric. Sci. Technol*. DOI: 10.1021/acsagscitech.1c00149

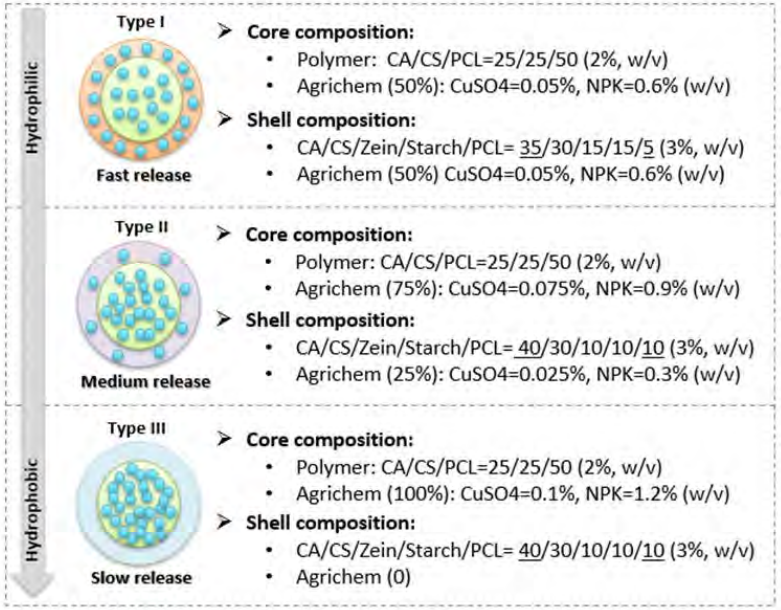
Responsive nanocapsules

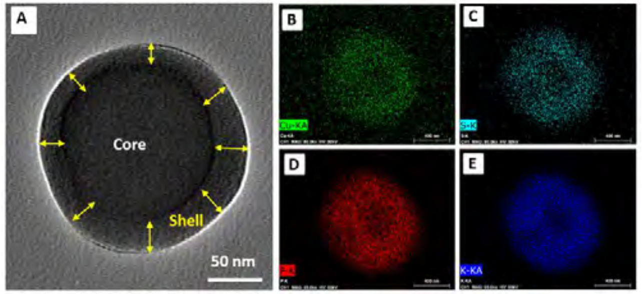
Nanyang Technological University – Harvard T.H. Chan School of Public Health
Initiative for Sustainable Nanotechnology

NANYANG TECHNOLOGICAL UNIVERSITY

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH

- Biopolymer-based multi stimuli responsive nanoplatform (i.e., core/shell nanostructure) was developed by a "green" electrospray approach for smart agrichemical delivery.
- The shell polymer was designed to be responsive to different triggers such as pH and microbial enzyme activity, and the core polymer was designed to continuously release the agrichemicals over the longer term.
- NPK and Cu were loaded at 100% and 25% label rates
- The pH and enzyme responsiveness was demonstrated by the analyte release kinetics as a function of chemical composition.
- Efficacy was evaluated in soil-based greenhouse studies using soybean and wheat.

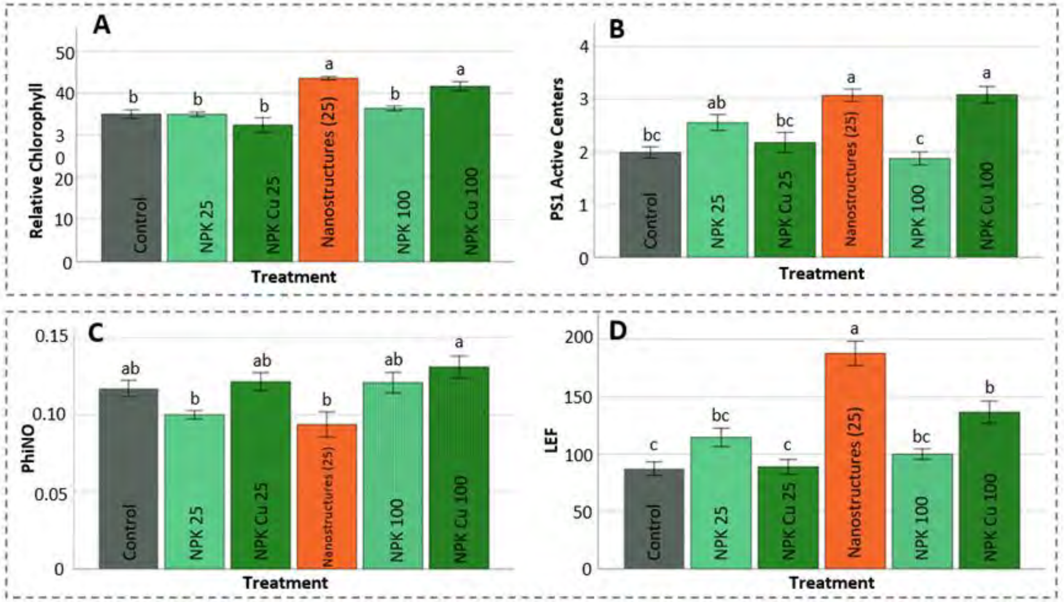


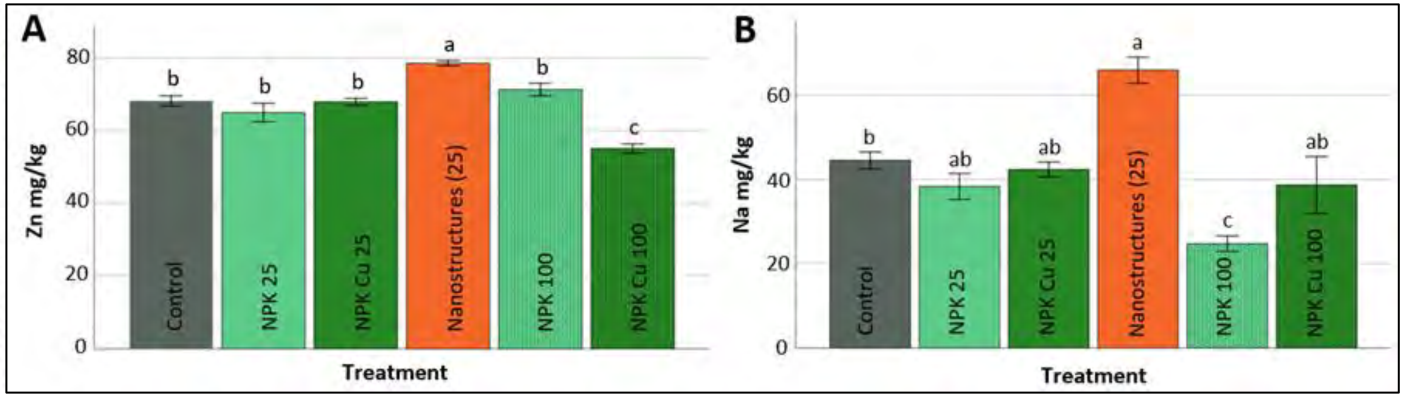


Xu et al. 2022 *ACS Nano*. 16, 4, 6034–6048

Responsive nanocapsules

- Amendment of the responsive nanostructure at 25% NPK/Cu resulted in enhanced photosynthetic parameters in both soybean and wheat, as compared to conventional fertilizer controls at 100% the label rate.
- Moreover, the Zn and Na content in the leaves of 4-week old soybean seedlings were significantly increased with nanostructure amendment, indicating that NPK and Cu in this nanoscale form can potentially be used to modulate the accumulation of other important micronutrients as part of a potential biofortification strategy.
- This responsive core/shell nanostructure represents a novel and significant advance in the development of precision sustainable agriculture.

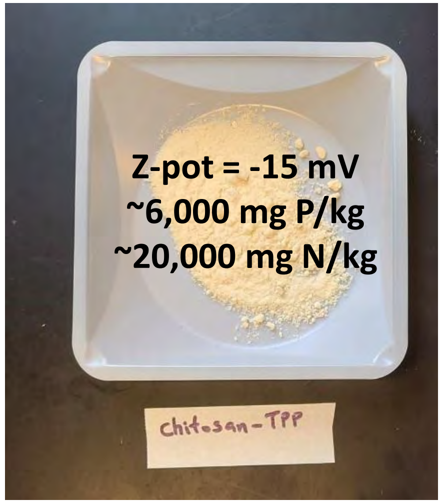


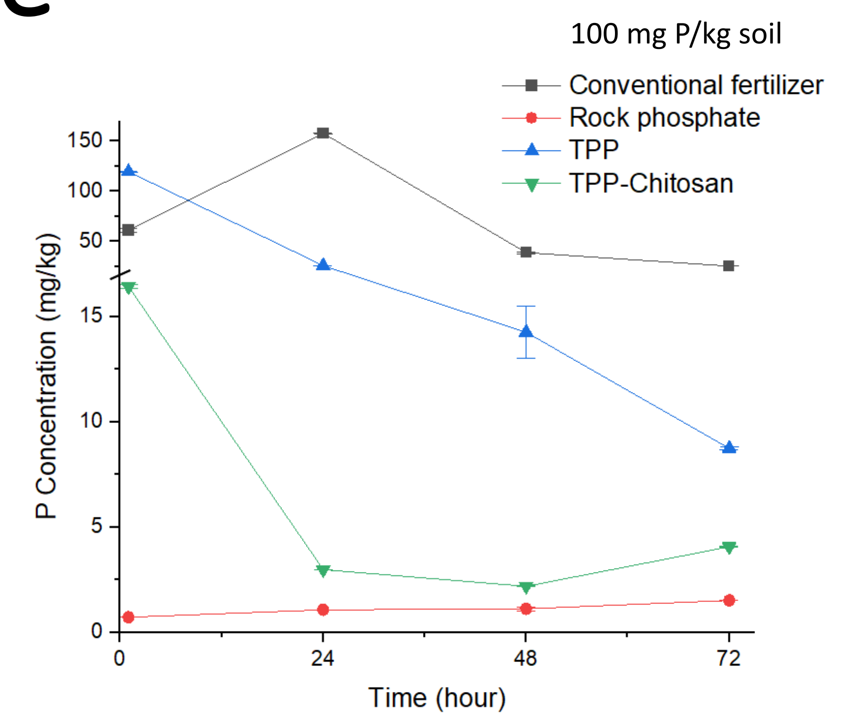


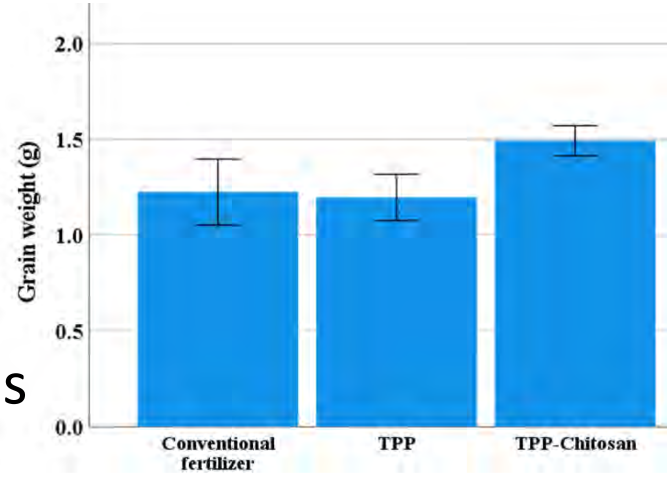
Xu et al. 2022 *ACS Nano*. 16, 4, 6034–6048

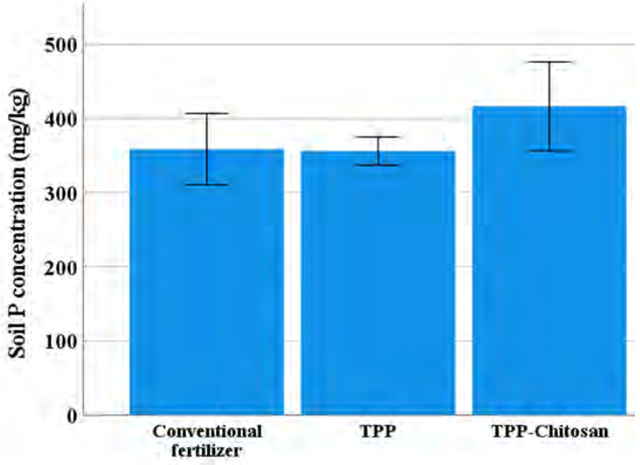
P from chitosan and tripolyphosphate

- Reduce P losses from plant-soil systems using nanotechnology?
- Repurposing tripolyphosphate (TPP) as P-fertilizer composited with chitosan: *nano-enabled P fertilizer*
- Chitosan-TPP nanofertilizer reduces P leaching in a wheat-soil system
- ≈20% increase in wheat yield over MAP and TPP
- 17% more P retained in soil after wheat harvest.
- Effect on P run-off being evaluated
- greater P retention which can reduce the input of new P in subsequent growing season
- Assess such fertilizers under field conditions



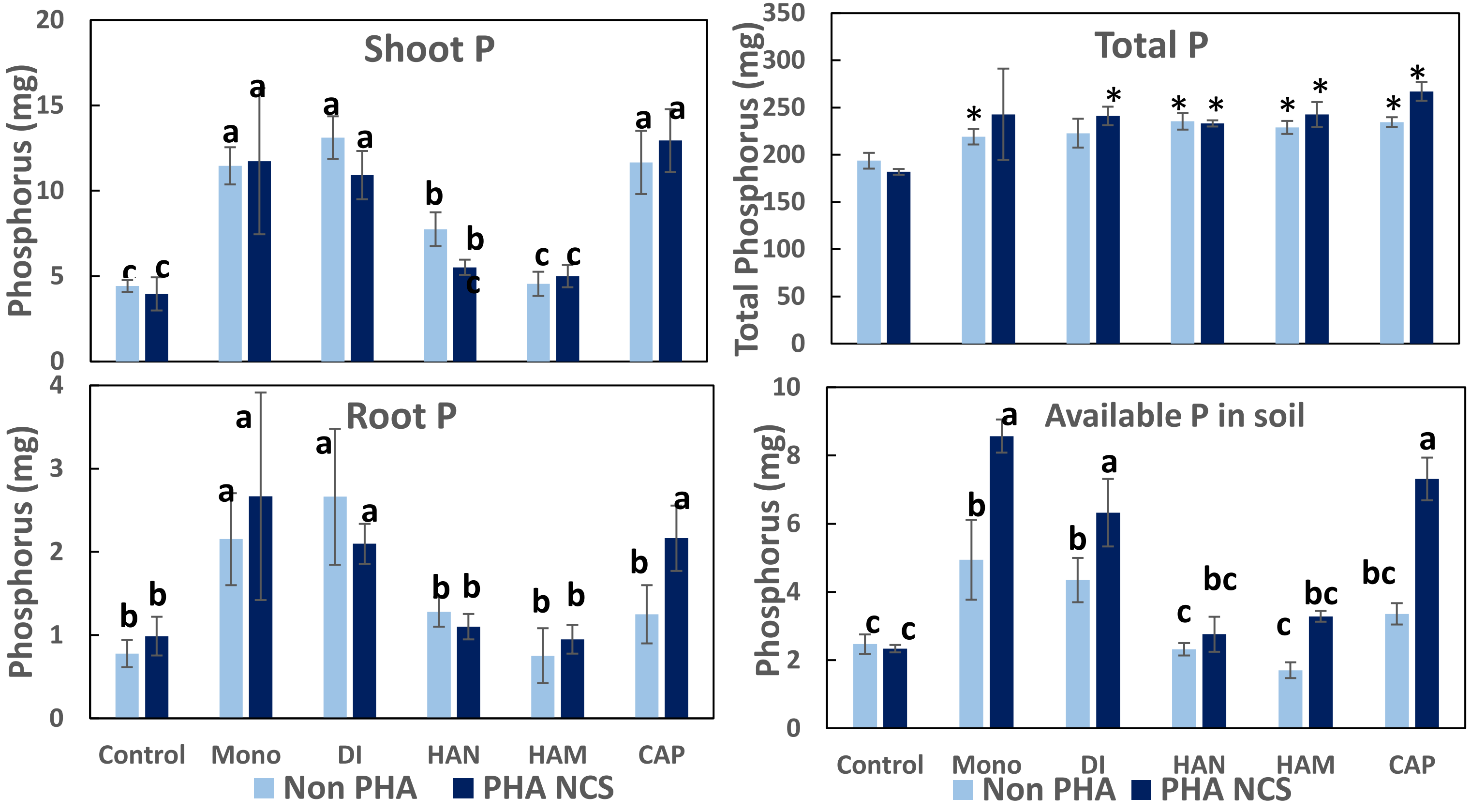




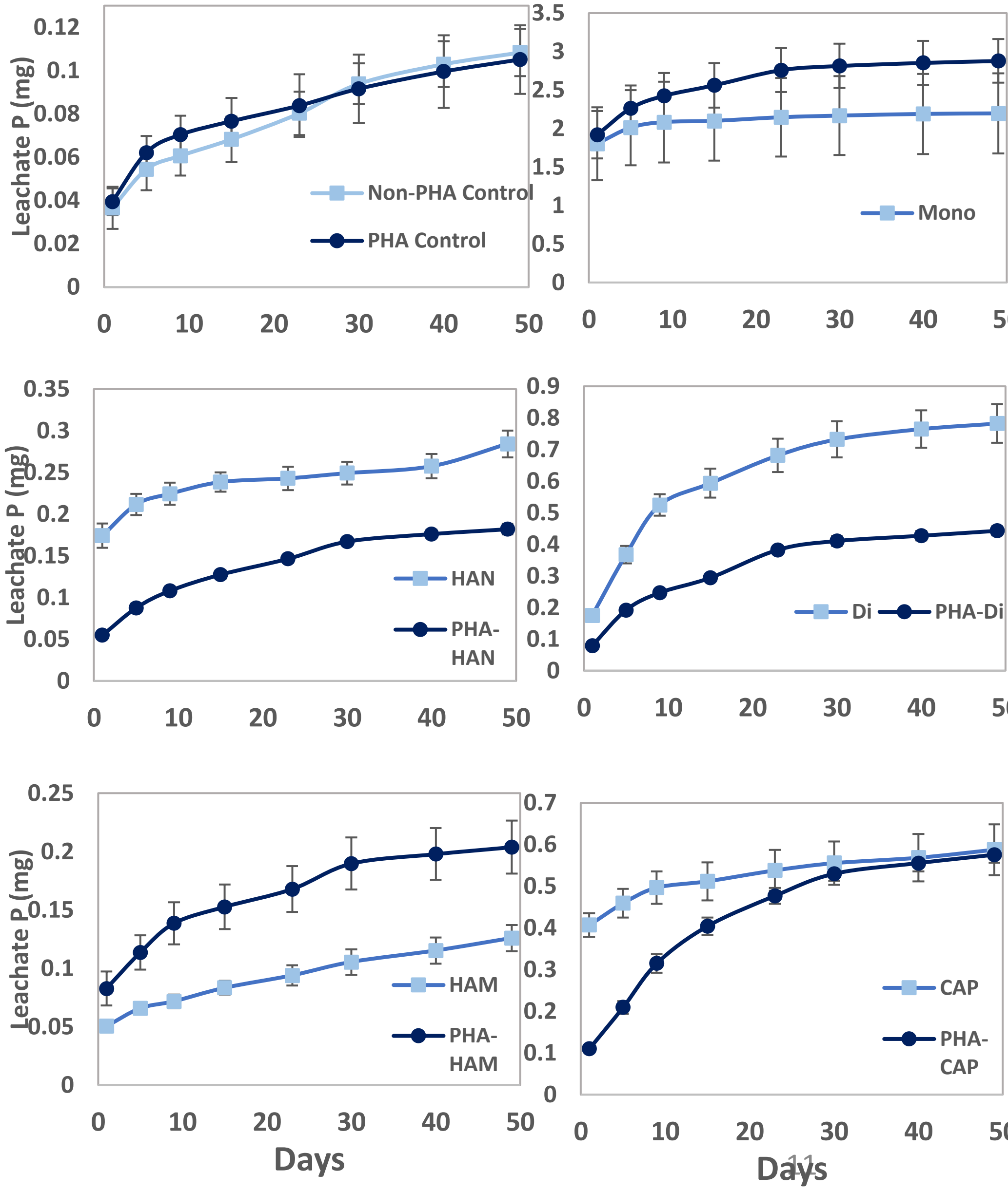


Manuscript in preparation

P from embedded materials in PHA



P leachate over time



Control PHA Mono PHA Mono DI PHA Di HAN PHA HAN HAM PHA HAM CAP PHA CAP

P from embedded materials in PHA

- Embedded materials withstood drought
- Next, treatments will be tested in the field

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CAES

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- Marmiroli et al.- Univ. of Parma, Italy
- Gardea-Torresdey et al.- UTEP; Cao et al.- CAAS
- Ri and Zhao et al.- Nanjing Univ.; Liu et al.- CAS
- Keller et al.- UCSB; Lin et al.- Zhejiang Univ.
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