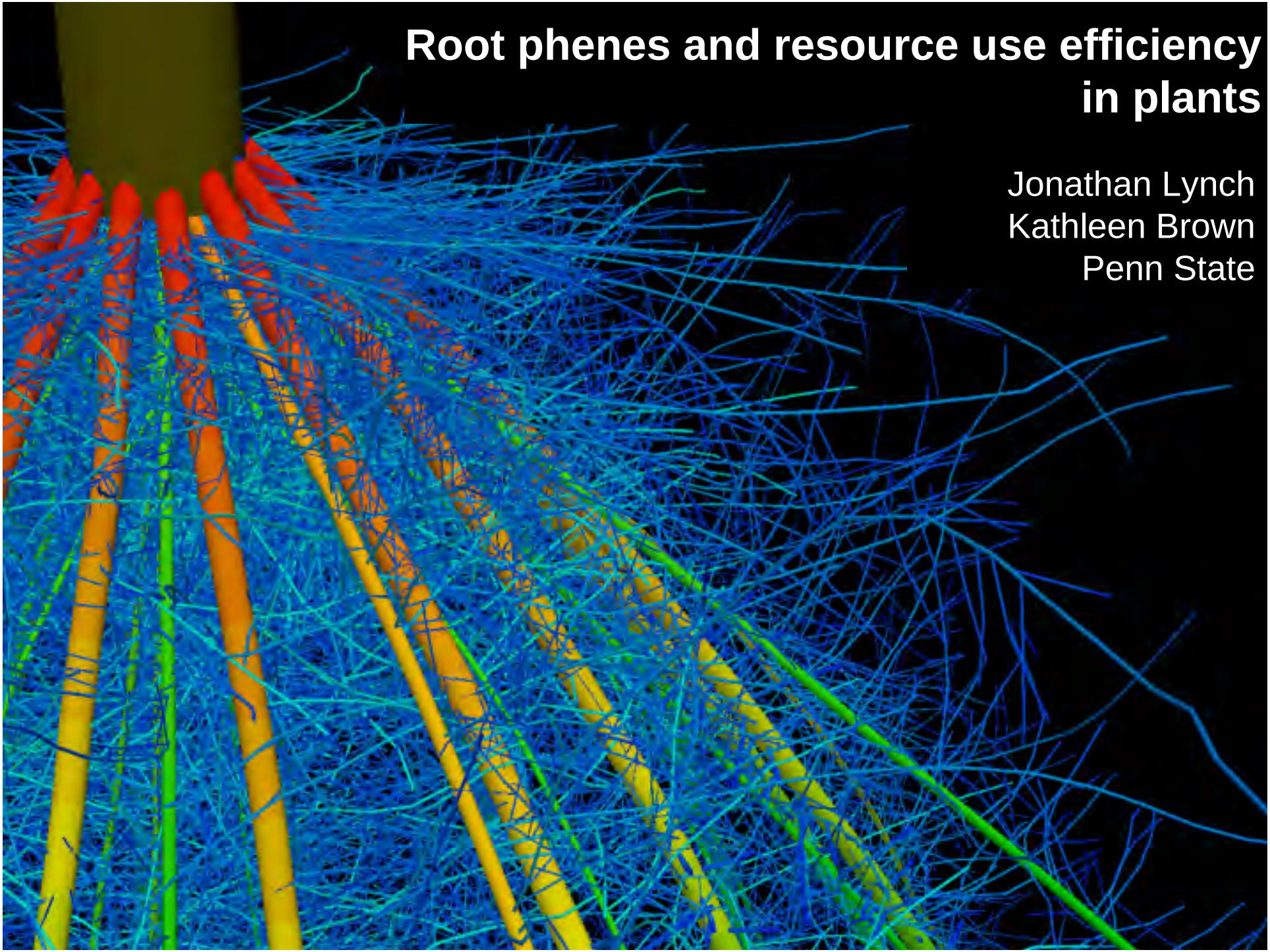
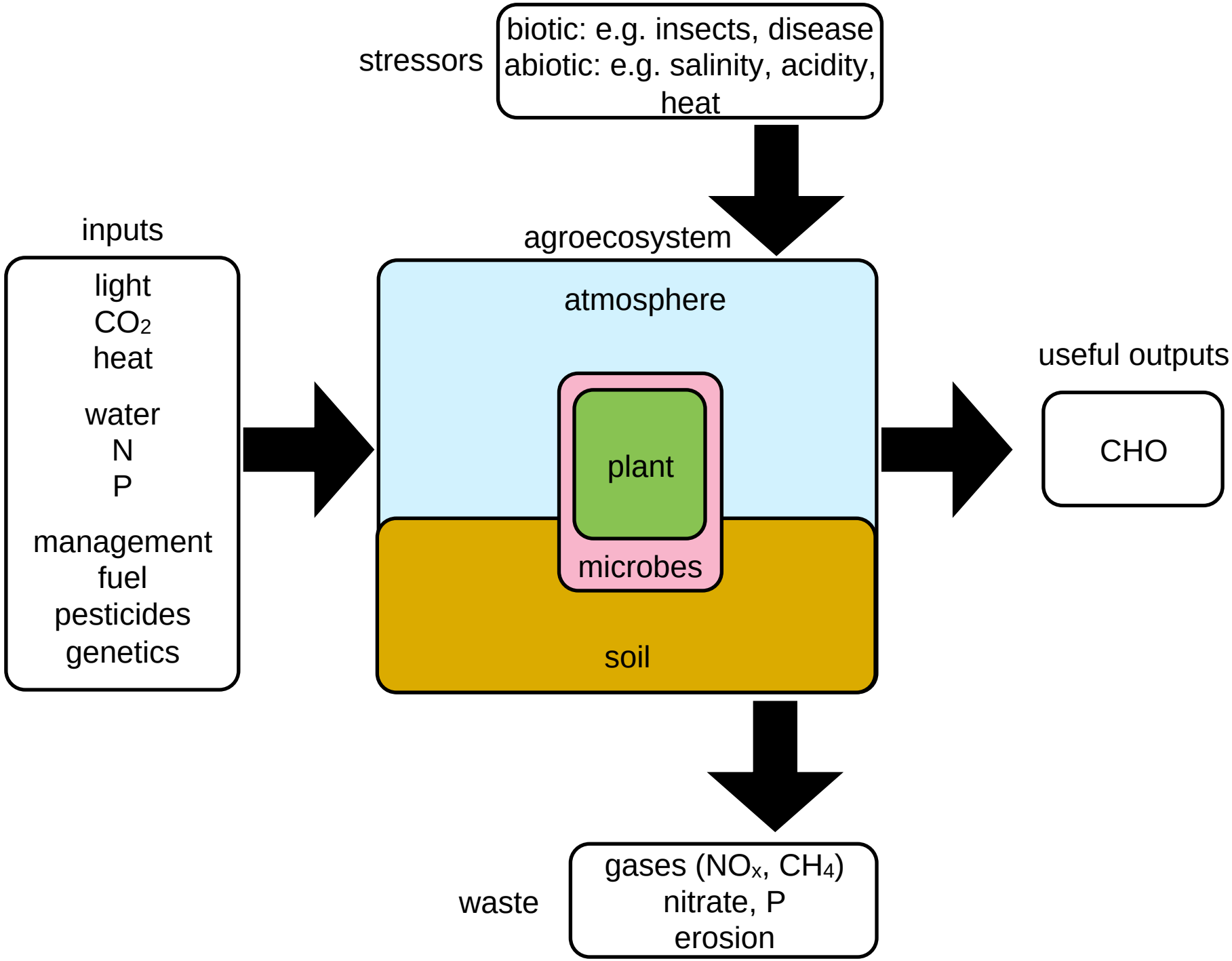
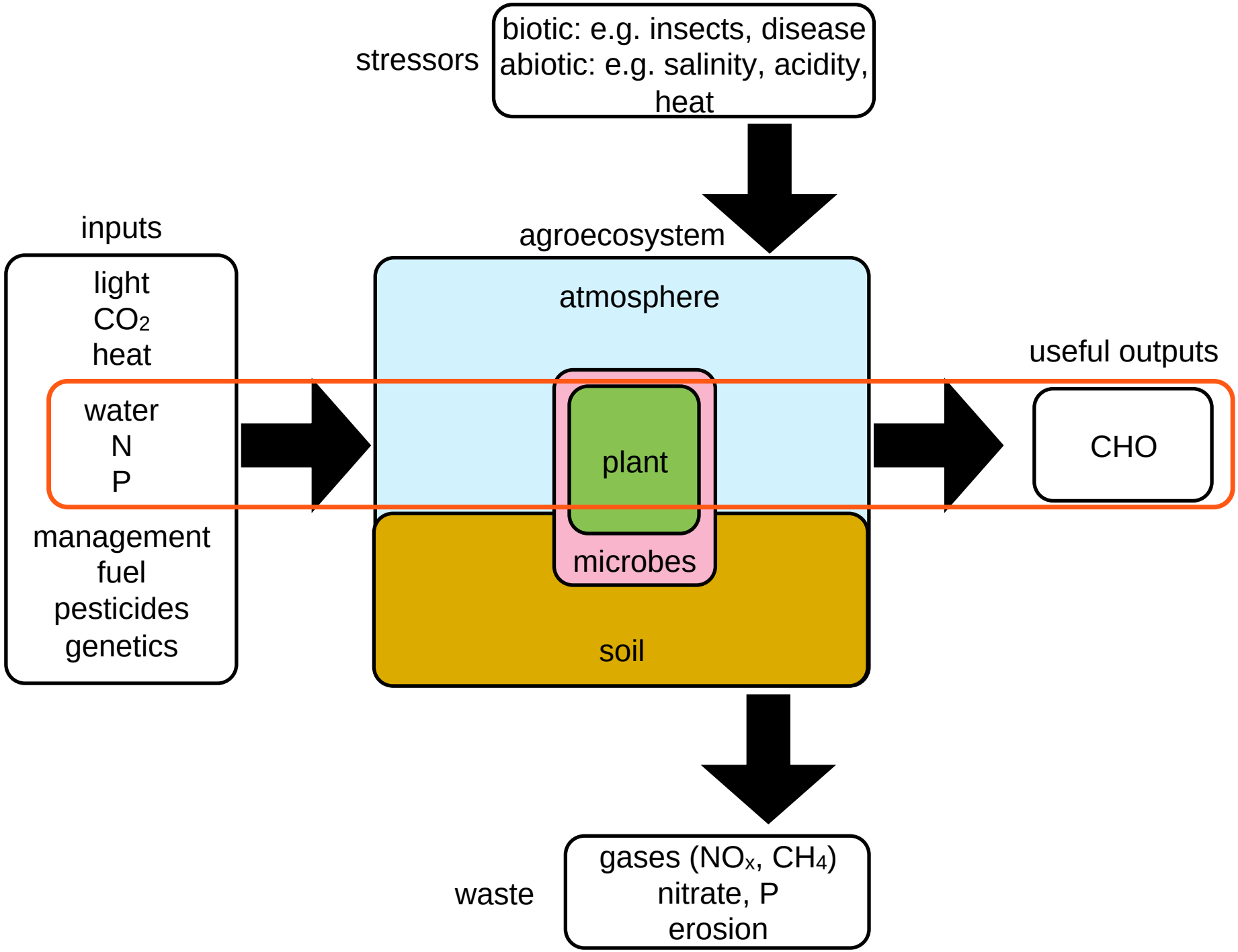
Root phenes and resource use efficiency in plants

Jonathan Lynch
Kathleen Brown
Penn State




stressors
biotic: e.g. insects, disease
abiotic: e.g. salinity, acidity, heat
inputs
light
CO_2
heat
water
N
P
management
fuel
pesticides
genetics
agroecosystem
atmosphere
plant
microbes
soil
useful outputs
CHO
waste
gases (NO_x, CH_4)
nitrate, P
erosion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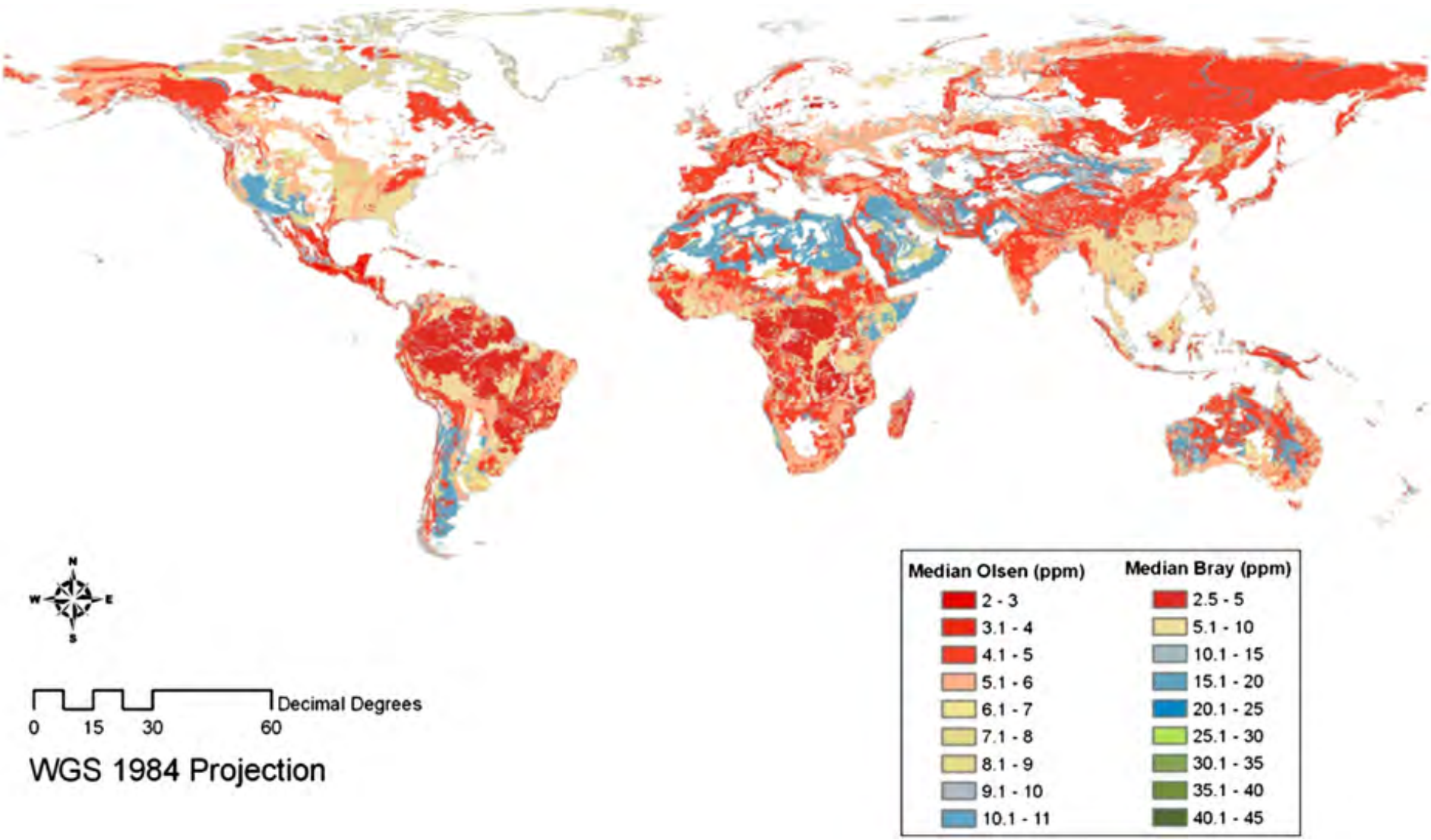
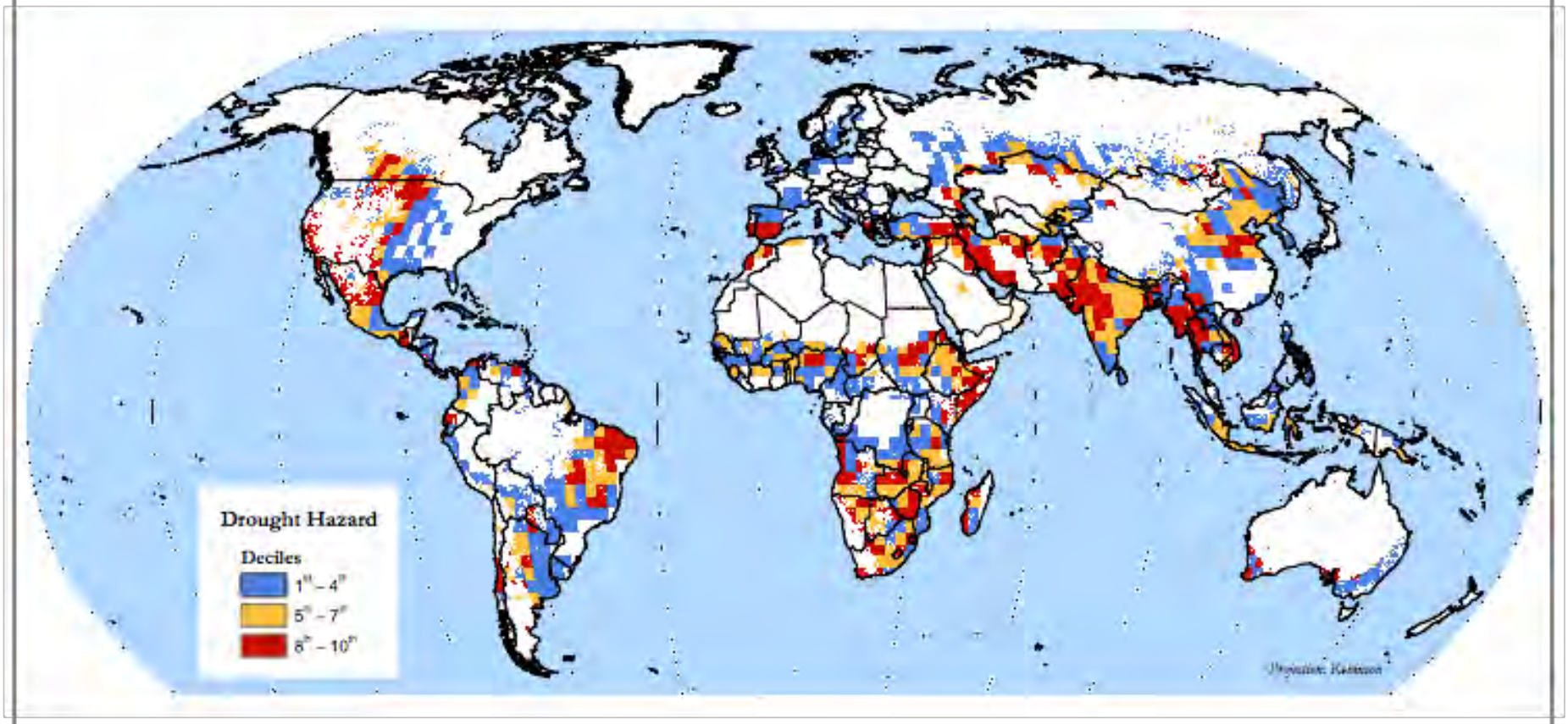
Low soil P availability is a primary constraint to life on earth



Jaramillo and Lynch, 2011

Global Drought Hazard Distribution



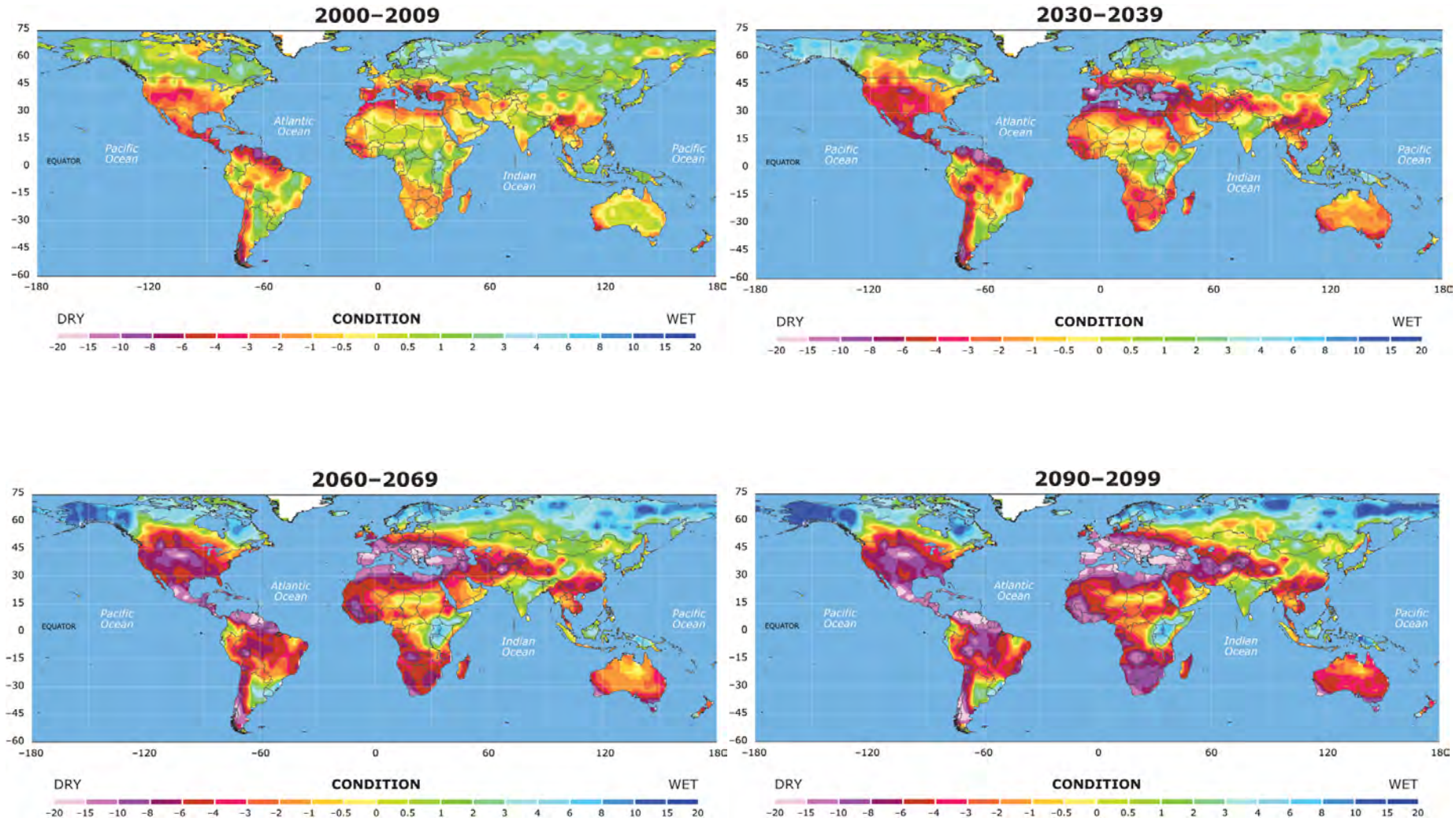
Drought periods were defined using an index known as the Weighted Anomaly of Standardized Precipitation (WASP). The WASP index assesses the precipitation deficit or surplus over a three-month running average for the 21-year period from 1980 – 2000. Findings show that about 38% of the world's land area has some level of drought exposure.

Source:

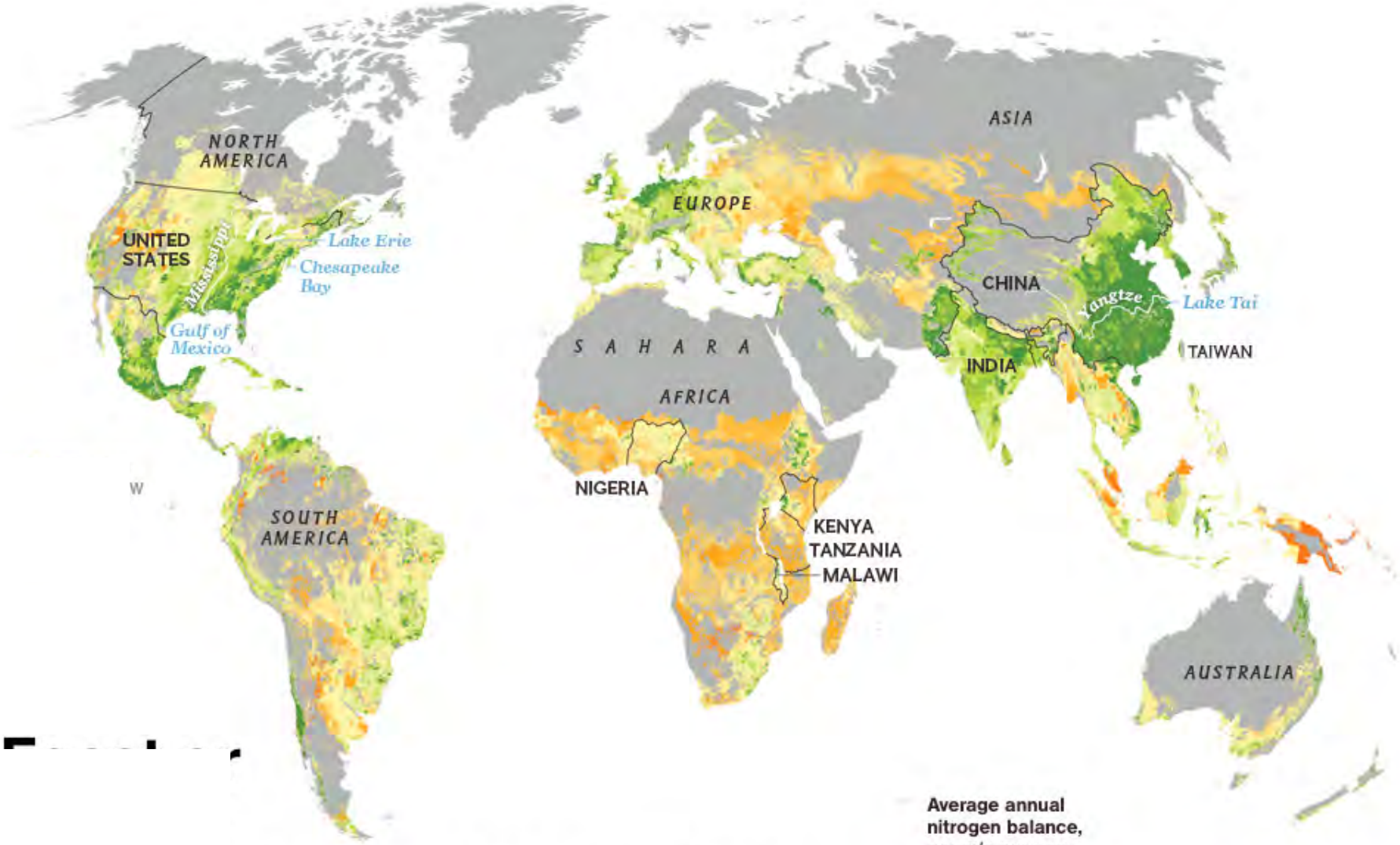
Dilley, Maxx, Robert S. Chen, Uwe Deichmann, Arthur L. Lerner-Lam, and Margaret Arnold. 2005. *Natural Disaster Hotspots: A Global Risk Analysis*. Washington, D.C.: World Bank.

Copyright 2005 International Bank for Reconstruction and Development/The World Bank and Columbia University.

Global climate change will intensify drought in this century



NCAR 2010 (moderate emissions scenario)



nearly half the people on the planet wouldn't be alive if not for the abundant

er.

Average annual nitrogen balance, *pounds per acre*

Deficiency — Excess

-200 0 220

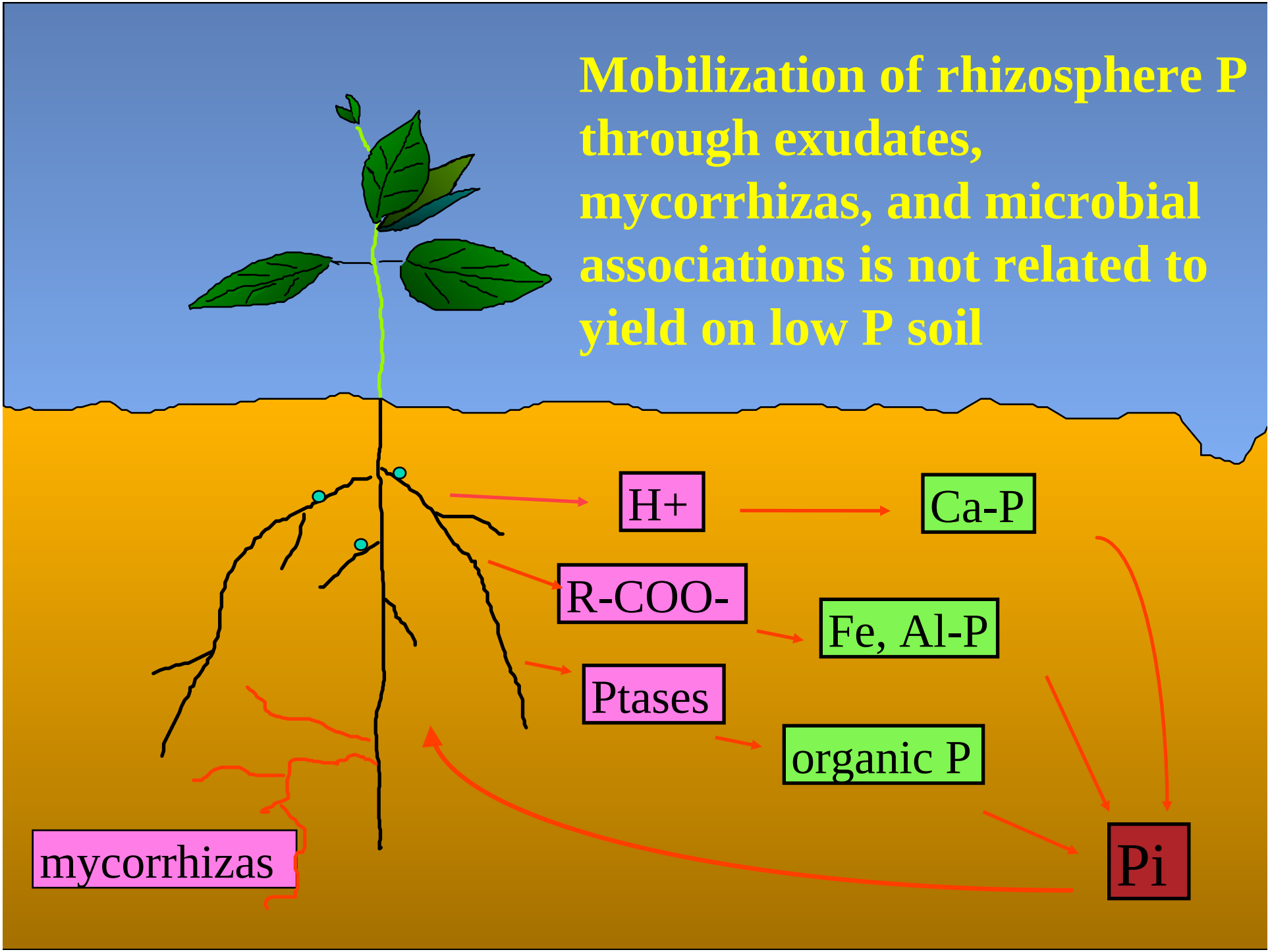
Little or no cropland

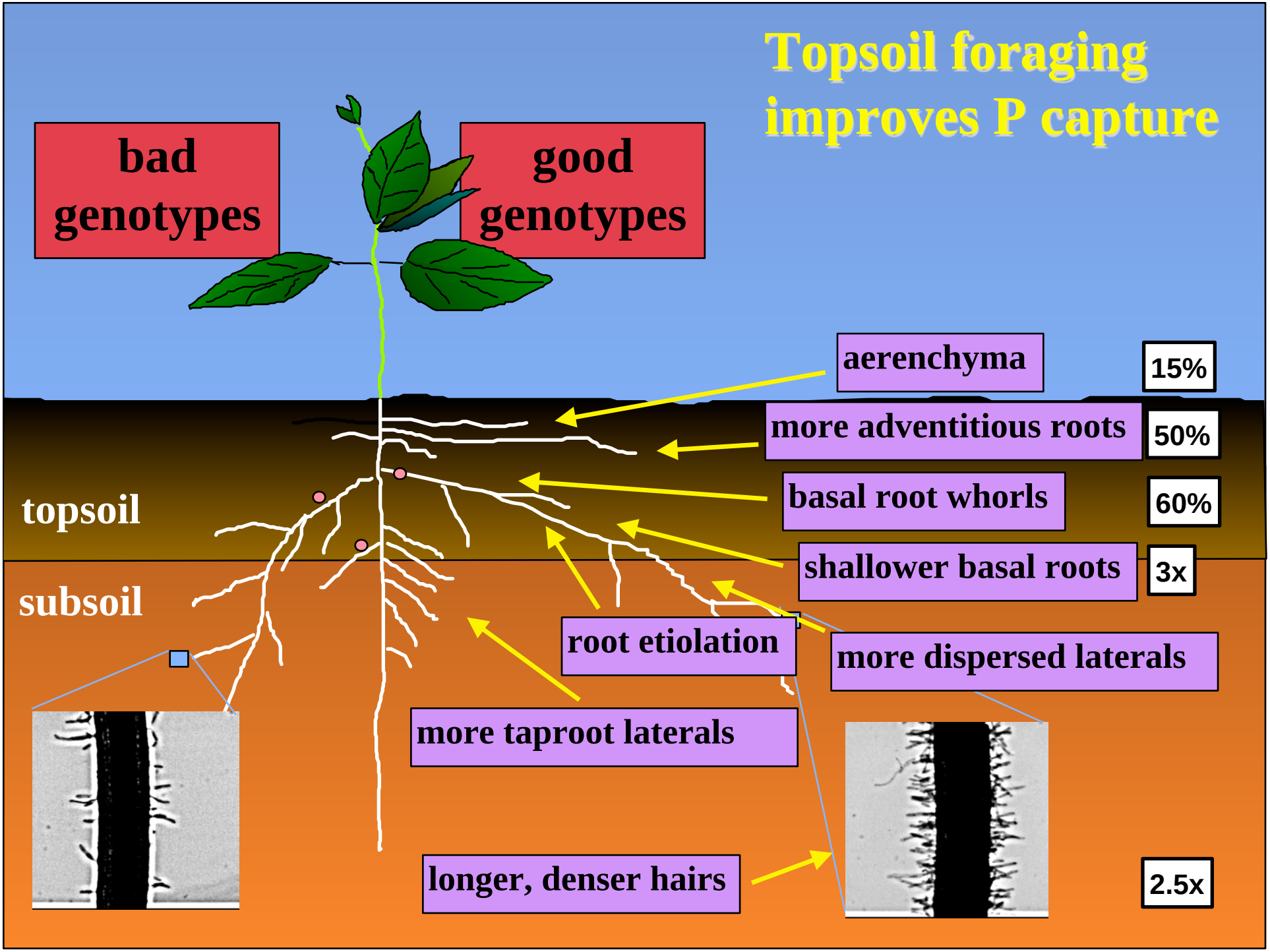
Zero means the crop used exactly the amount of nitrogen applied. The ideal range varies due to local conditions.

JEROME N. COOKSON AND LAWSON PARKER, NGM STAFF
SOURCE: PAUL C. WEST, INSTITUTE ON THE ENVIRONMENT, UNIVERSITY OF MINNESOTA

Common bean - Phaseolus vulgaris

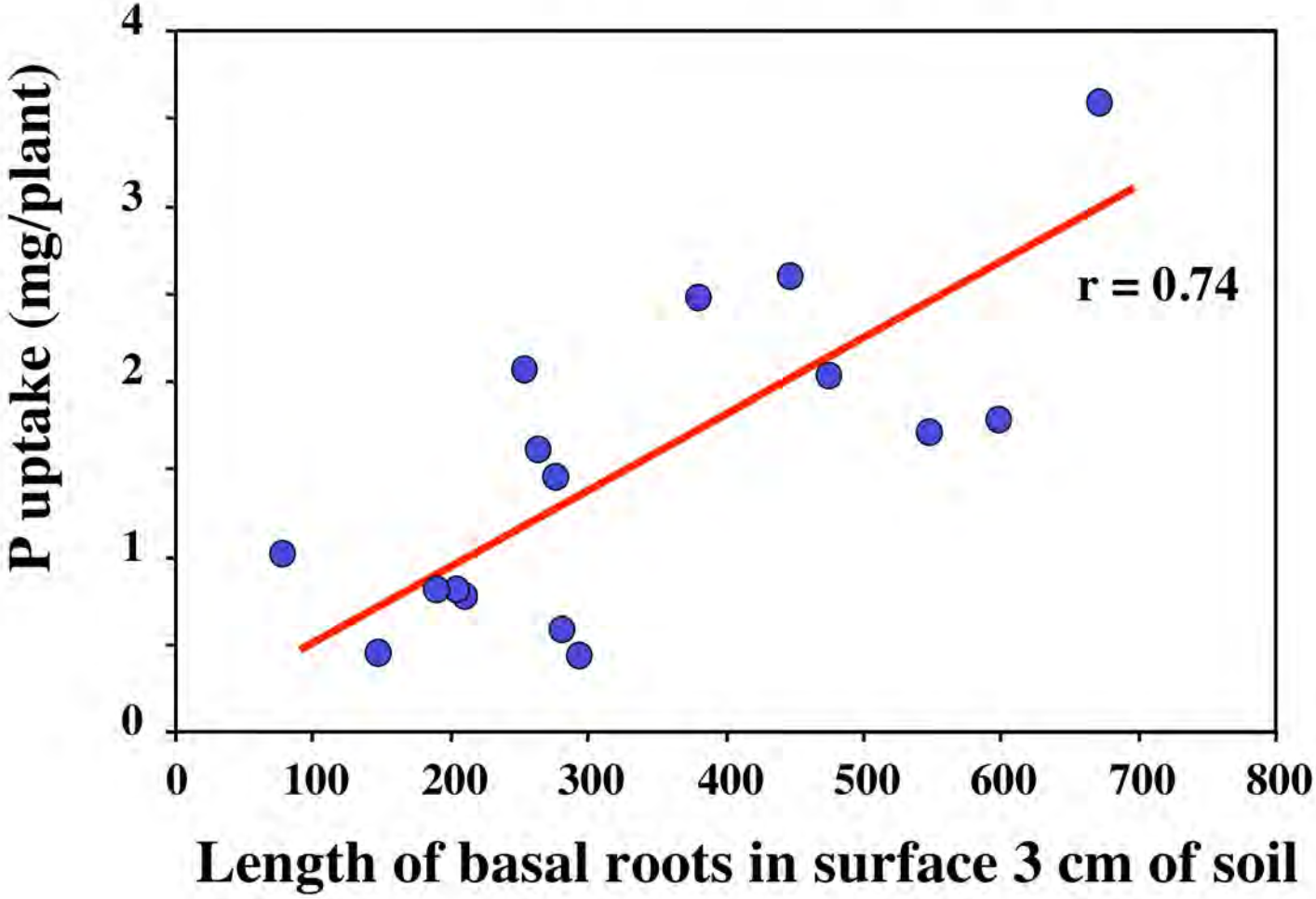
-P


Mobilization of rhizosphere P through exudates, mycorrhizas, and microbial associations is not related to yield on low P soil
H+
Ca-P
R-COO-
Fe, Al-P
Ptases
organic P
mycorrhizas
Pi


Topsoil foraging improves P capture
bad genotypes
good genotypes
aerenchyma
15%
more adventitious roots
50%
basal root whorls
60%
shallower basal roots
3x
topsoil
subsoil
root etiolation
more dispersed laterals
more taproot laterals
longer, denser hairs
2.5x

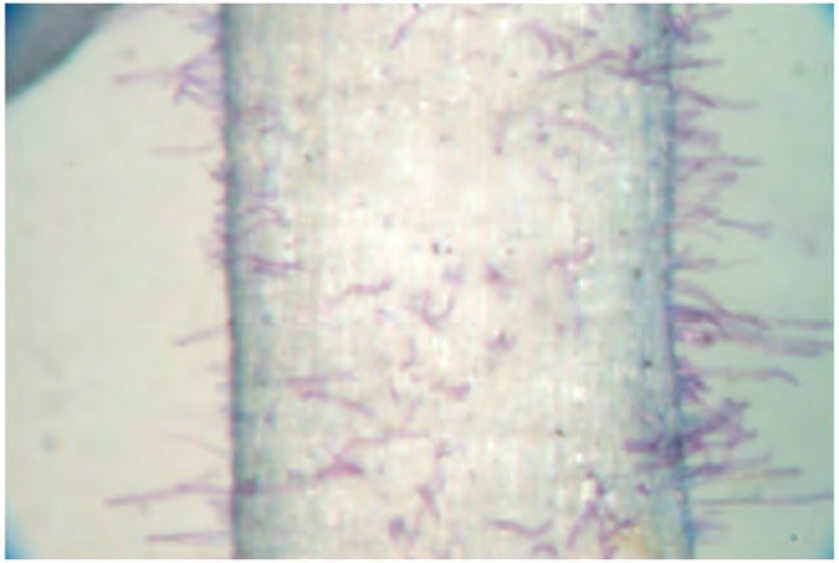
Shallow vs deep root architecture in two bean genotypes grown in the field in Honduras

Basal root shallowness is correlated with P uptake from soil among RILs

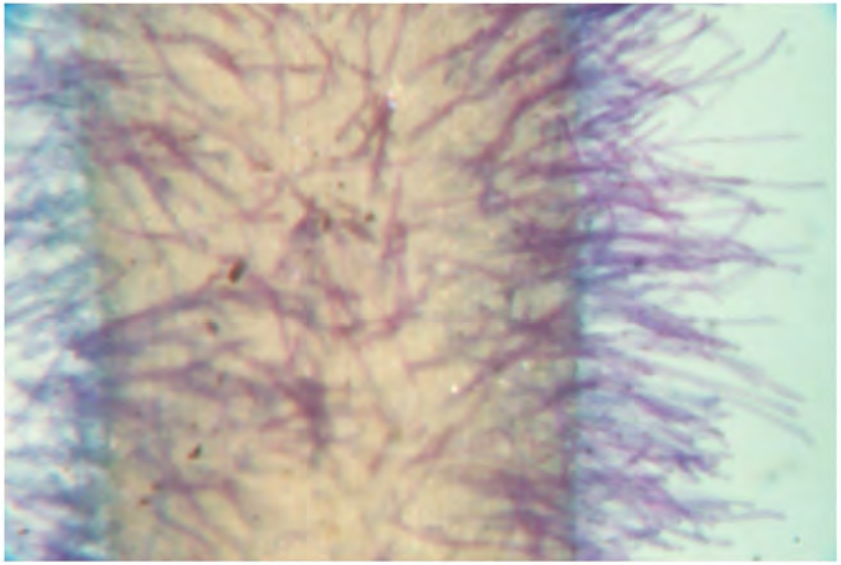


QTL for basal root growth angle of seedlings cosegregate with yield in low P soil *Liao et al., 2001*

Root hairs



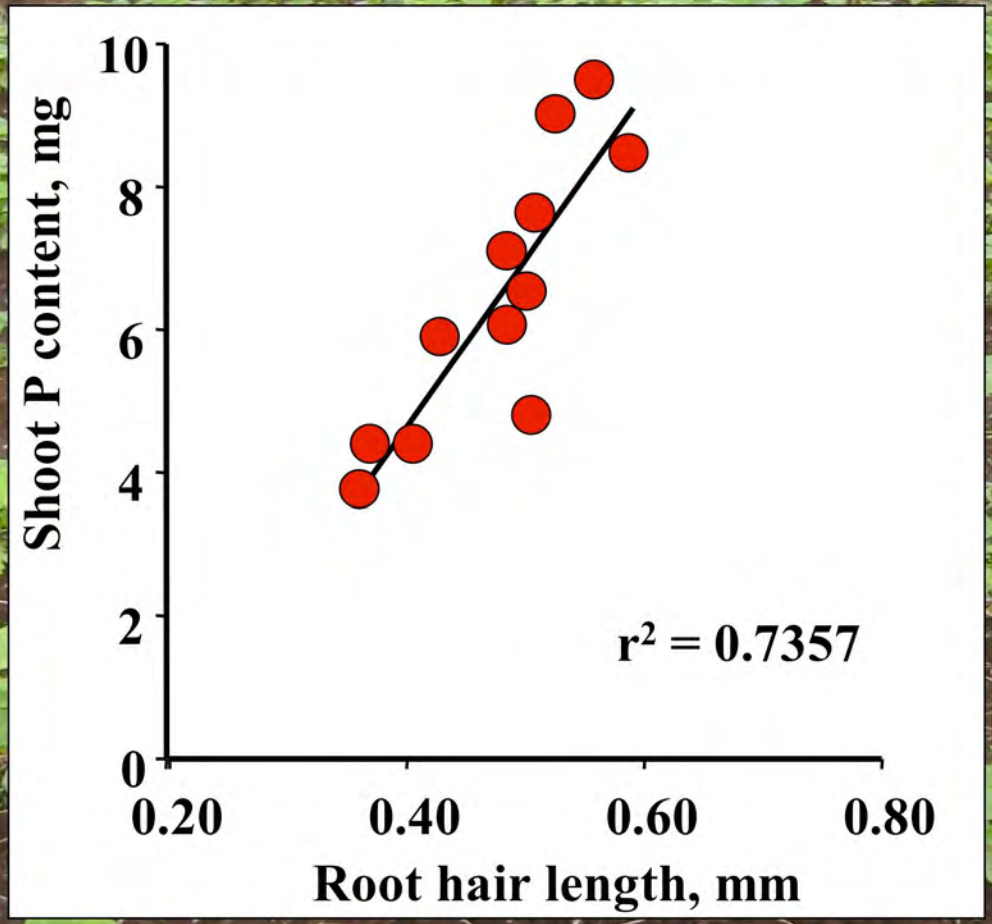
Short root hair genotype



Long root hair genotype

Miguel et al., 2004

P acquisition strongly correlated with root hair length among RILs

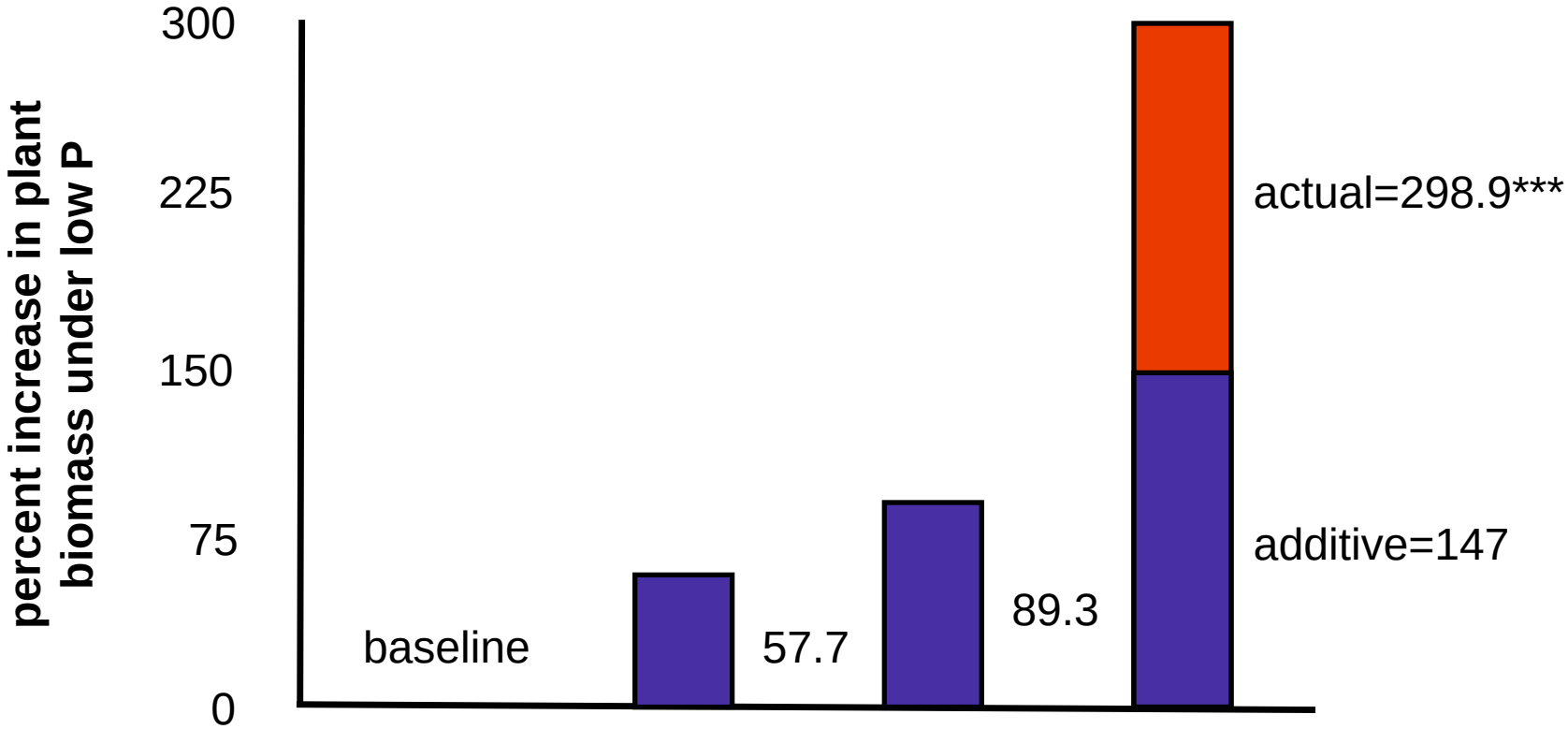


Field trial in low P soil at Fraijanes, Costa Rica

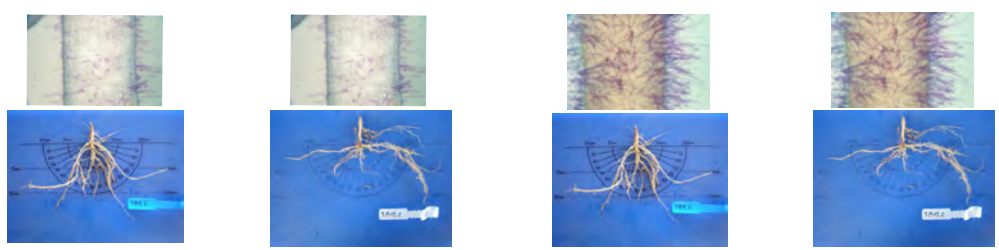
6 QTL explain 55% genetic variation for root hairs

Phene synergism for P acquisition

3 RILs per phenotype, field study in low P soil in Mozambique

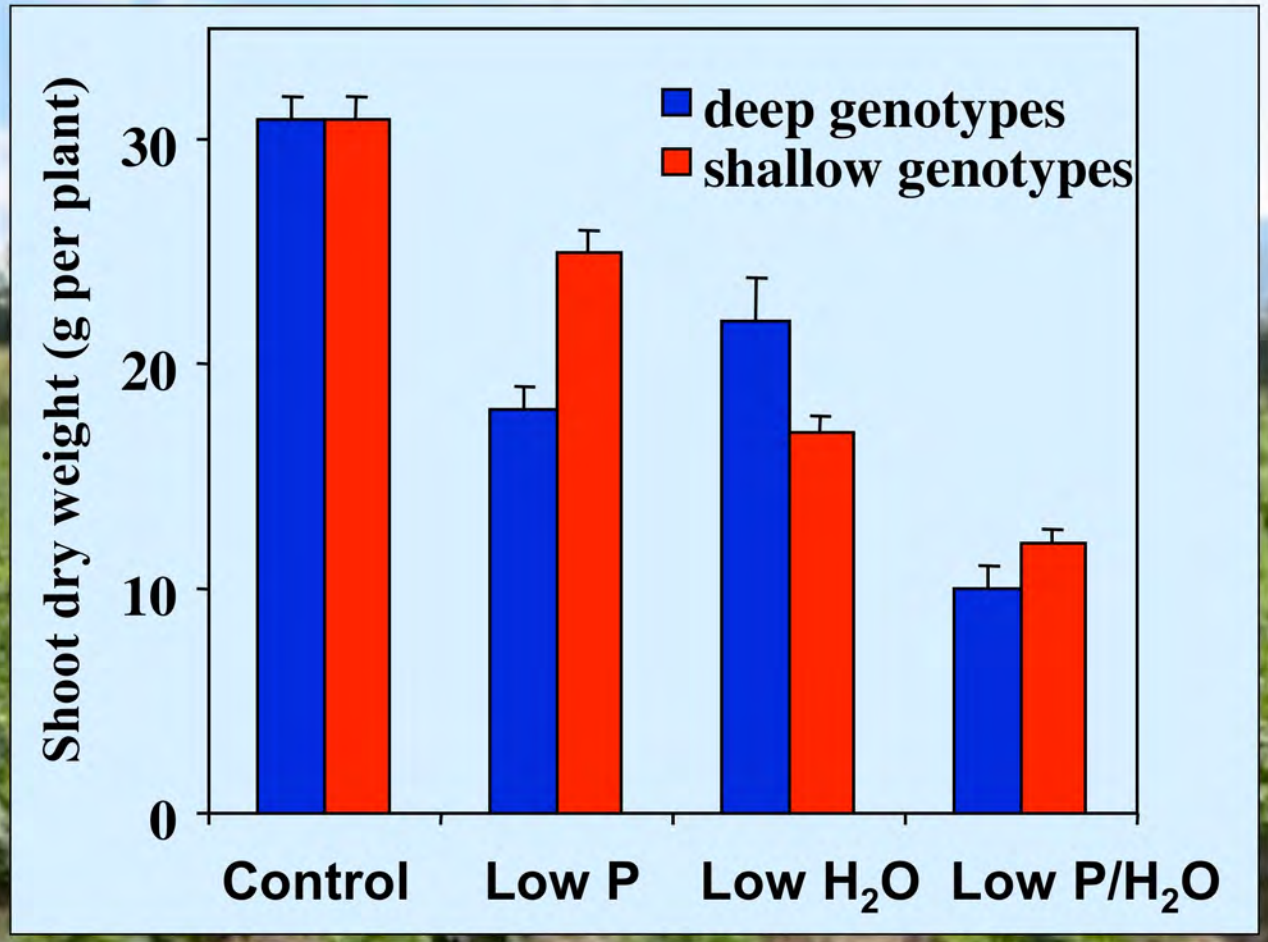


hair length	**short**	**short**	**long**	**long**
growth angle	**deep**	**shallow**	**deep**	**shallow**

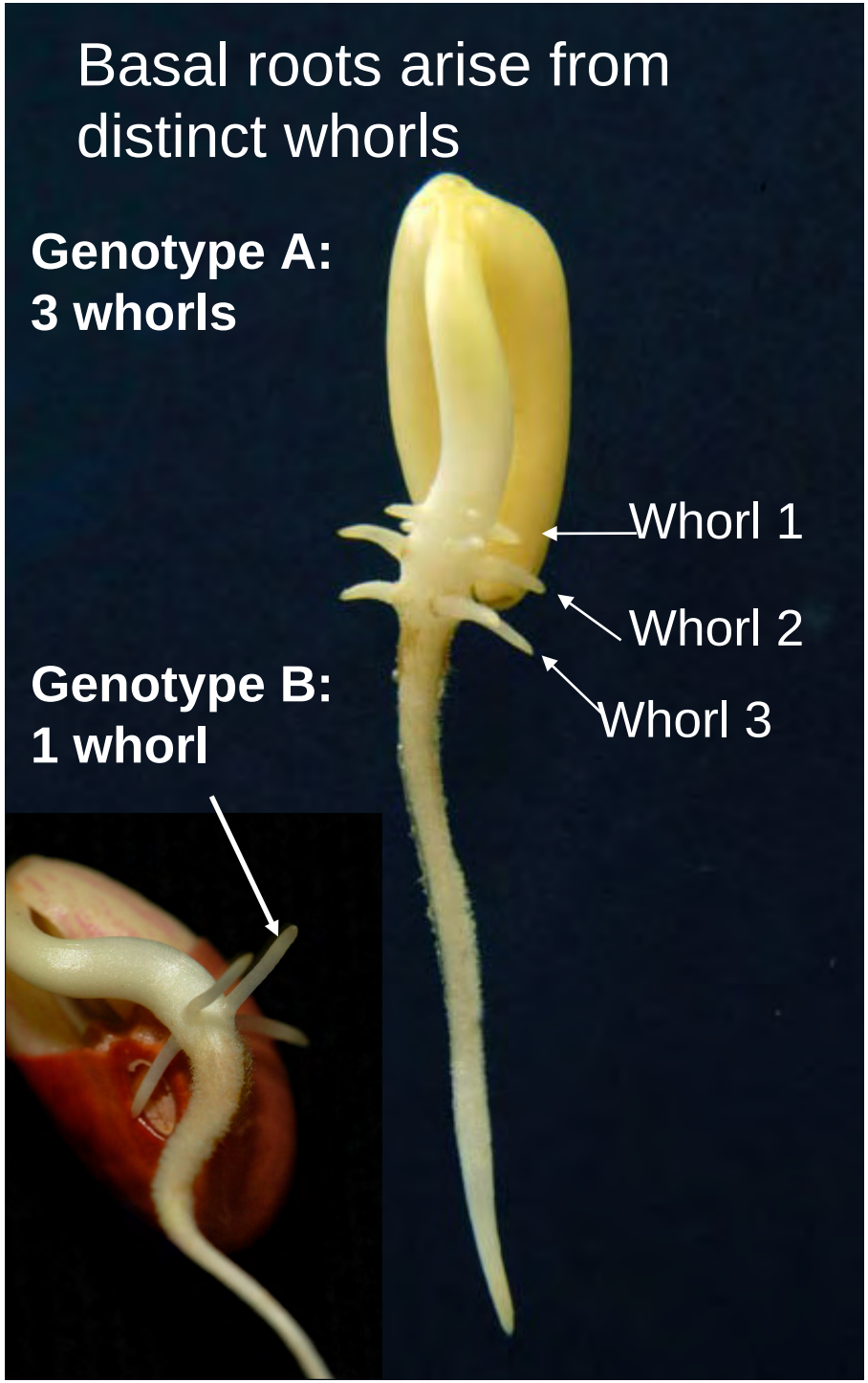


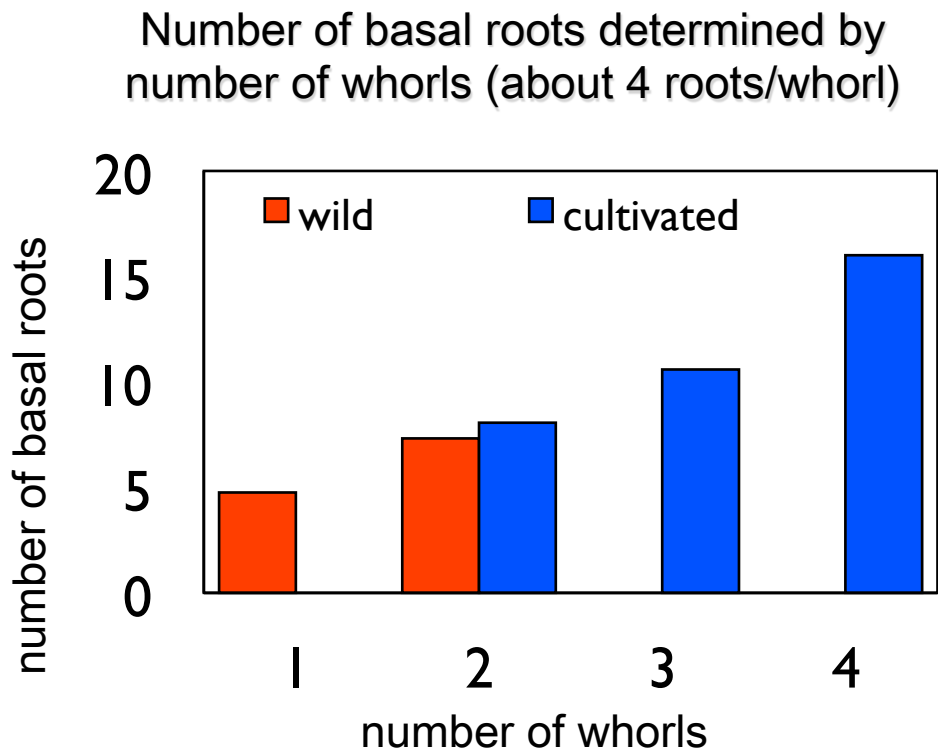
Miguel et al 2015

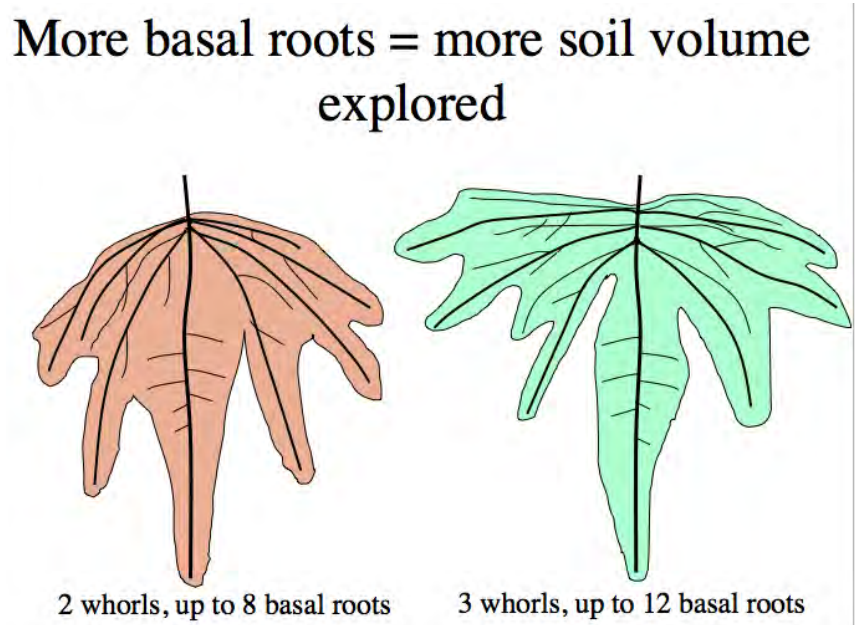
Tradeoffs between water and phosphorus acquisition in the field in Honduras



(Ho et al. 2004)


Basal roots arise from distinct whorls
Genotype A:
3 whorls
Whorl 1
Whorl 2
Whorl 3
Genotype B:
1 whorl

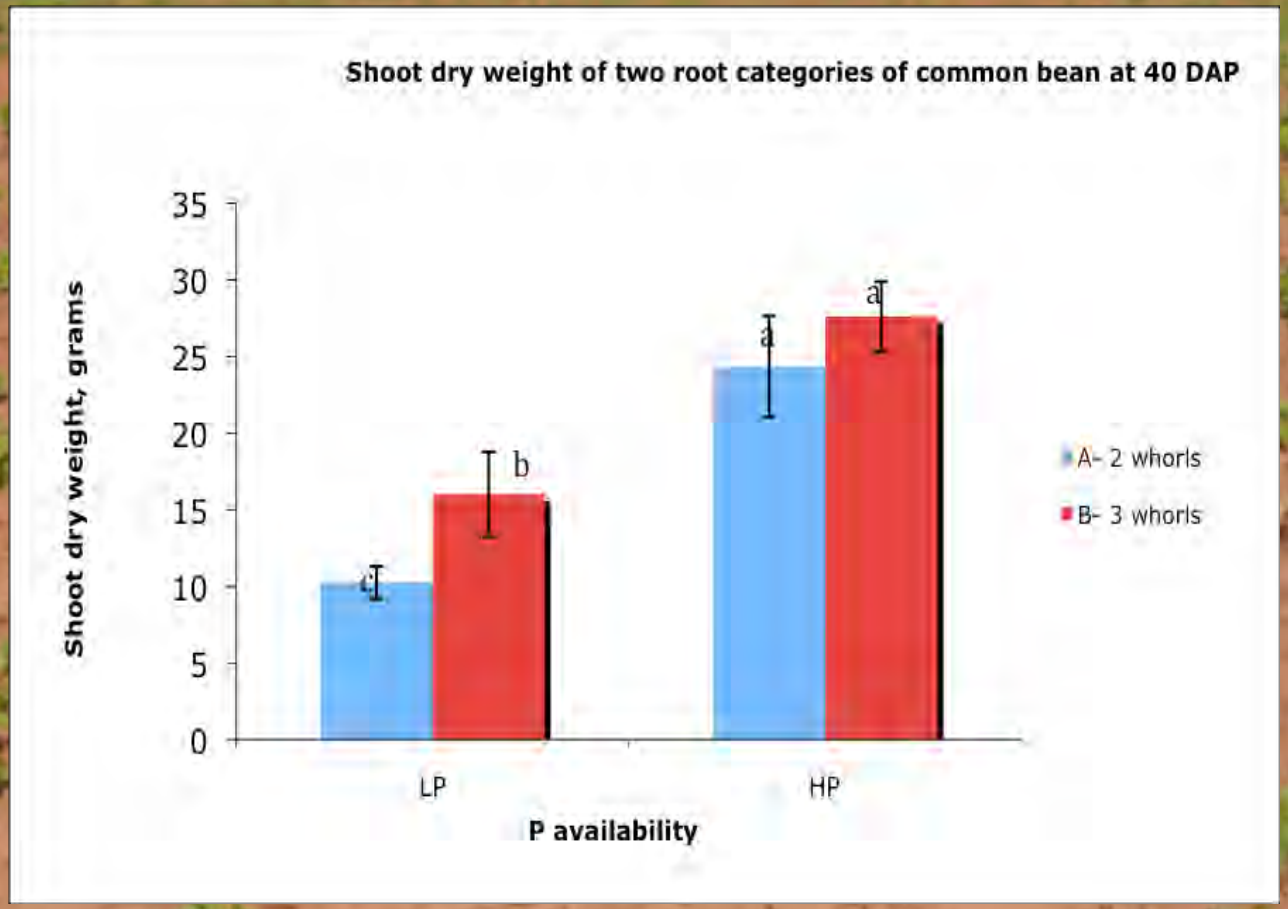

Number of basal roots determined by number of whorls (about 4 roots/whorl)
number of basal roots
20
15
10
5
0
wild
cultivated
1
2
3
4
number of whorls


More basal roots = more soil volume explored
2 whorls, up to 8 basal roots
3 whorls, up to 12 basal roots

1 whorl 2 whorls 3 whorls 4 whorls

research of Harini Rangarajan

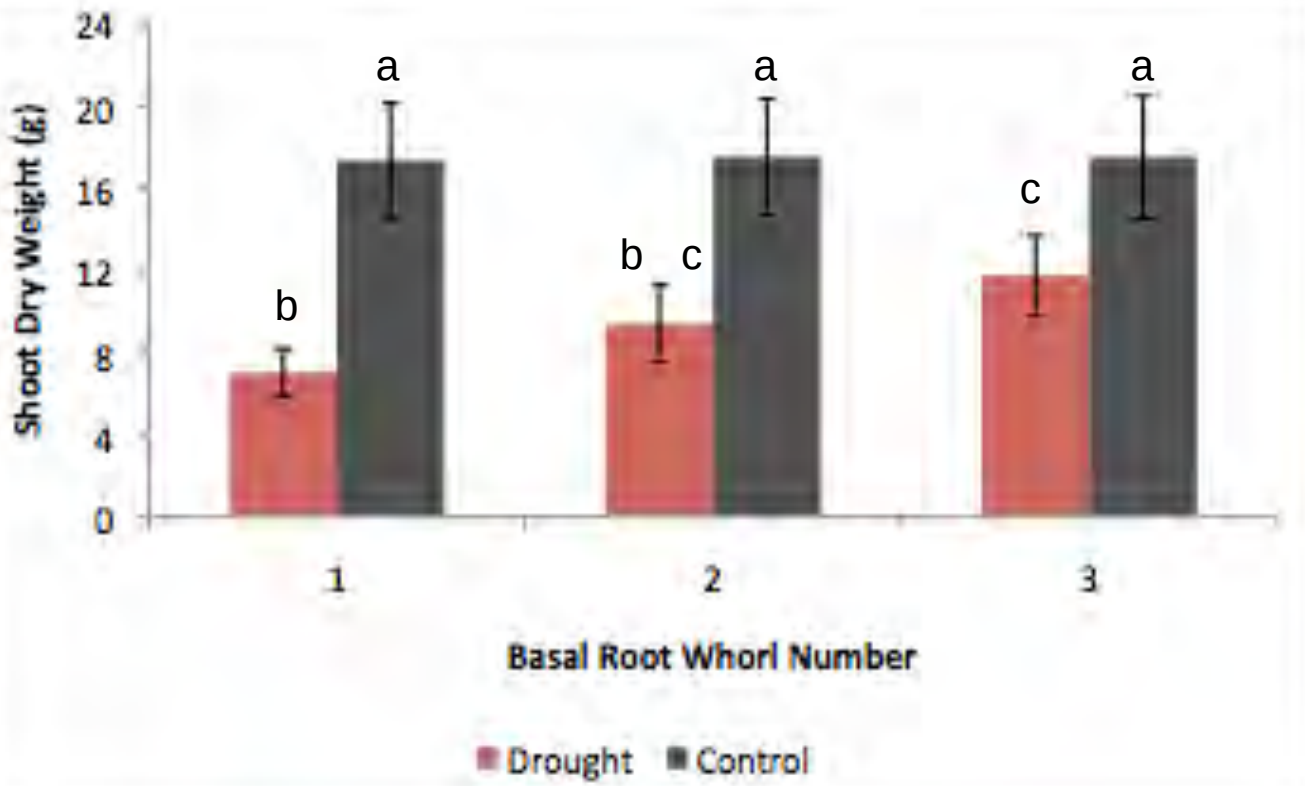
More whorls = 60% greater growth at low P



Miguel,Lynch 2013

Greater BRWN improves growth under drought

More whorls =>70 % greater growth under drought



research of Katy Barlow

15 new bean lines with 50-150% better yield in low P

new bean lines have greater BNF

new bean lines have less soil erosion

new bean lines perform well in maize intercrops

checking if new bean lines utilize RP better

Better beans for Africa

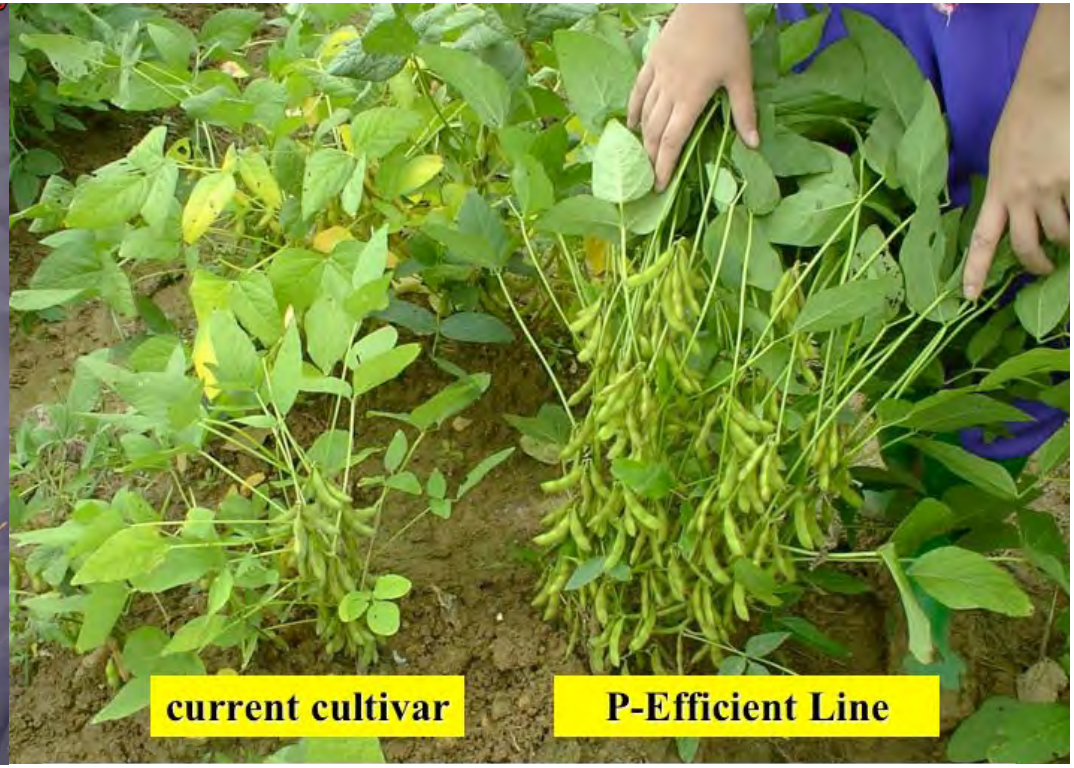
McKnight Foundation, Generation Challenge Program, USAID, Howard G Buffett Foundation

IIAM, CIAT, Zamorano

do new bean lines benefit people?

Root architecture and P efficiency in soybean

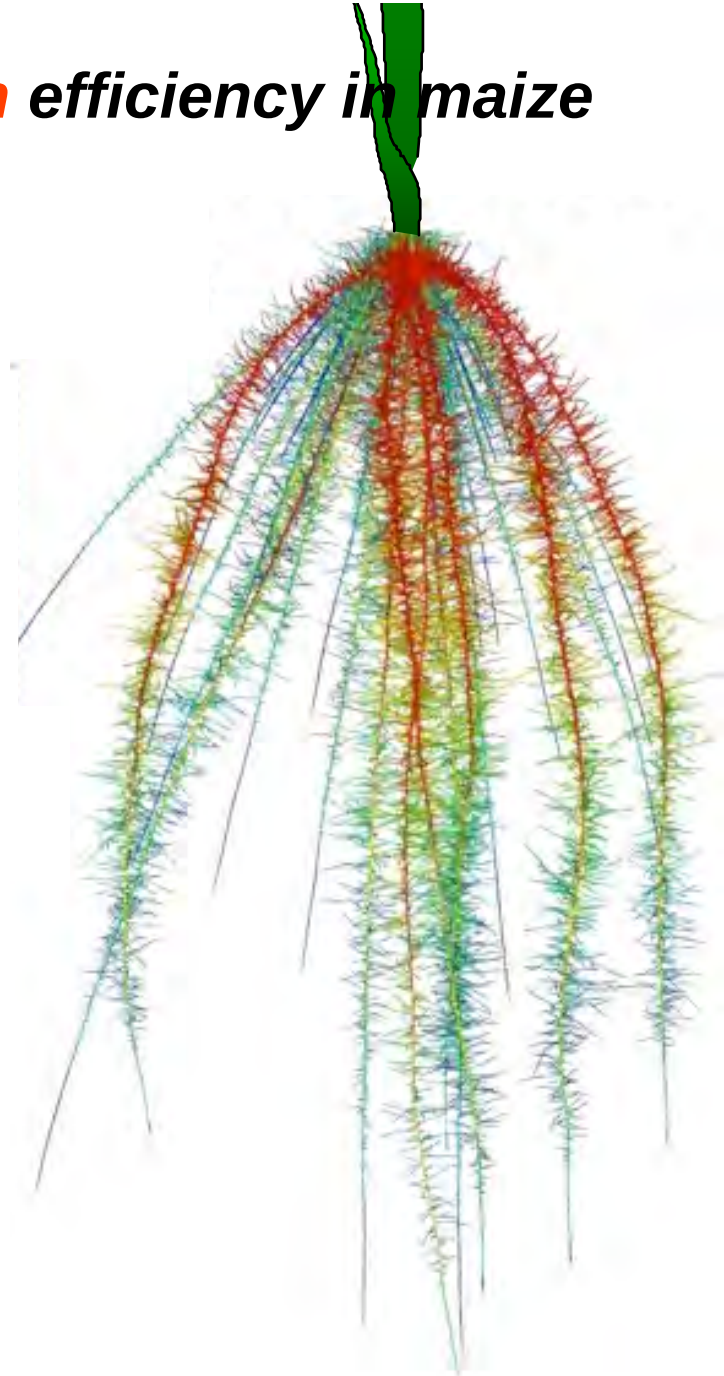
Collaboration with Xiaolong Yan, South China Ag University

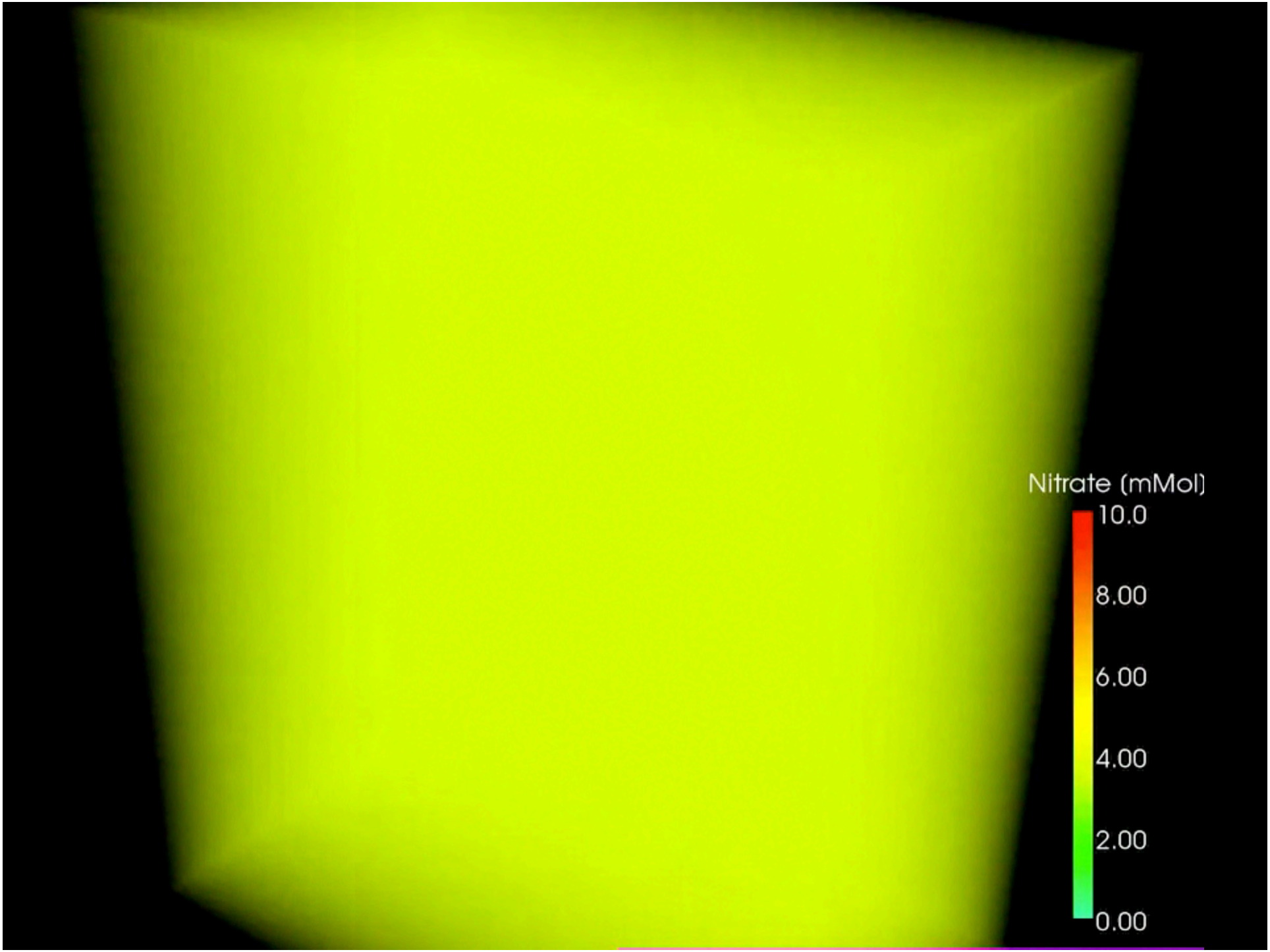


15 P-efficient soybean lines released in China
3 P-efficient soybean lines released in Mozambique

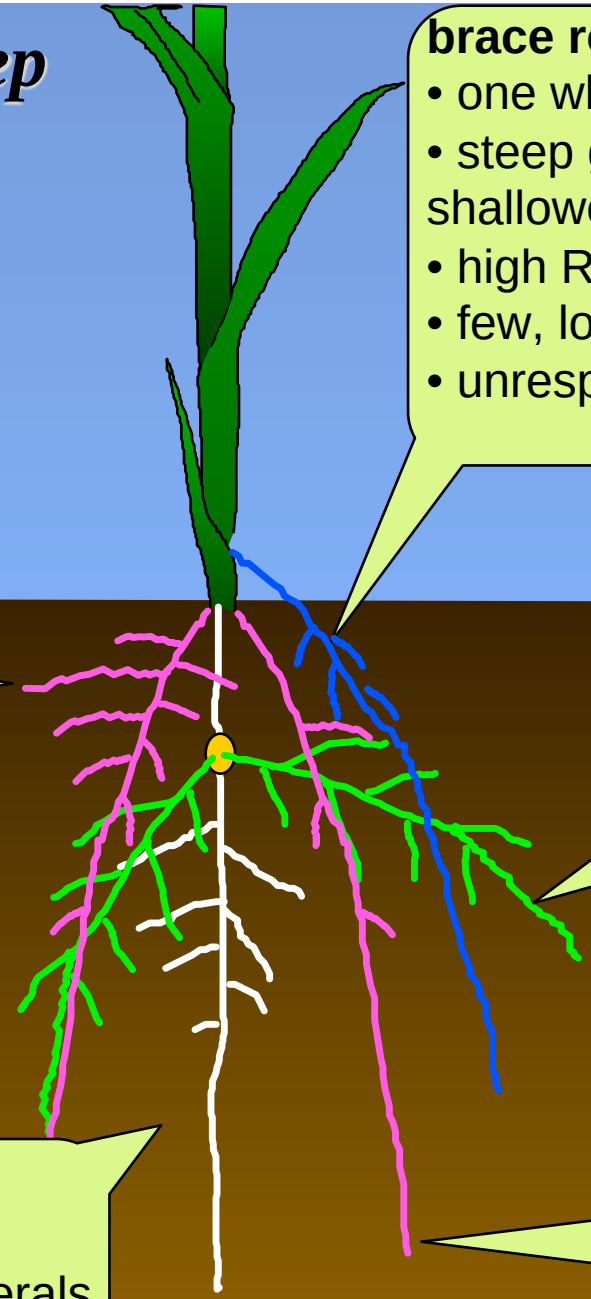
The need for greater water/nitrogen efficiency in maize

- in poor nations, water and N strongly limit yield and food security
- drought biggest risk in high-input maize production
- N fertilizer is the primary energy, economic, and environmental cost of maize production
- cost of N fertilizer has risen dramatically with energy costs
- over half of applied N fertilizer wasted




Nitrate (mMol)
10.0
8.00
6.00
4.00
2.00
0.00

steep, cheap, and deep



brace roots
- one whorl of high occupancy
- steep growth angle, but shallower than crown roots
- high RCA
- few, long laterals
- unresponsive to N

OR
seminal roots
- ~~shallow~~ deep
- ~~thin~~ thick
- high RCA
- ~~many~~ few, long laterals

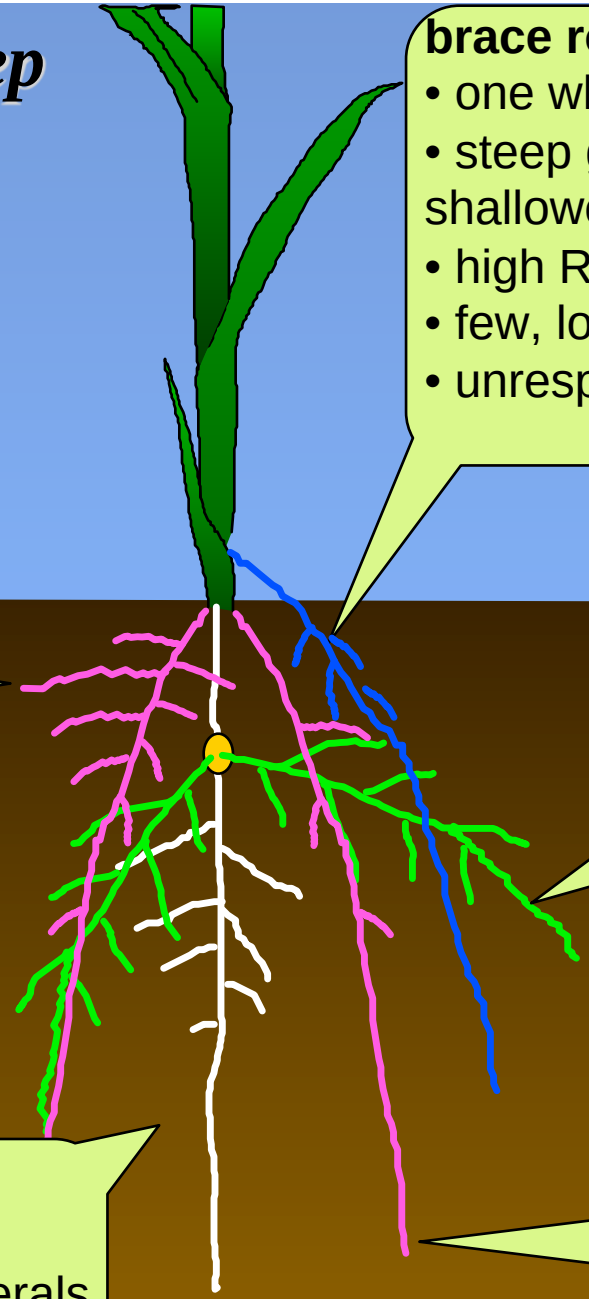
coupled with
many laterals from initial crown roots

seminal roots
- shallow
- thin
- high RCA
- many laterals
- long hairs

crown roots
- steep growth angle
- high RCA
- few, long laterals
- unresponsive to N
- high Vmax
- optimal number

primary root
- thick
- few, long laterals
- cold tolerant

steep, cheap, and deep



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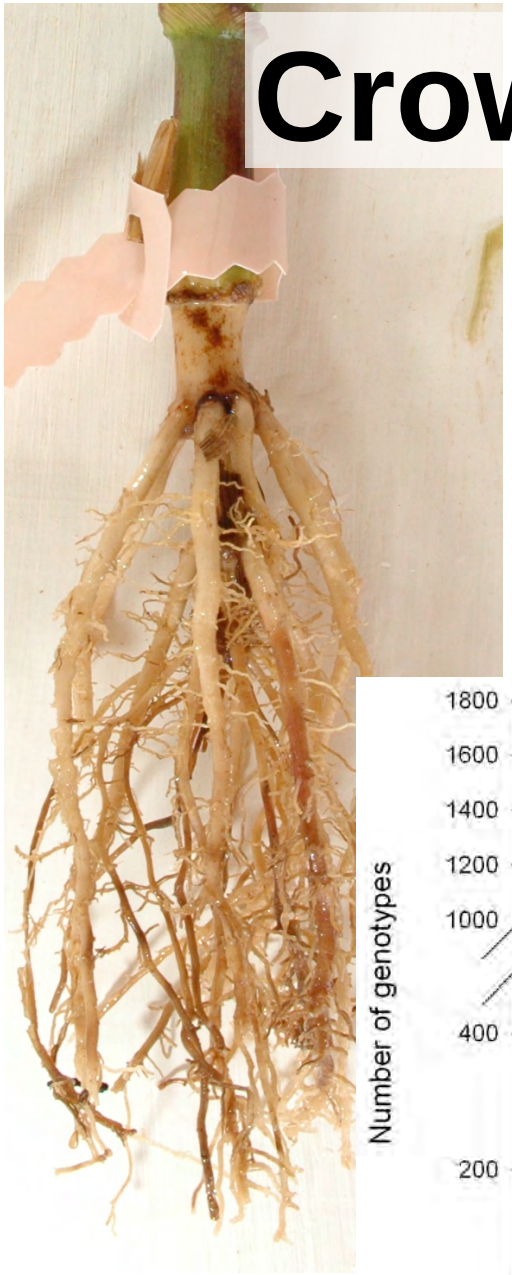
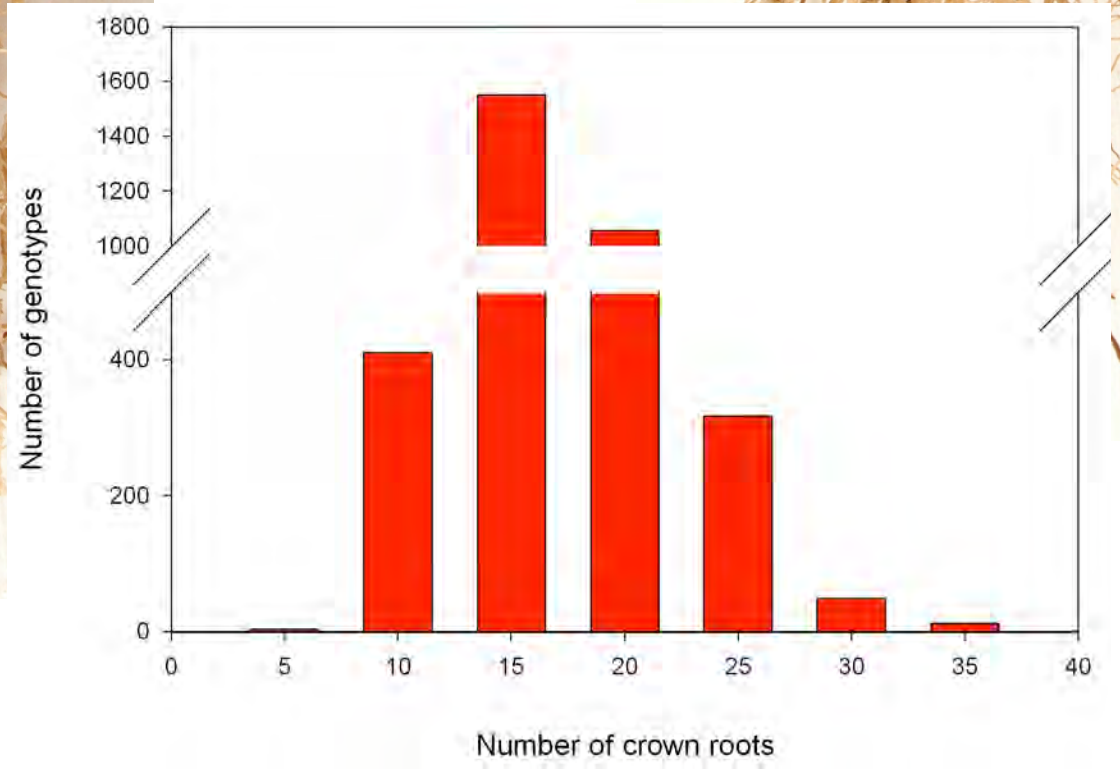
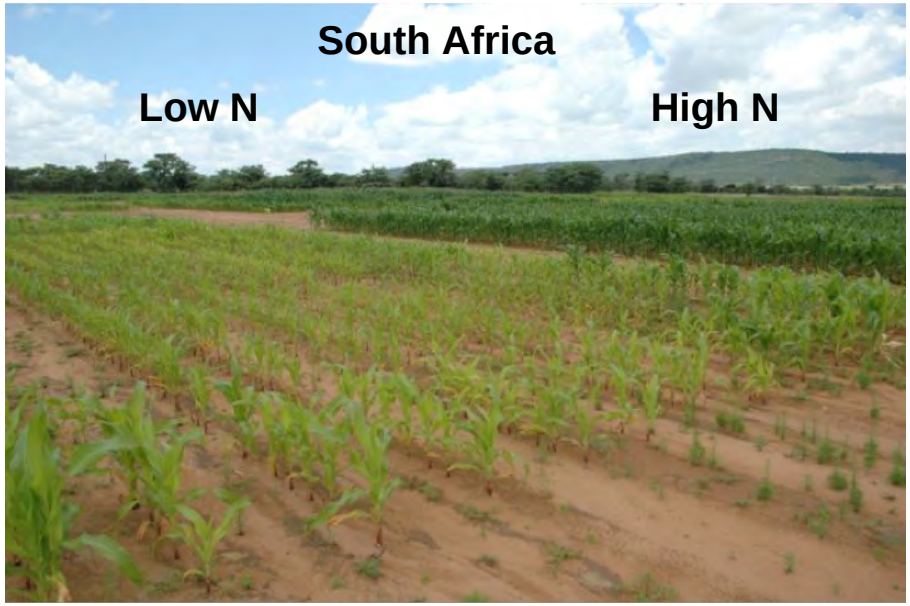
Crown root number

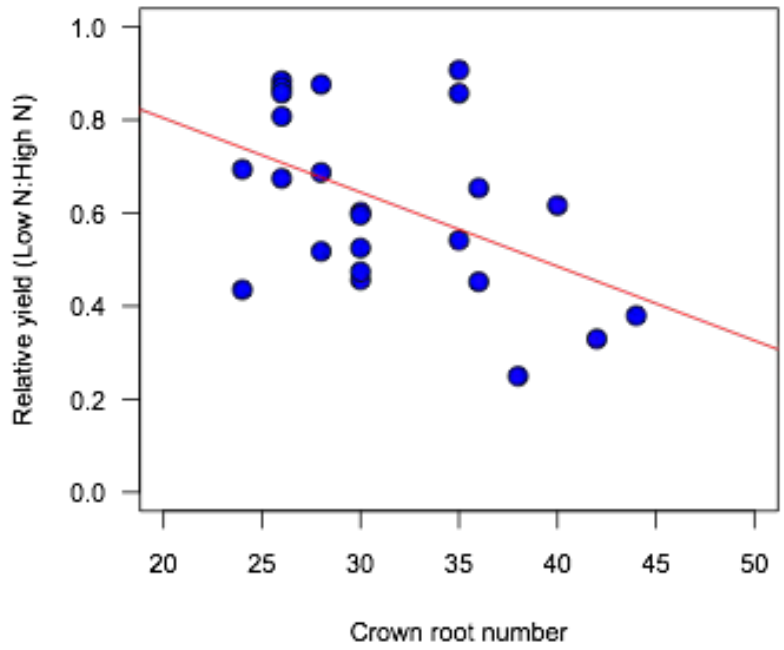




research of Larry York

Reduced crown root phenotype improves yield under low N





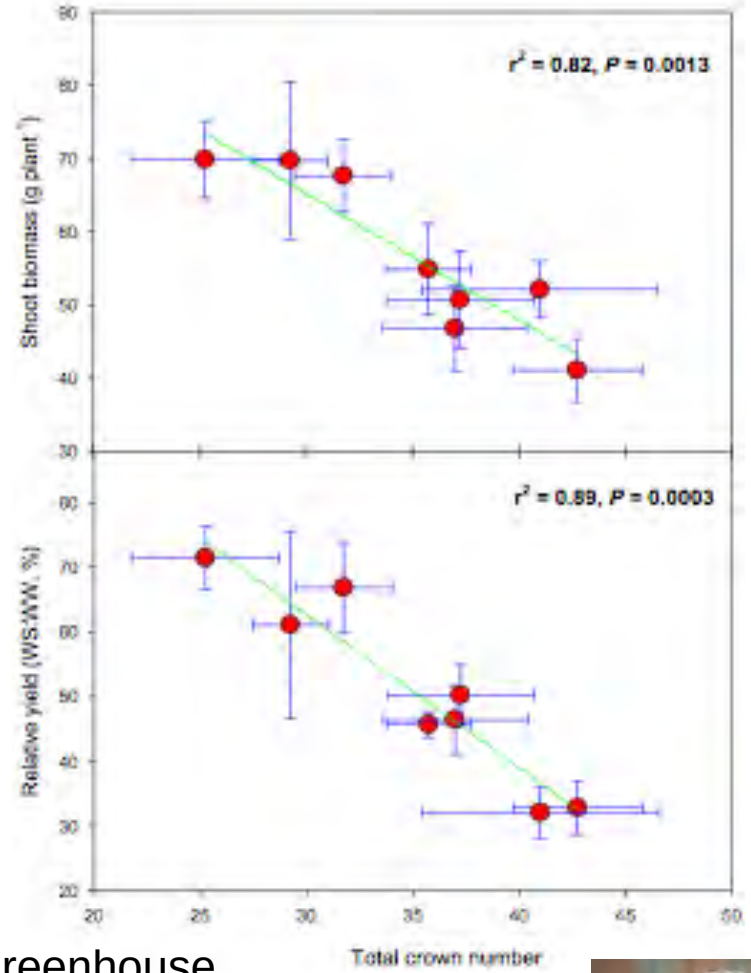
Under N stress in field studies in the USA and South Africa and greenhouse mesocosms, low CN lines had

- 45% deeper rooting
- 200% better capture of deep 15N
- 50-100% better N accumulation, leaf and canopy photosynthesis
- 25-85% better growth
- 180% more yield

Saengwilai, Lynch 2014

Reduced crown root phenotype improves yield under drought

rainout shelters-PA

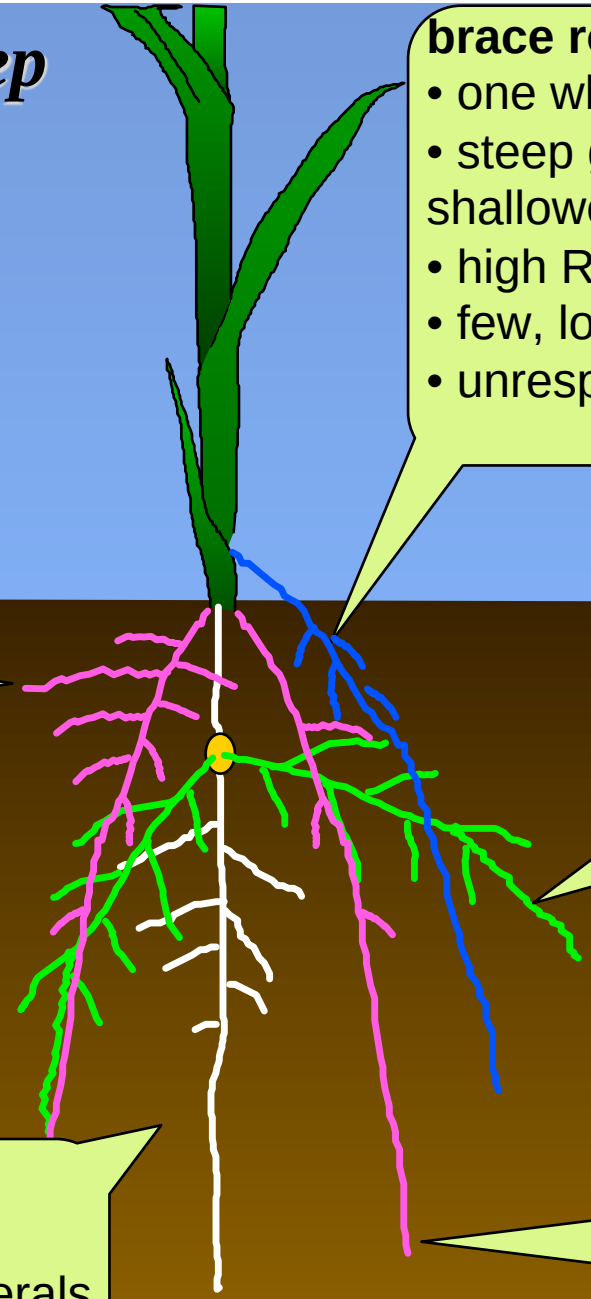


Under water stress in field studies in the USA and greenhouse mesocosms, low CN lines had

- 20-40% deeper rooting
- 10-13% greater leaf RWC
- 40-124% better growth
- 60-116% more yield

research of Yingzhi Gao

steep, cheap, and deep



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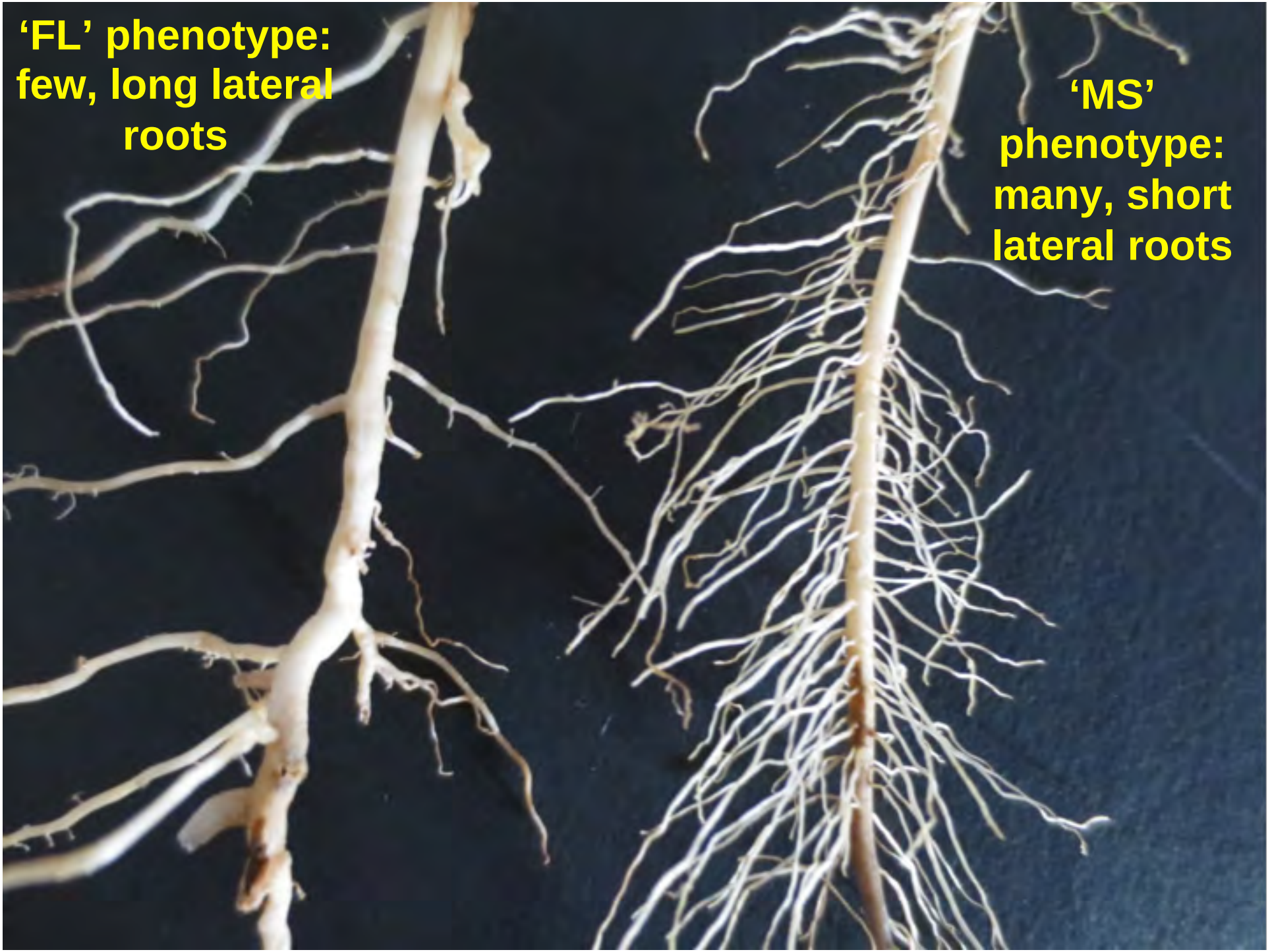
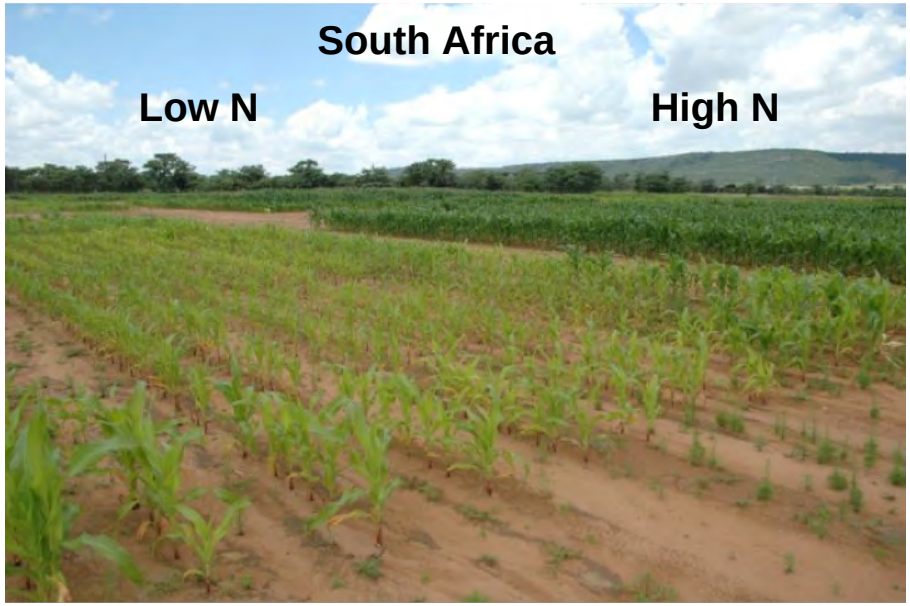
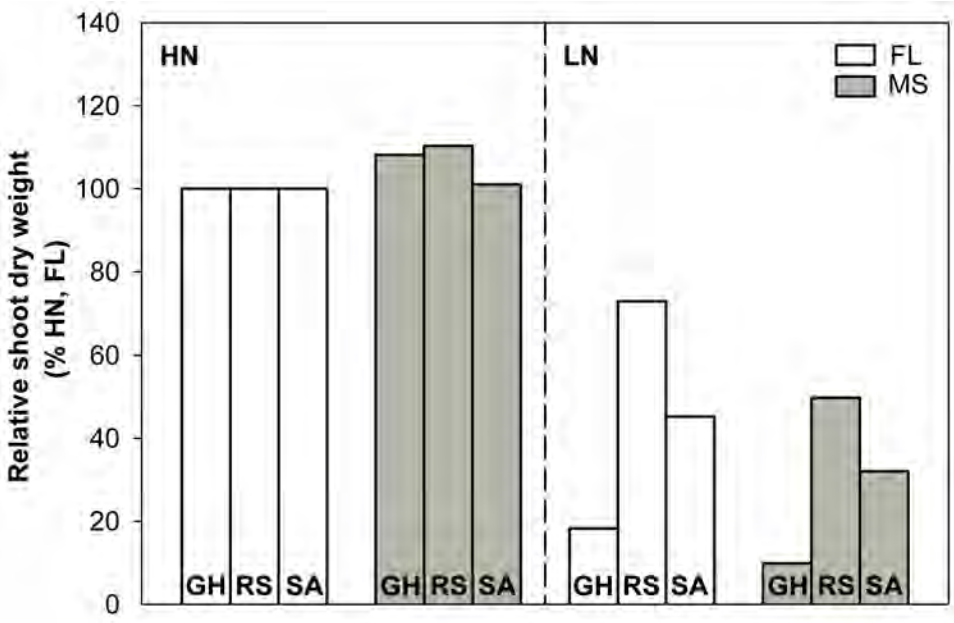

‘FL’ phenotype:
few, long lateral
roots
‘MS’
phenotype:
many, short
lateral roots

Postma, Dathe, Lynch 2014

‘Few long’ lateral root phenotype improves yield under low N



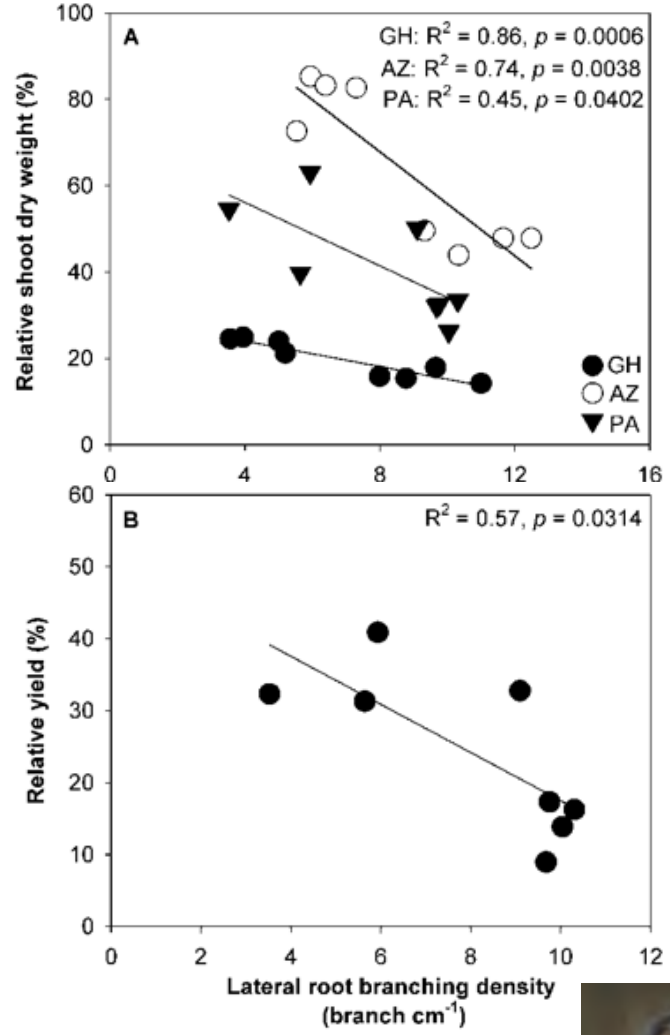


Under N stress in field studies in the USA and South Africa and greenhouse mesocosms, FL lines had

- 67% less lateral root respiration
- 17-20% deeper rooting
- 33-34% better N capture
- 33-39% better leaf photosynthesis
- 41-46% better growth
- **32% more yield**

Zhan, Lynch 2014

‘Few long’ lateral root phenotype has better growth under drought

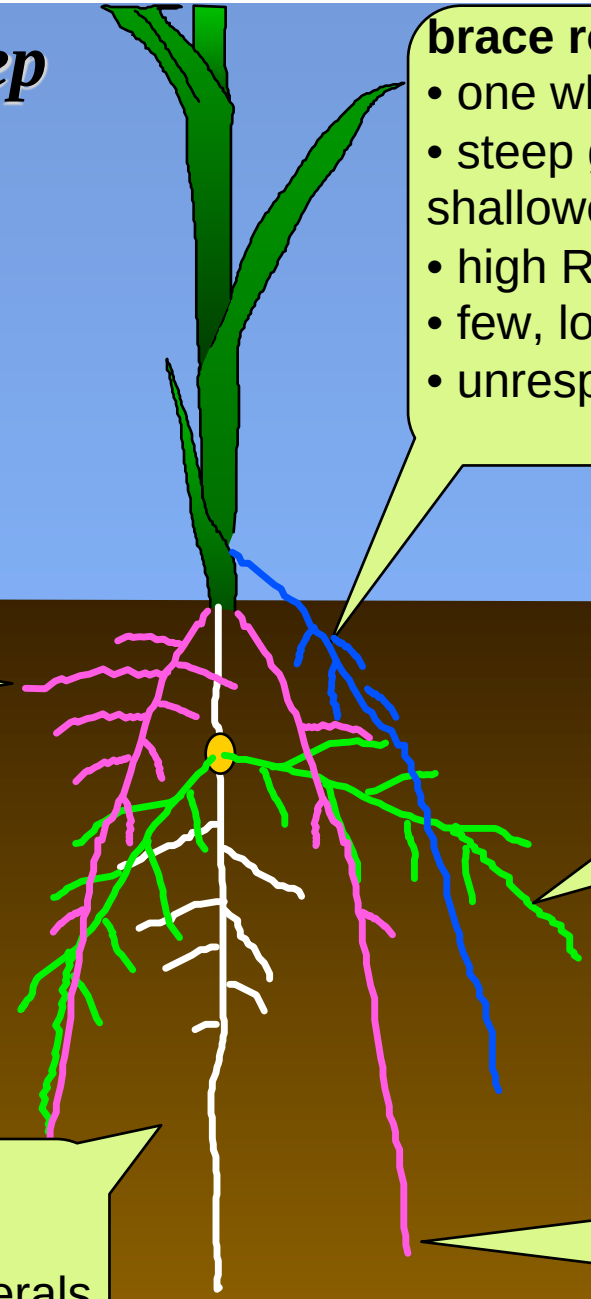


Under water stress in field studies in AZ and PA and greenhouse mesocosms, FL lines had

- 46% less specific root respiration
- 20-35% deeper rooting
- 44-46% deeper water capture (18O analysis)
- 5-13% better leaf relative water content
- 46-88% better stomatal conductance
- 42-79% better leaf CO2 assimilation
- 8-34% better growth
- **61% more yield**

Zhan, Schneider, Lynch 2015

steep, cheap, and deep



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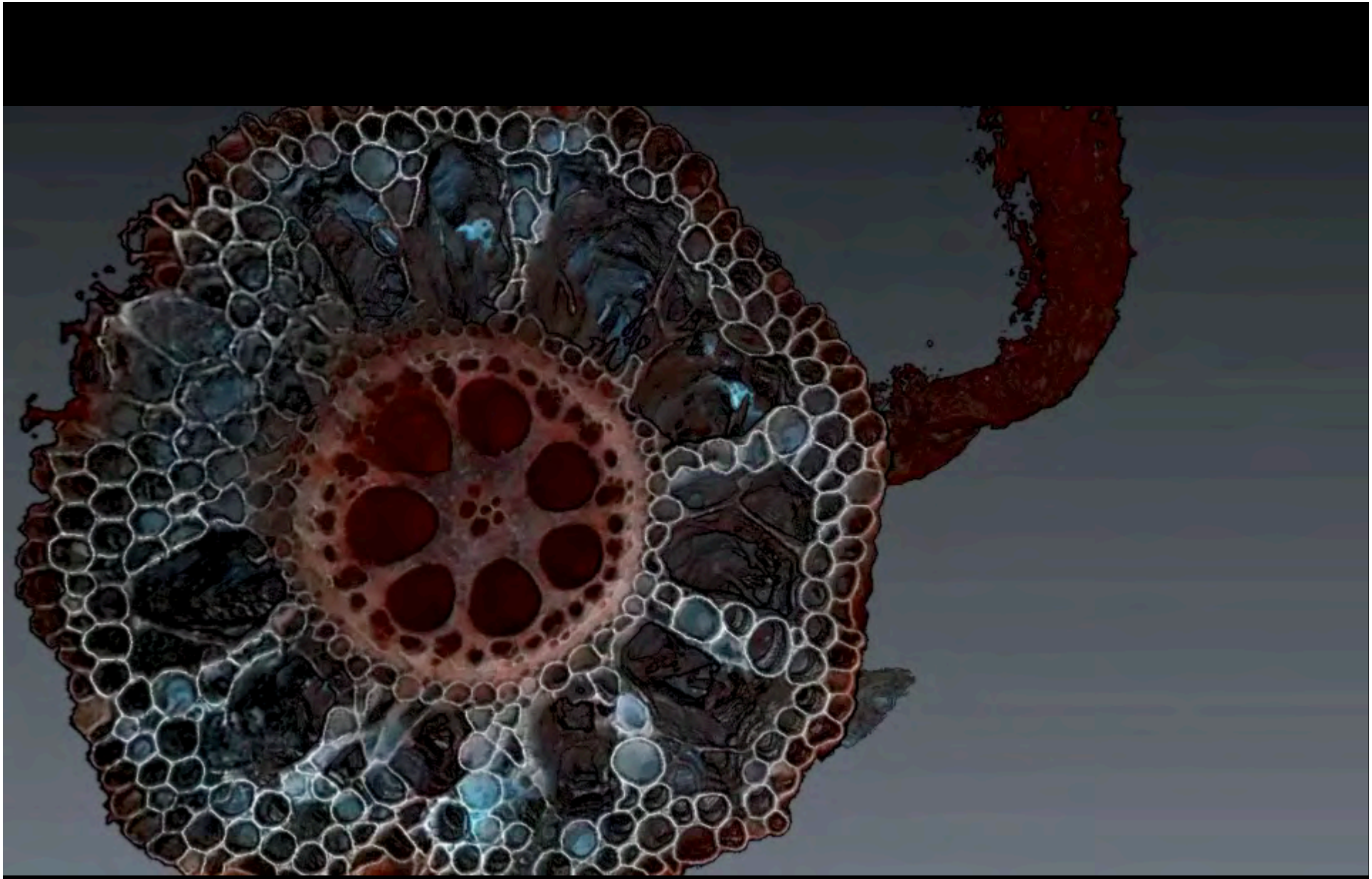
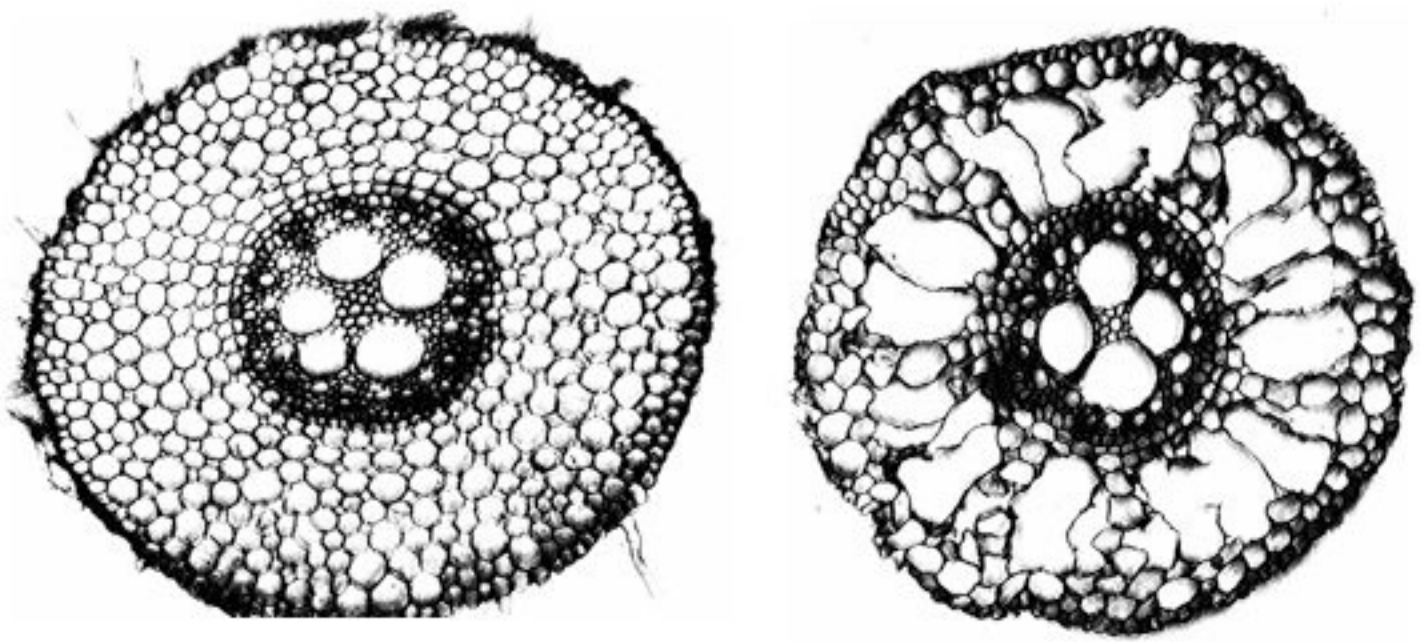


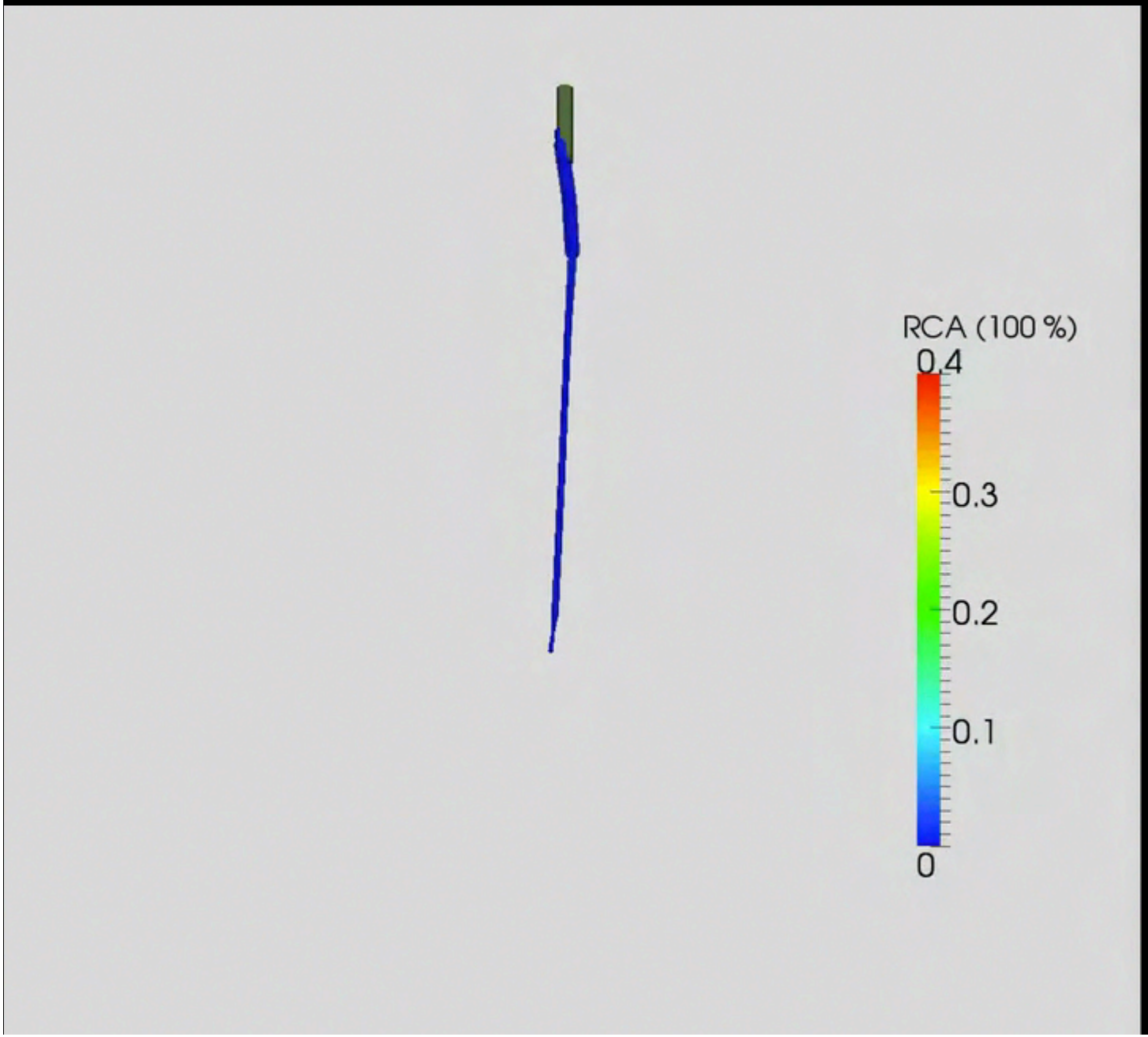
laser ablation by Ben Hall

Cheap: root cortical aerenchyma



Cross sections of seminal roots of maize showing genotypic difference in cortical aerenchyma formation, which replaces living cortical cells (left) with air-filled lacunae (right). Genotypes are RILs of OH43 x W64a.

spatial map of aerenchyma distribution



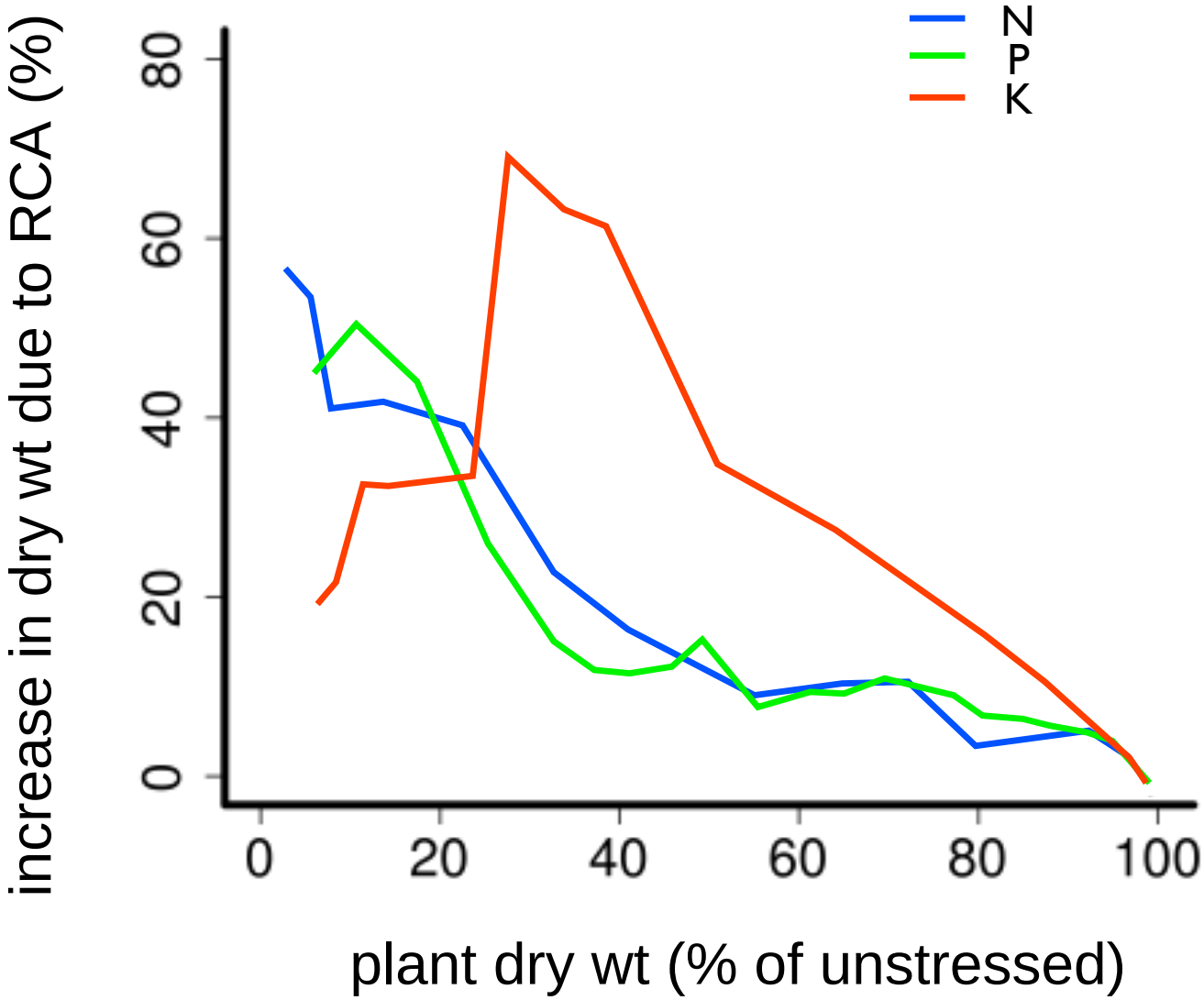
research of Johannes Postma

without RCA

with RCA

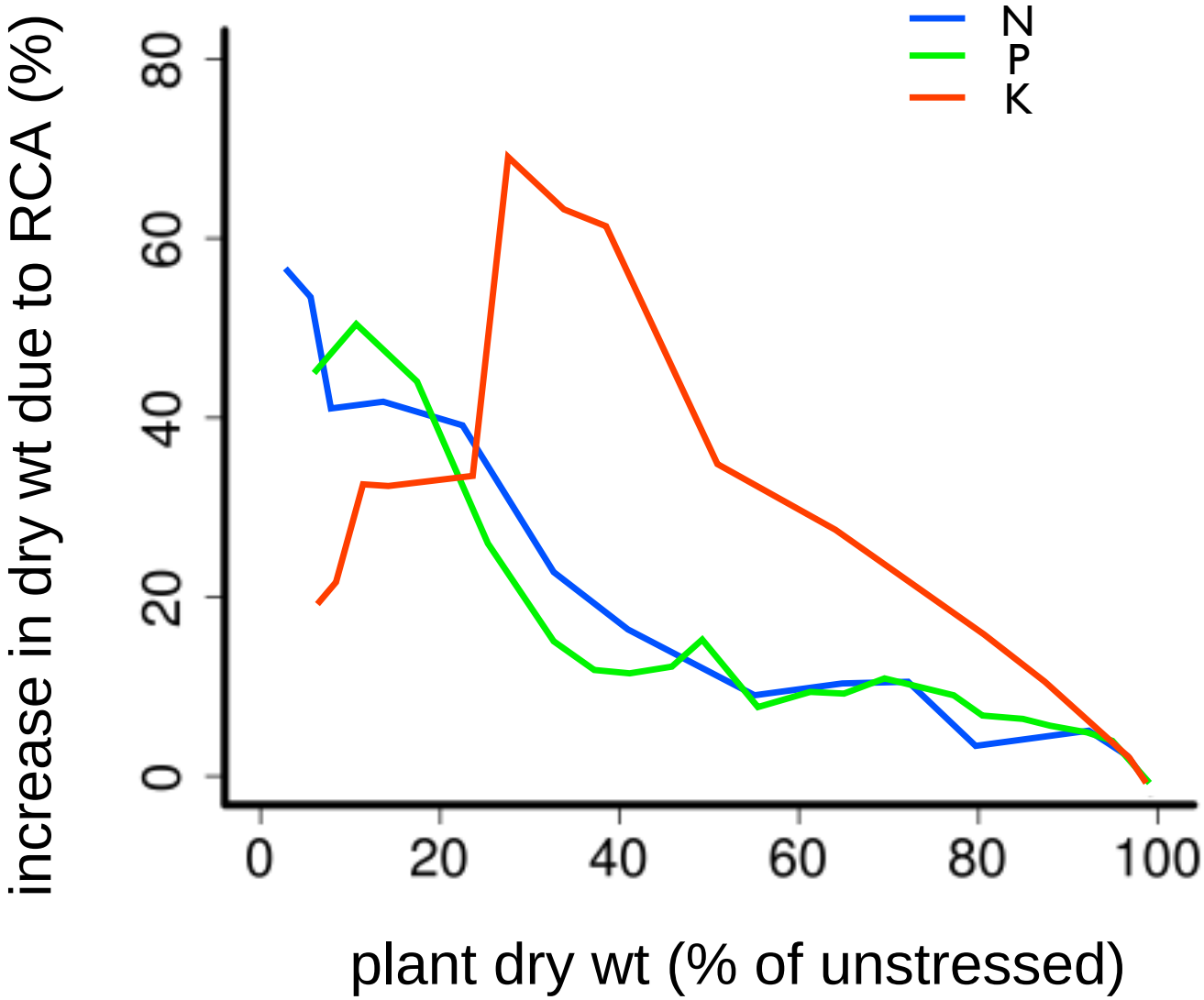
Postma and Lynch 2010

SimRoot: RCA improves growth under suboptimal N,P,K



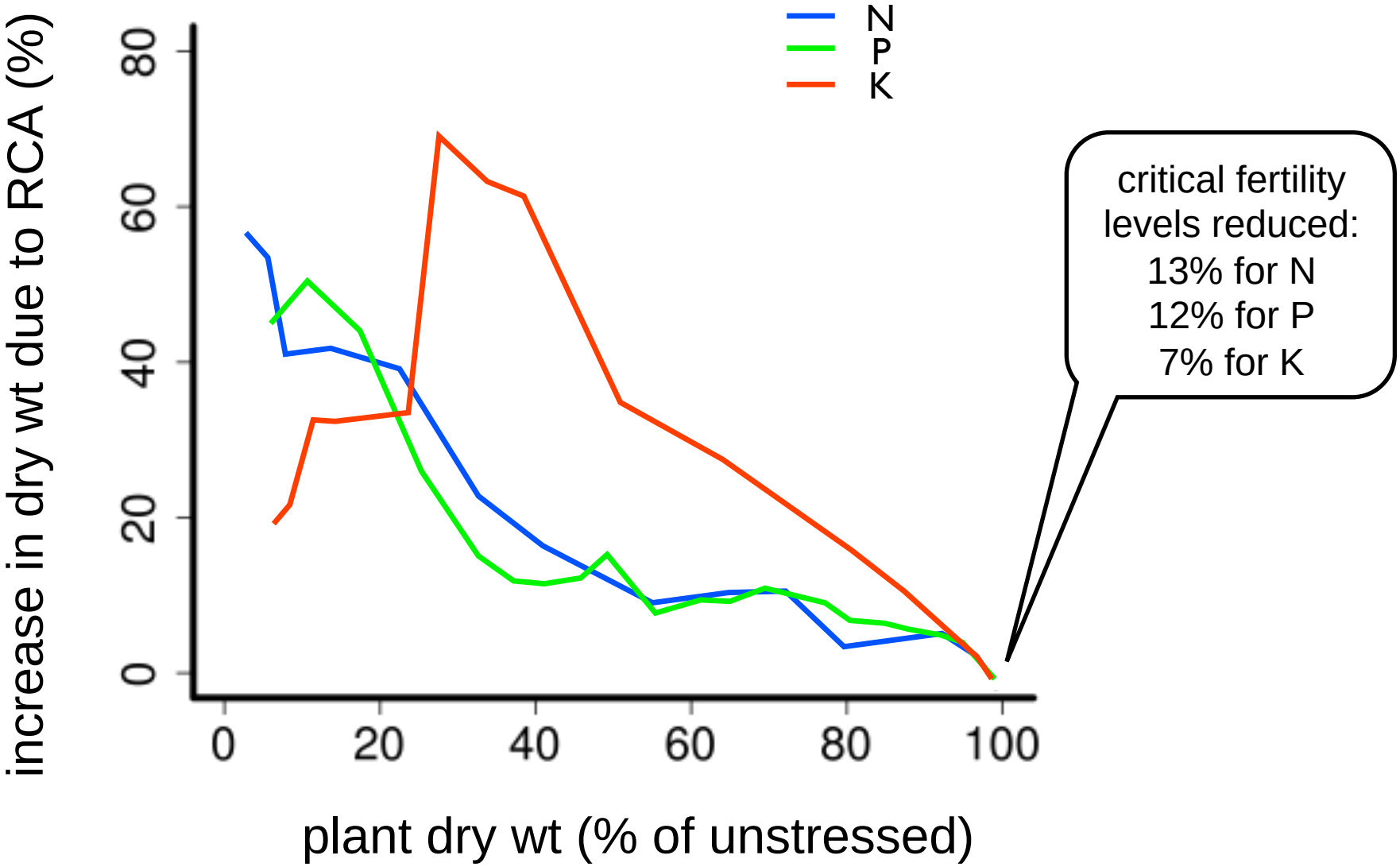
Postma and Lynch, 2011

SimRoot: RCA improves growth under suboptimal N,P,K



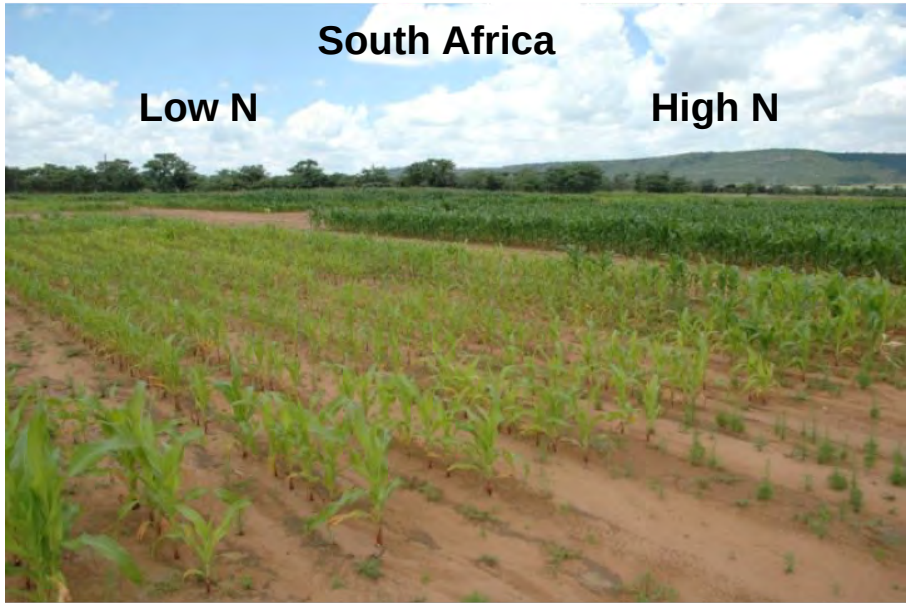
Postma and Lynch, 2011

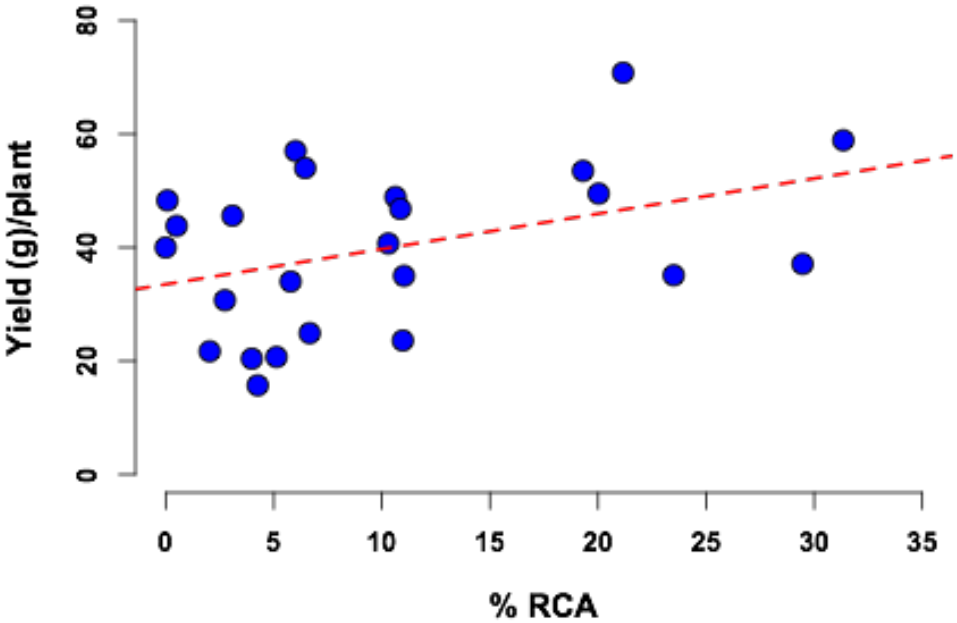
SimRoot: RCA improves growth under suboptimal N,P,K and reduces fertilizer requirement for maximum growth



Postma and Lynch, 2011

High RCA improves yield under low N



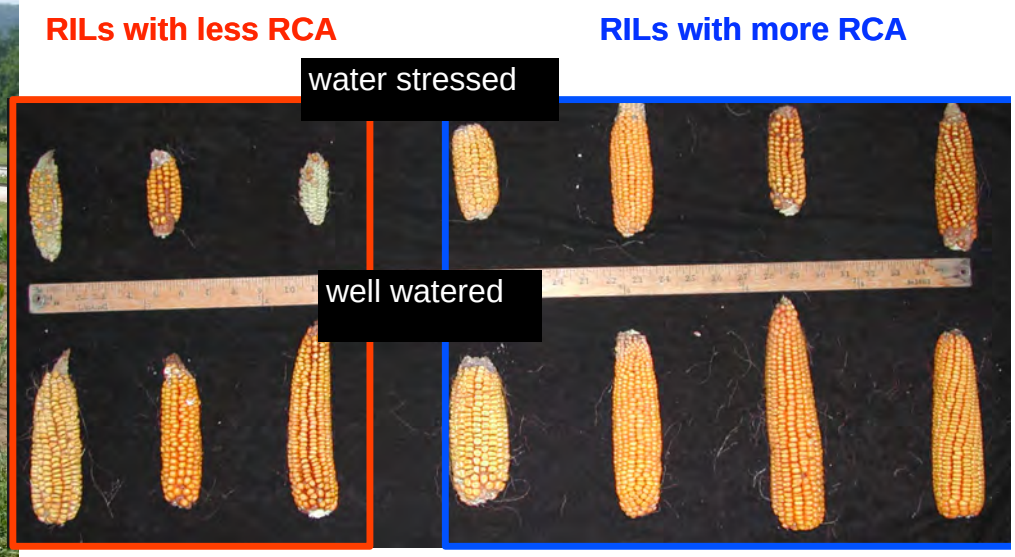


Under N stress in field studies in South Africa and PA and greenhouse mesocosms, high RCA lines had

- 42% less specific root respiration
- 15-31% deeper rooting
- 28-81% greater leaf N content
- 22% greater leaf CO2 assimilation
- 31-66% better growth
- 58% more yield

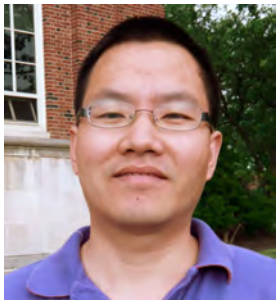
Saengwilai and Lynch 2014

High RCA improves yield under drought



Under water stress in field studies in the USA and greenhouse mesocosms, high RCA lines had

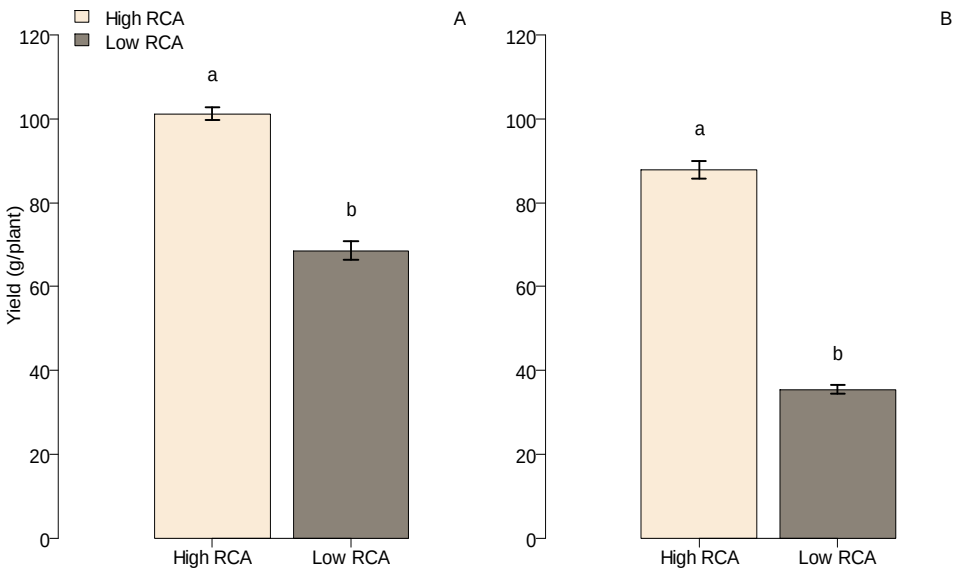
- 55% less specific root respiration
- 340% more roots 40-50 cm deep
- 10% greater leaf RWC
- 43% better growth
- 800% more yield



Zhu and Lynch 2010

High RCA improves yield under drought on farm in Malawi

10 lines in 14 farmer's fields in two regions of Malawi

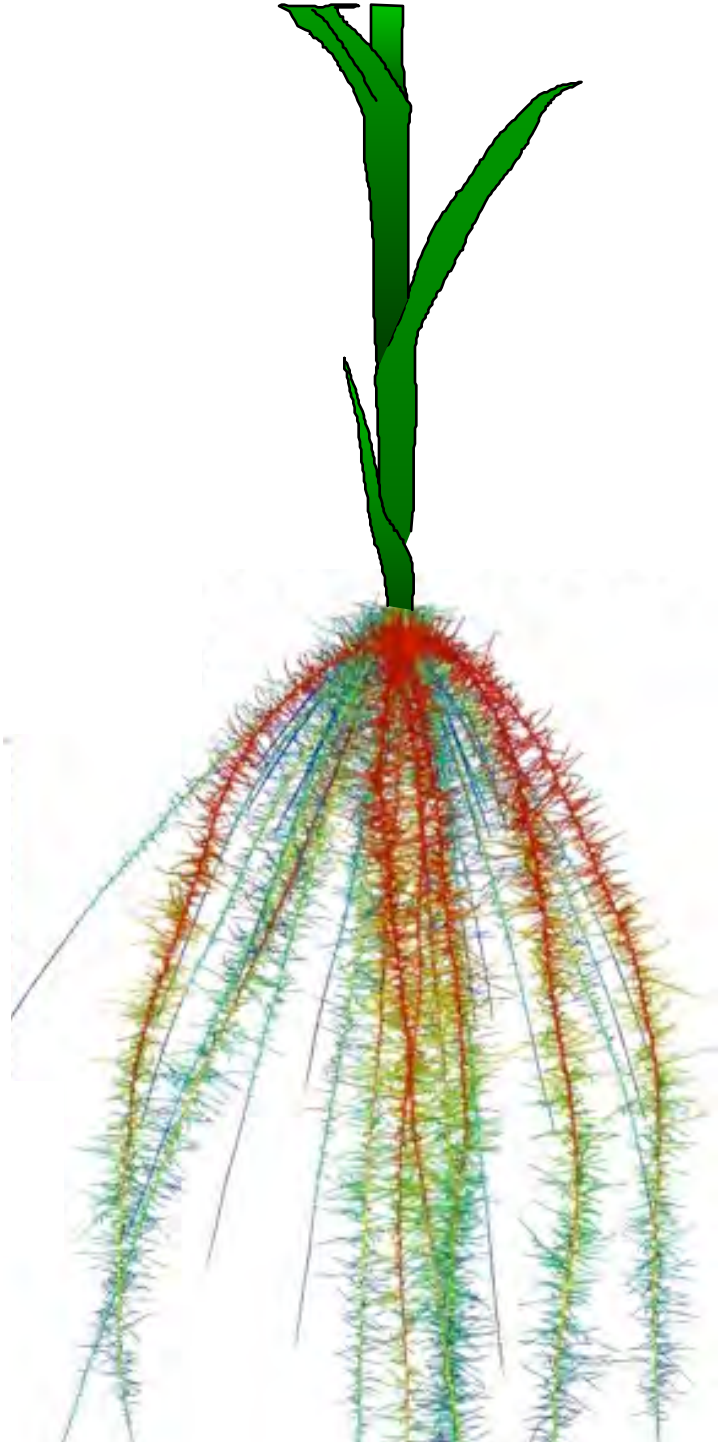


Under water stress in field on farm and on station in Malawi, high RCA lines among existing cultivars had

- 23-29% greater leaf RWC
- 67-96% better shoot biomass
- 78-143% more yield under drought

Chimungu et al 2015

water use efficiency
or
carbon use efficiency?



CO_2

H_2O

WUE, TE, etc

CO_2

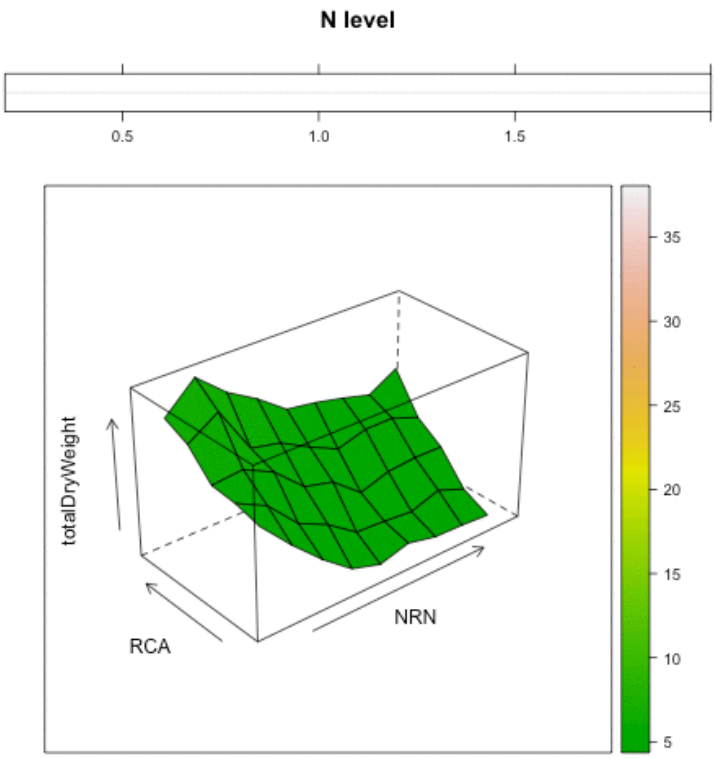
H_2O

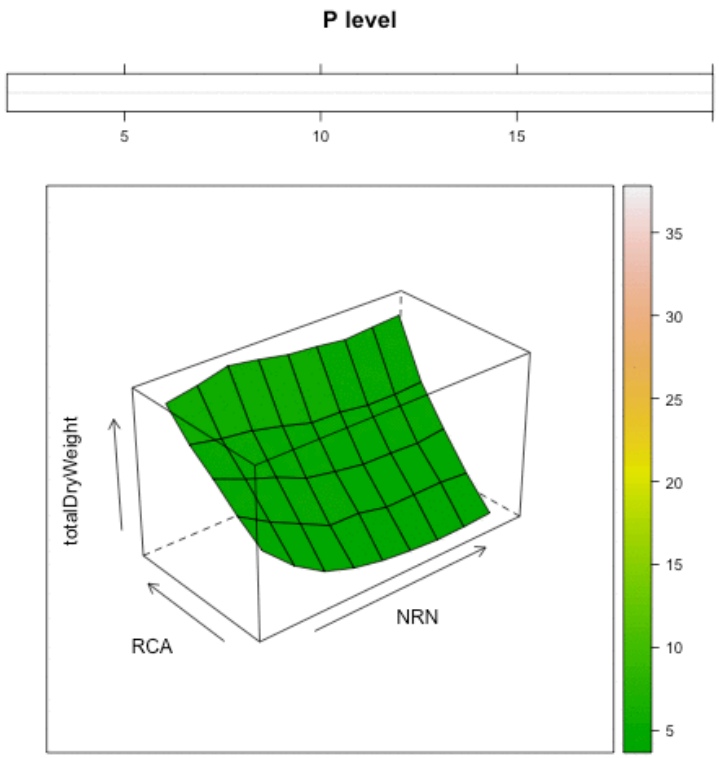
CUE

RCA, CCFN, CCS act via CUE, not WUE

Maize breeder Dr. Moses Maliro of LUANAR, Malawi evaluating new C efficient lines with a smallholder farmer

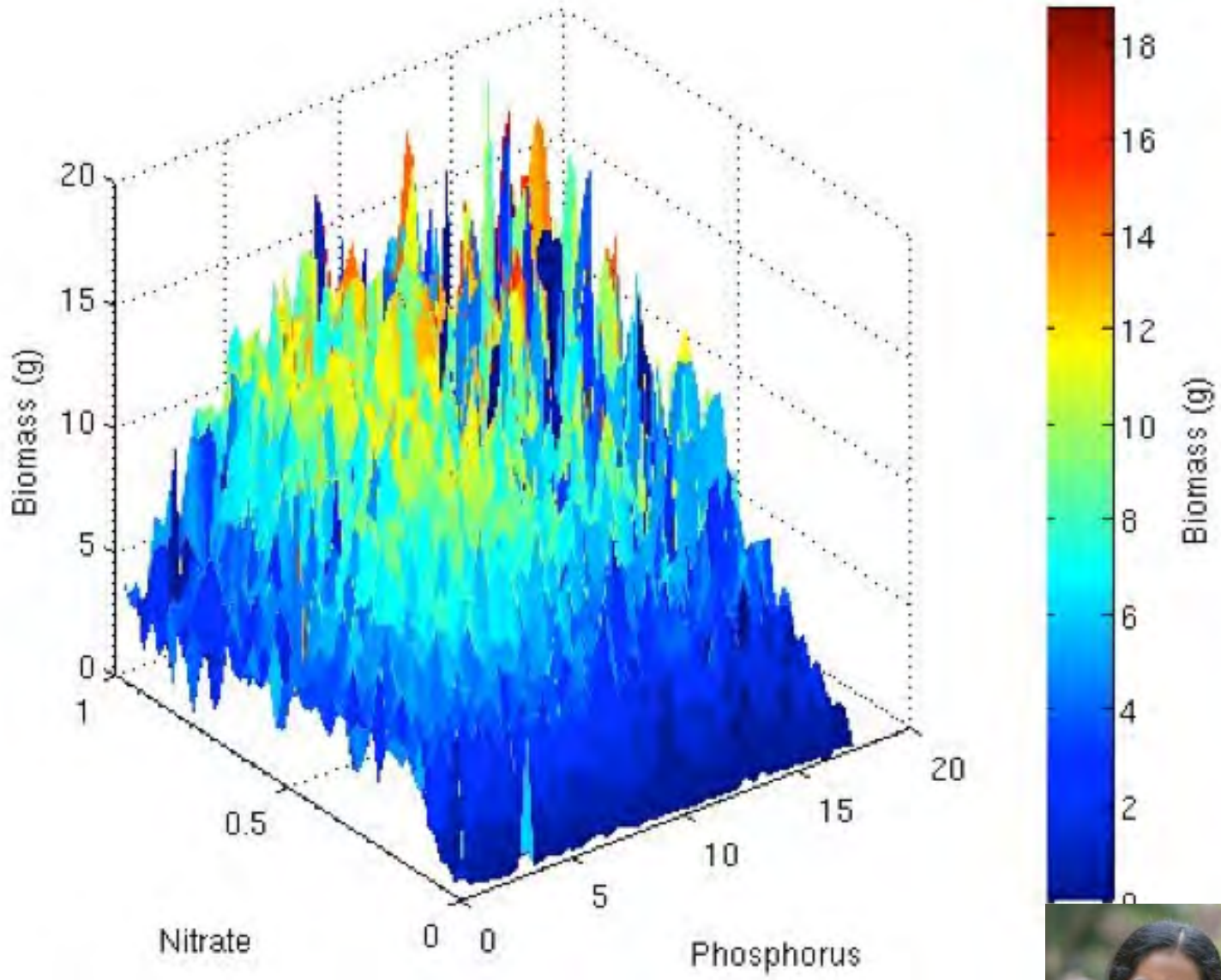
SimRoot/RootSlice: synergism between architectural and anatomical phenes





Dry weight as a function of RCA and nodal root number under different N and P levels

research of Eric Nord, Larry York

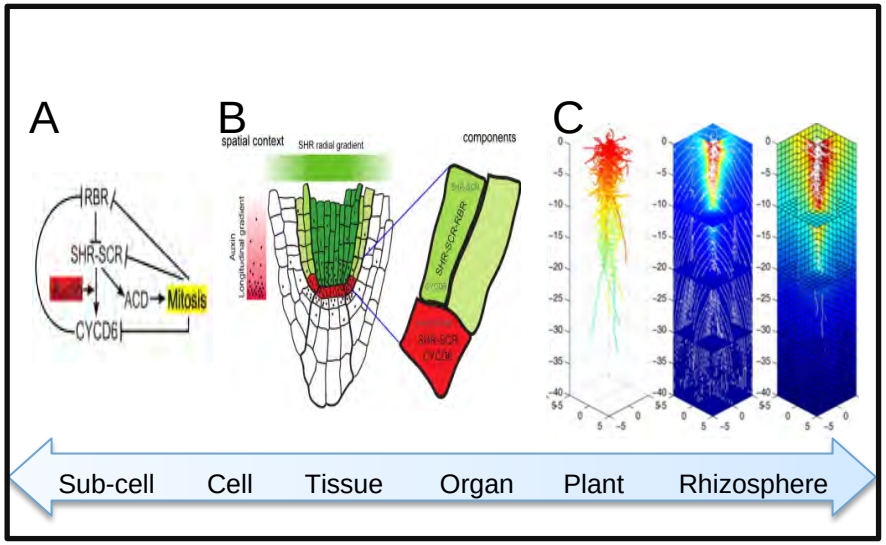


optimization using multi-objective genetic algorithm
250k scenarios selected out of ca. 10^{23} possibilities (1M h CPU time)

research of Harini Rangarajan

Multiscale functional modeling in silico biology from gene to ecosystem

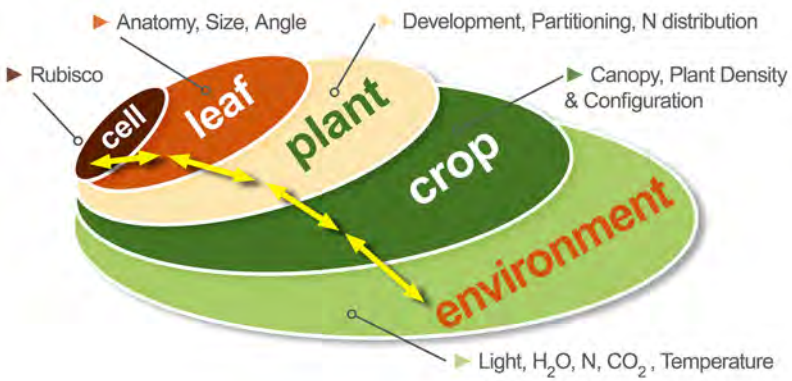
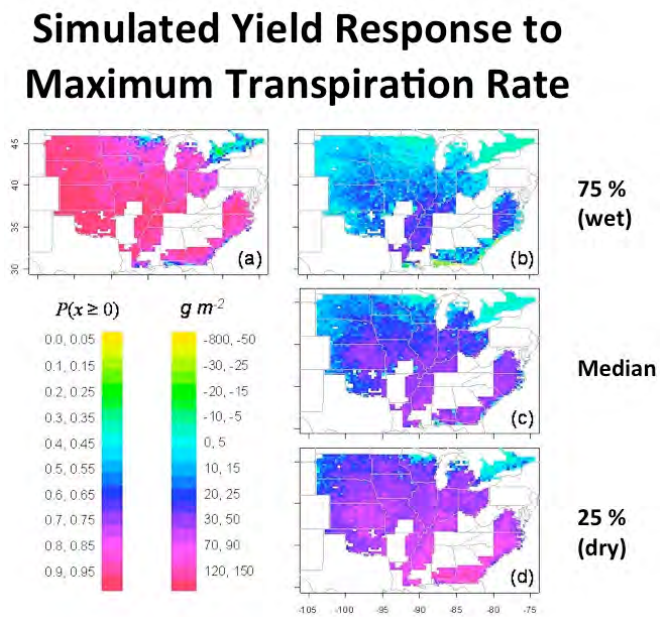
Malcolm Bennett, U Nottingham



Opportunity: link genomic to ecosystem processes via mechanistic, testable models. Note that such models have heuristic as well as predictive value.

Challenge: training and support base very weak in US- e.g. 3/160 US based researchers at 2013 FSPM.

Graeme Hammer, U Queensland



Tom Sinclair, UNC