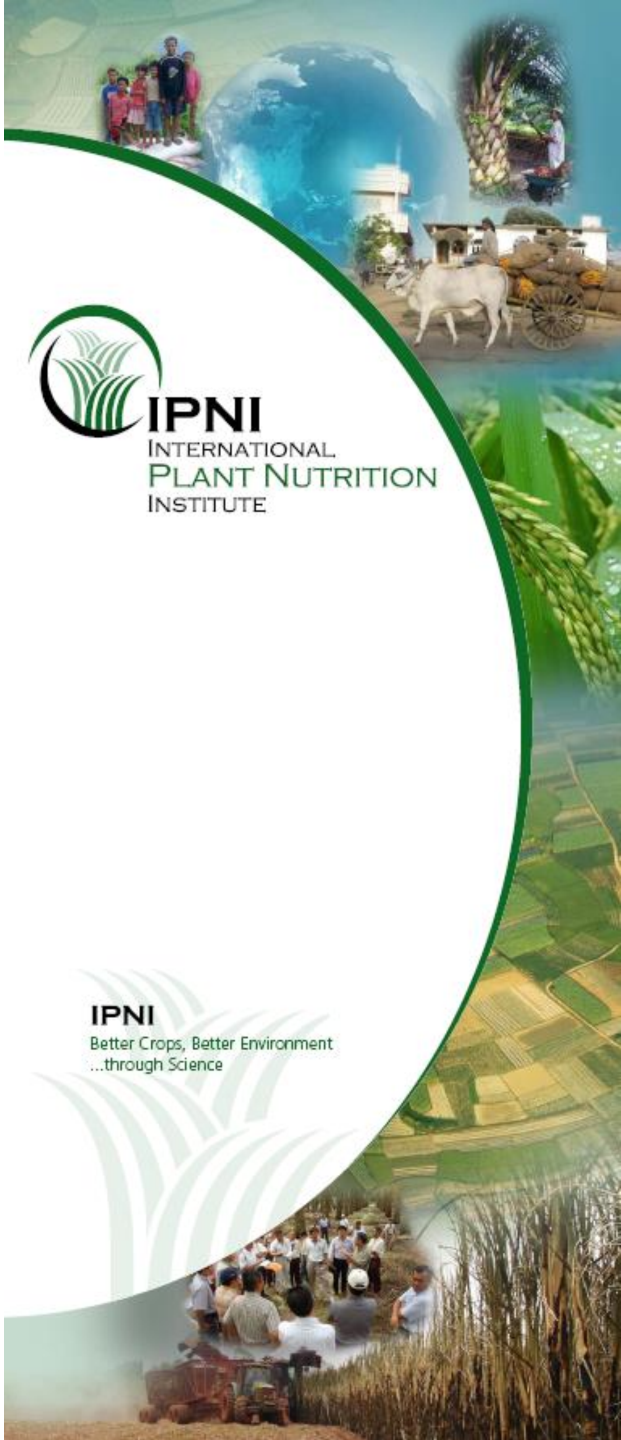
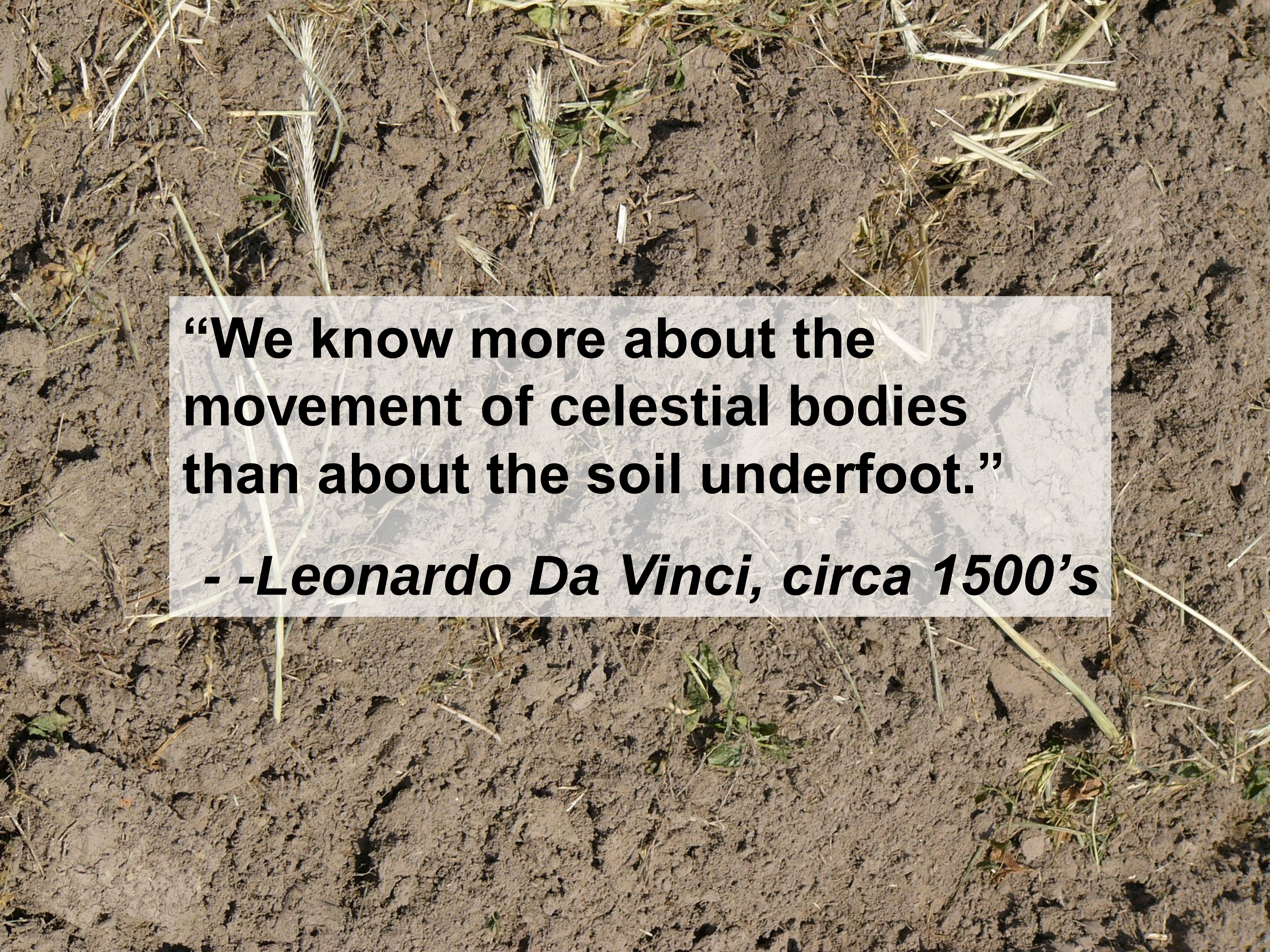
Getting to the Root of Nutrient Availability

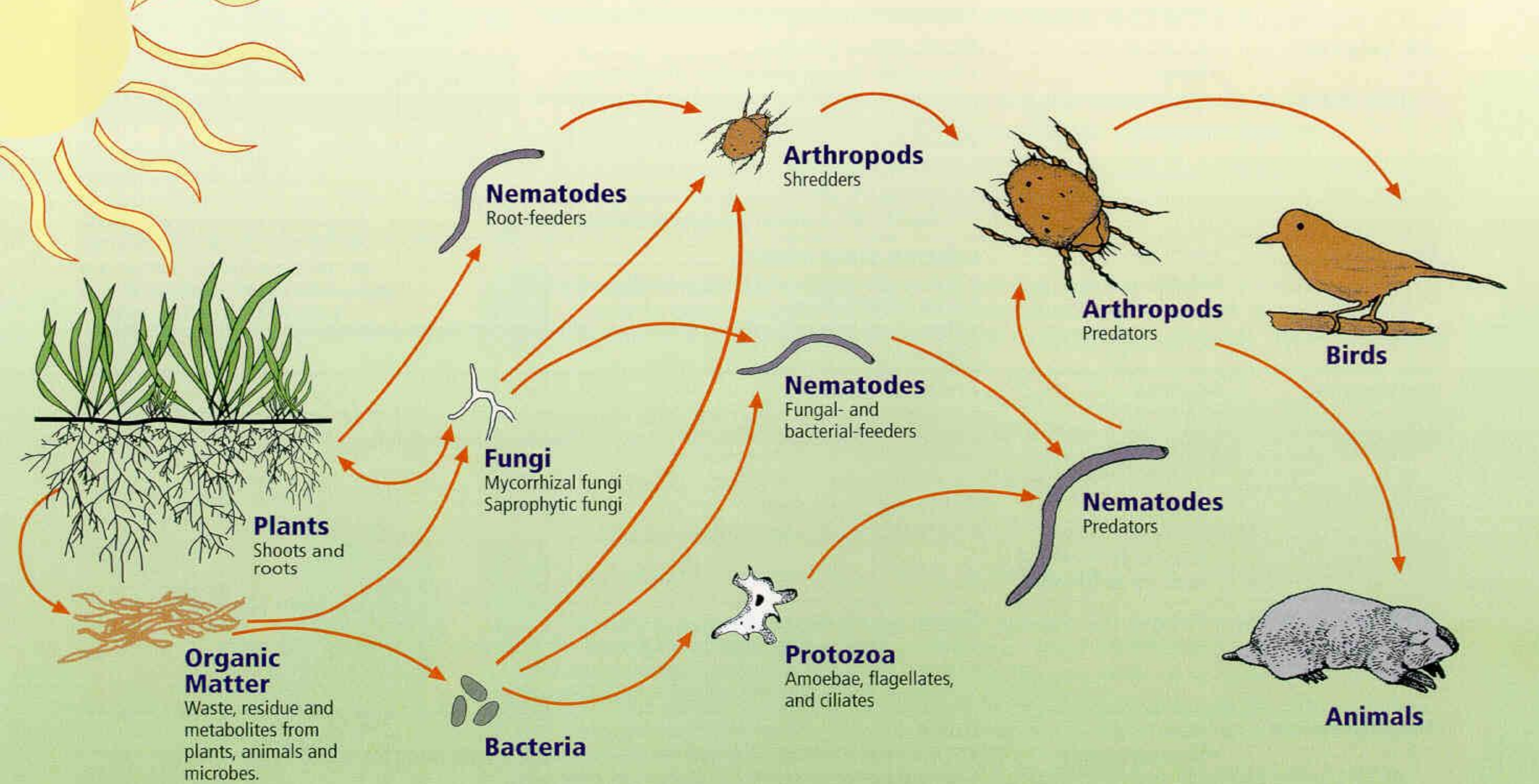
T. Scott Murrell
Director, North American Program

2014 Fluid Fertilizer Marketing and Technology Workshop, Sacramento, CA. 9-10 Dec.




"We know more about the movement of celestial bodies than about the soil underfoot."
- -Leonardo Da Vinci, circa 1500's

The Soil Food Web



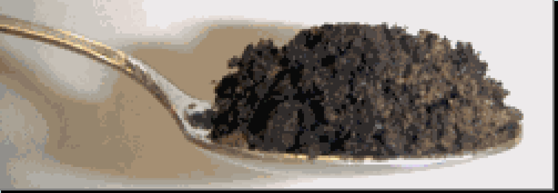
First trophic level:
Photosynthesizers

Second trophic level:
Decomposers
Mutualists
Pathogens, parasites
Root-feeders

Third trophic level:
Shredders
Predators
Grazers

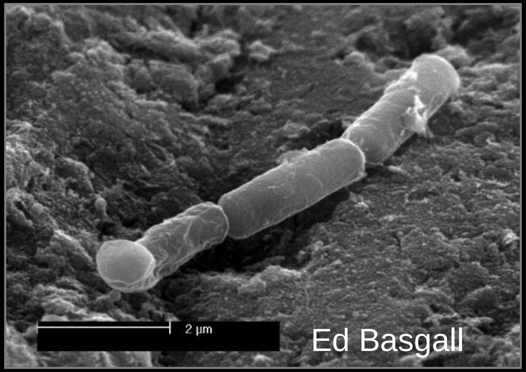
Fourth trophic level:
Higher level predators

Fifth and higher trophic levels:
Higher level predators

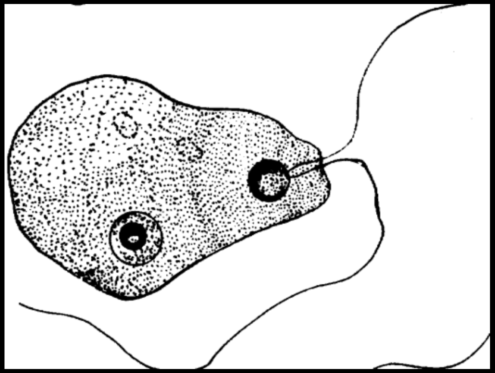


One teaspoon of soil contains:

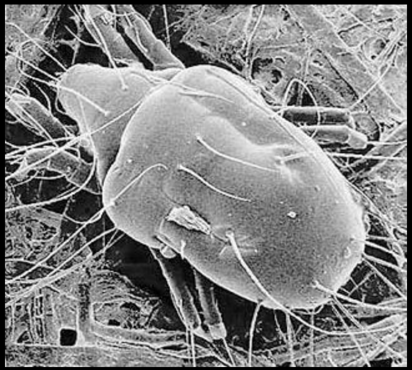
Bacteria:
100 million to 1 billion



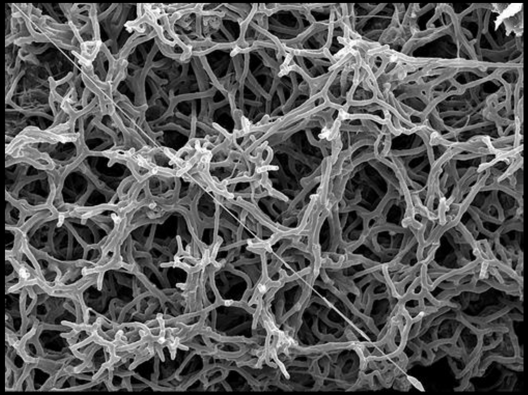
Protozoa:
1000 to 100,000



Arthropods:
up to 100



Fungal hyphae:
3 ft. to 40 miles



Nematodes:
10s to 100s

Root knot juvenile penetrating a tomato root

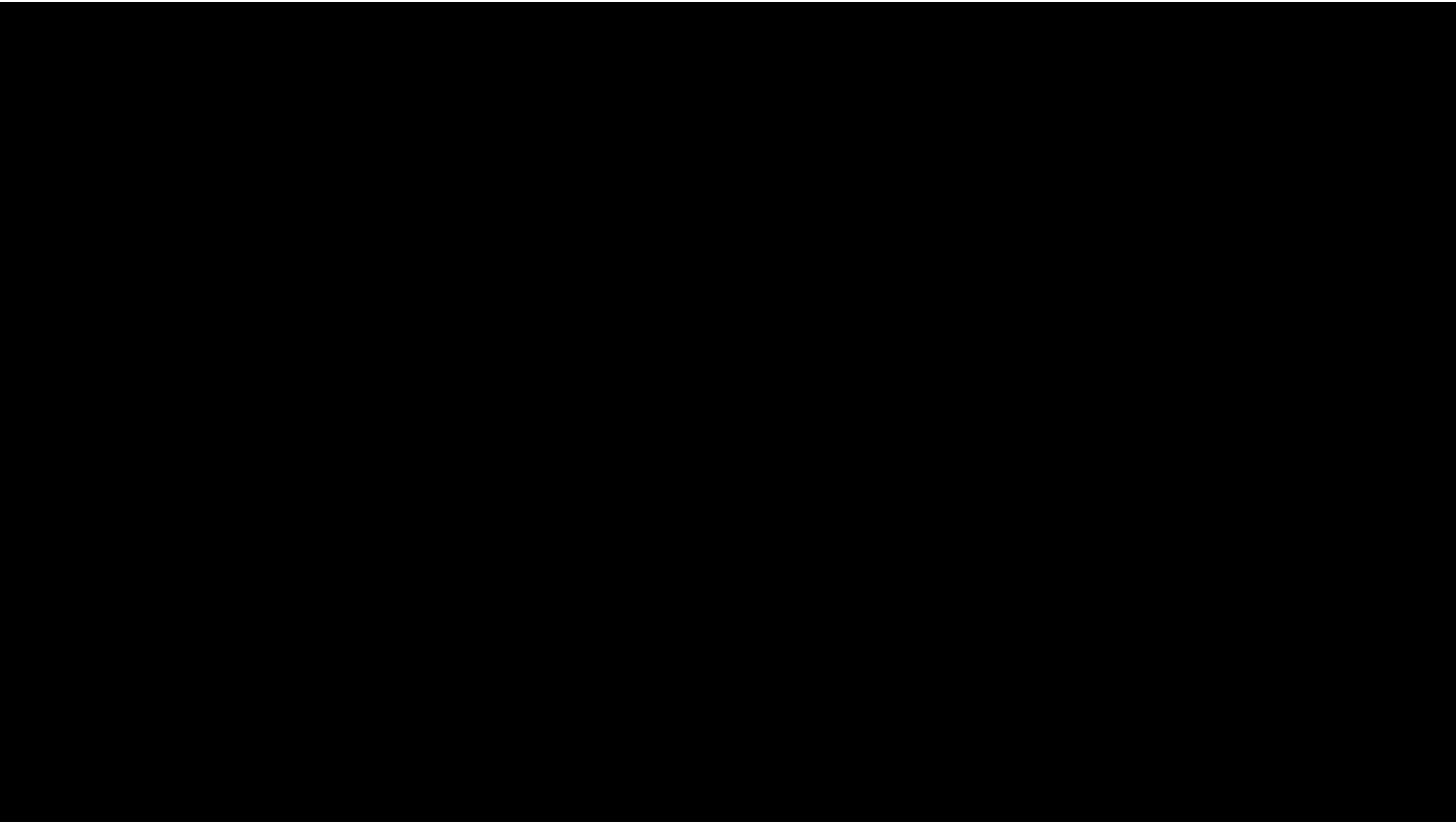
Annelids:
5 or more

Presenting

Germination Station

A series of "rootimentary" short films.

Corn germination and growth



Film: Gregor Skoberne

Wheat

Film: Neil Bromhall

Germination and root growth of maize/corn (Zea Mays) Time Lapse

Wheat germination and growing time lapse

THE END

Gregor Skoberne

Neil Bromhall

https://www.youtube.com/watch?v=ev9I6dXr6Iw

https://www.youtube.com/watch?v=y0oMtZWczq0

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International
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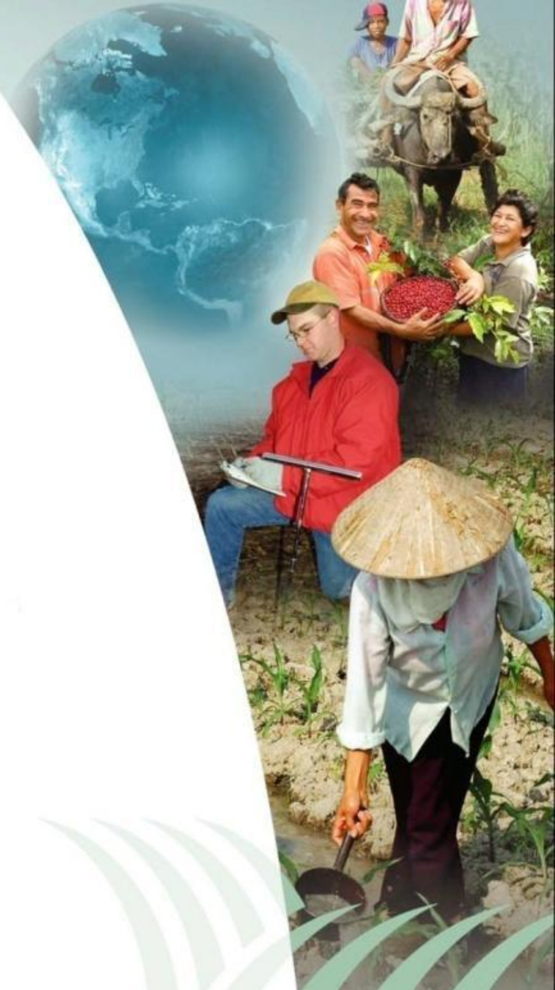
Looking More Closely at What’s Underground

- OR –

Rooting for Plant Nutrition!



Source: Nielsen, R. 2013. Root development in young corn. http://www.agry.purdue.edu/ext/corn/news/timeless/roots.html

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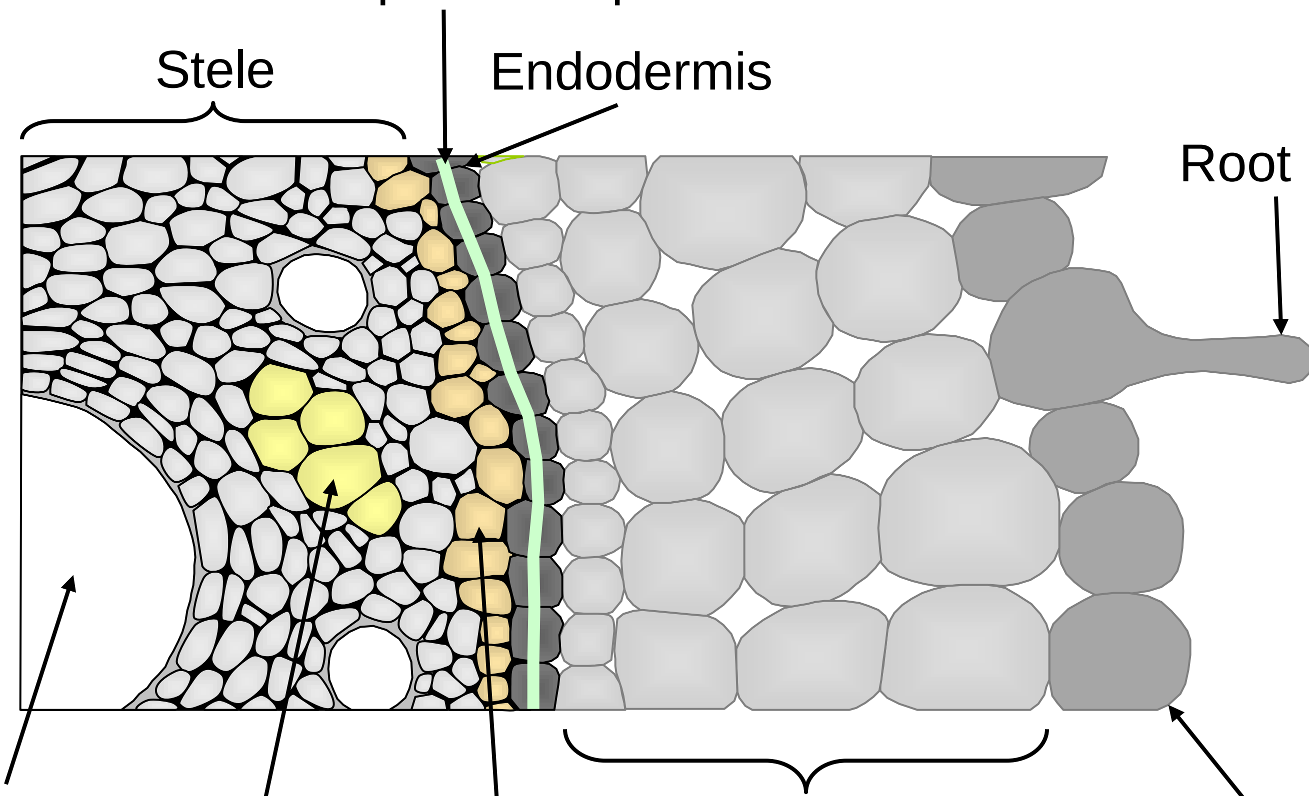
A HAIR-RAISING TALE

Corn root: Horizontal cross section



Russell, R.S. 1977. Plant root systems: Their function and interaction with the soil. McGraw-Hill, New York, NY.

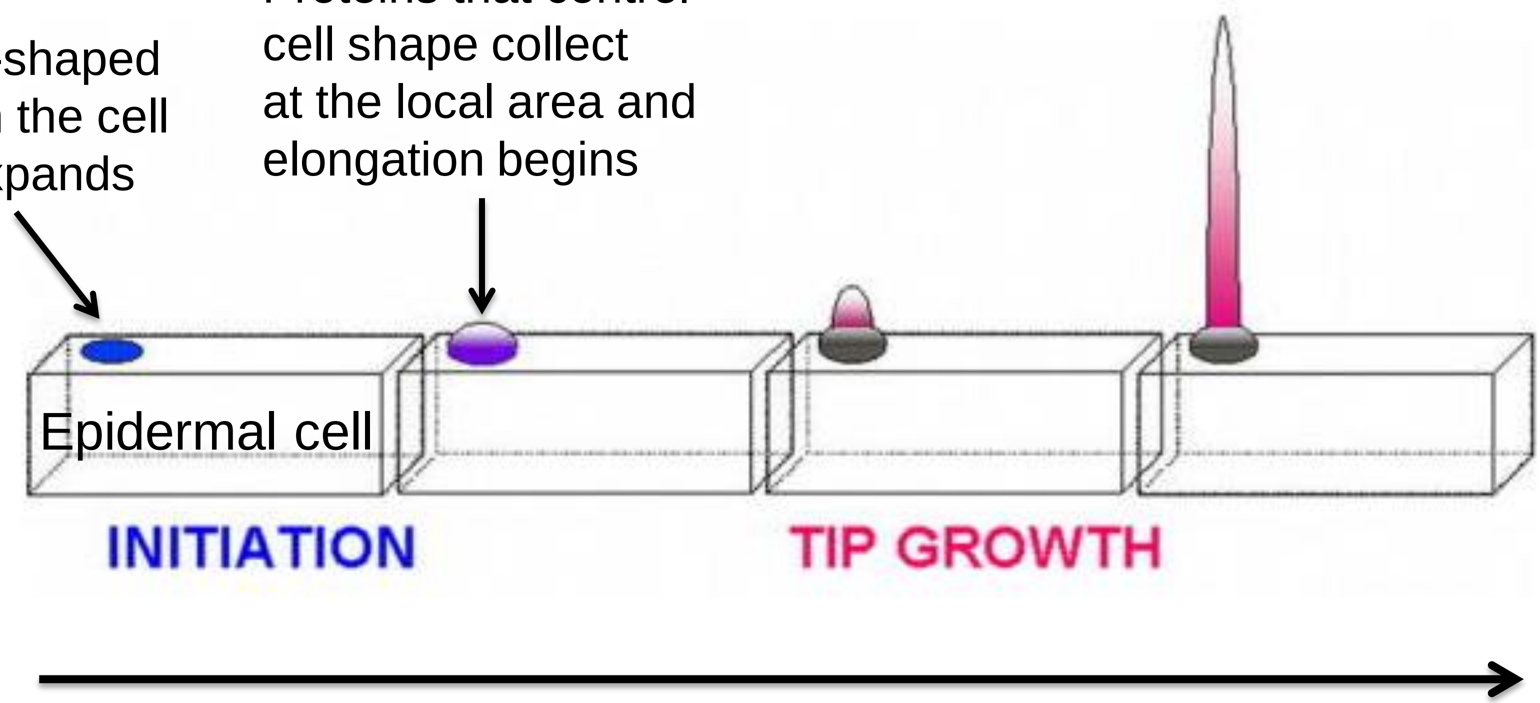
Formation of root hairs

The plant "decides" which root epidermal cells form root hairs.

New cell wall material is created and secreted specifically at the tip of the developing root hair.

A disc-shaped area in the cell wall expands

Proteins that control cell shape collect at the local area and elongation begins

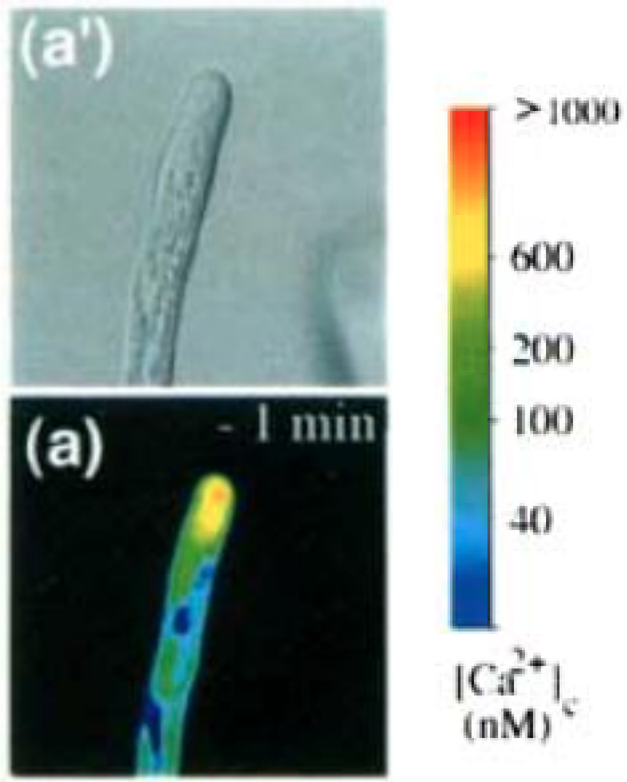


Time (minutes)

Grierson, C. and J. Schiefelbein. 2002. Root hairs. The Arabidopsis Book. American Society of Plant Biologists. Available online at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3243358/ (verified 6 Dec. 2014).

Tip Growth during Root Hair Formation

- The calcium ion (Ca^{2+}) accumulates at the tip of the root hair where cell wall material is being built
- The concentration of Ca^{2+} can be imaged using a fluorescent dye (indo-1) and a confocal microscope



Wymer, C.L. et al. 1997. Cytoplasmic free calcium distributions during the development of root hairs of *Arabidopsis thaliana*. Plant J. 12(2):427-439.

“The first and simplest emotion which we discover in the human mind, is curiosity.”

-- Edmund Burke
(Irish statesman)

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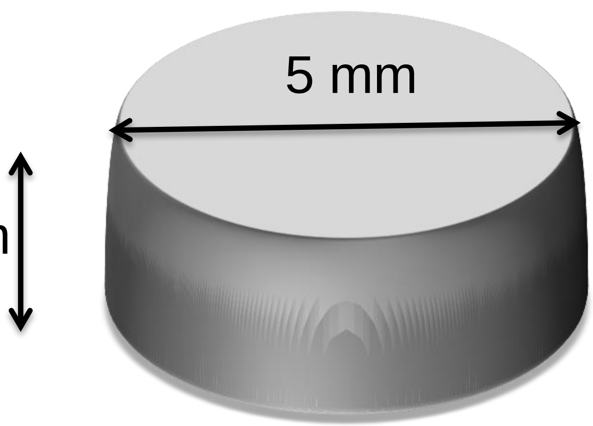
Daddy, why do people care about root hairs?

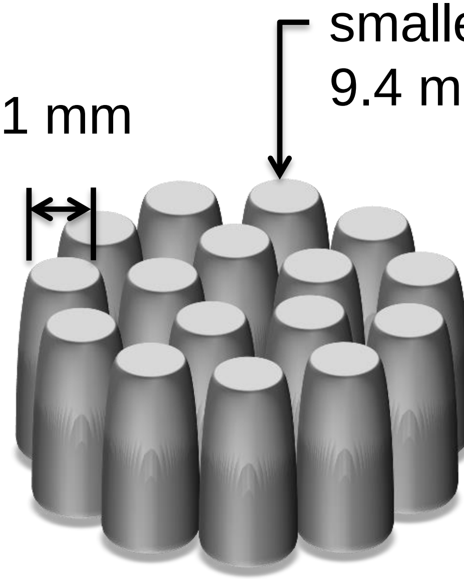
Root Hairs Increase Surface Area:
Concepts

A larger number of smaller diameter roots increases surface area, providing more nutrient absorption.

Conceptual example (larger scale):



Surface area: 47 mm^2



Surface area: 151 mm^2

Root Hairs Increase Surface Area:
Observations

Genotype	Root hair length (mm)	Number of root hairs (per mm of root length)	Inrease in surface area due to root hairs (%)
Winter wheat			
Kraka	1.27 ± 0.26	38 ± 3	341
Foreman	0.74 ± 0.25	25 ± 2	142
Kosack	0.49 ± 0.20	24 ± 3	95
Spring barley			
Canut	1.00 ± 0.24	31 ± 1	245
Alexis	0.64 ± 0.19	30 ± 2	143

Average root diameter = 0.16 ± 0.04 mm
Average root hair diameter = 0.012 ± 0.001 mm

Gahoonia, T.S et al. 1997. Root hairs and phosphorus acquisition of wheat and barley cultivars. Plant Soil 191:181-188.

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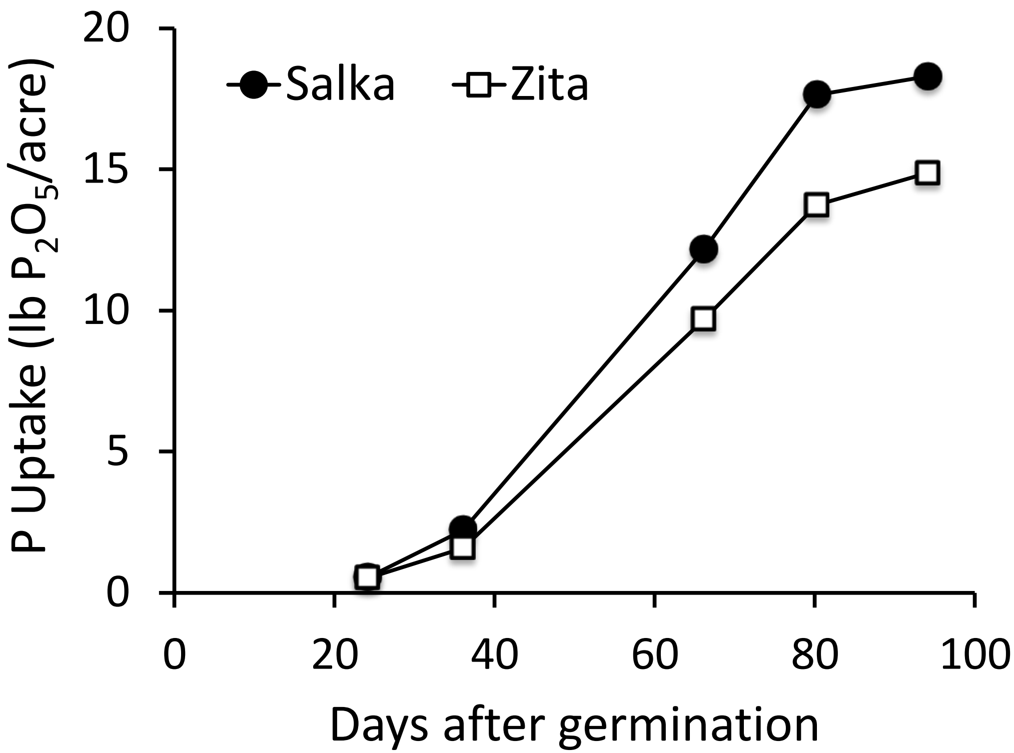
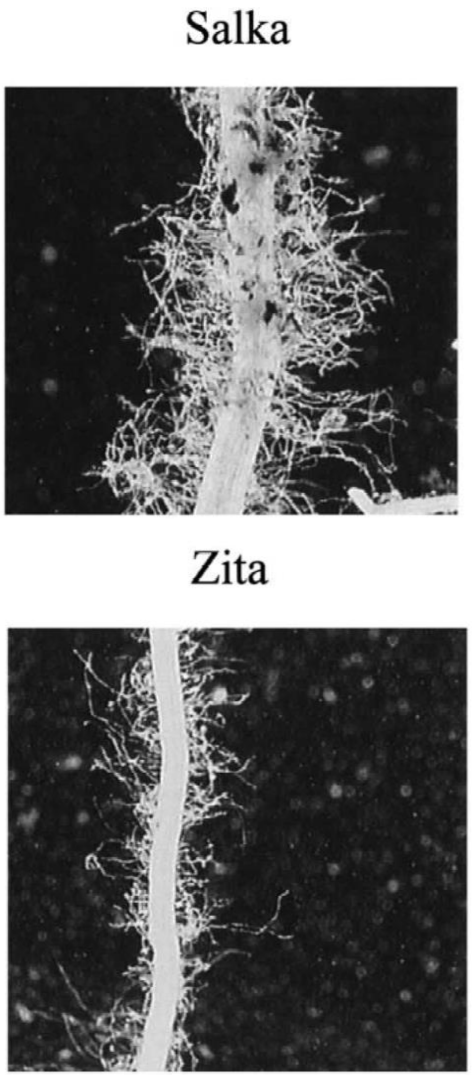
Differences in Root Hair Density:
Barley





Gahoonia, T.S. et al. 2001. A root hairless barley mutant for elucidating genetic of root hairs and phosphorus uptake. Plant Soil 235:211-219.

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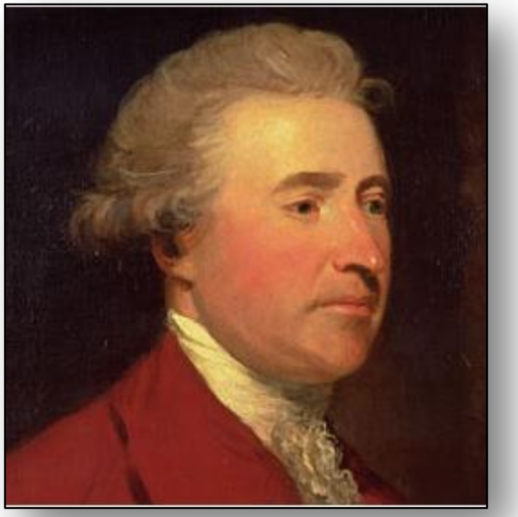
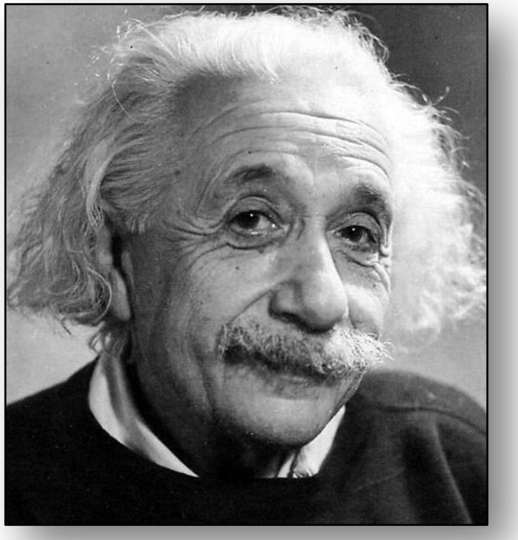


“It’s a miracle curiosity survives formal education.”

-- Albert Einstein




MAP OF THE
UNITED STATES
AND
TERRITORIES.
TOGETHER WITH
CANADA &c.
BRITISH AMERICA
UNITED STATES
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
MEXICO
NEBRASKA
COLORADO
KANSAS
OREGON
MONTANA
ARIZONA
NEW MEXICO
TEXAS
INDIAN TERRITORY
ISLAND OF NEWFOUNDLAND
SCALE OF MILES.
Constructed & Engraved by W. Williams Philadelphia.

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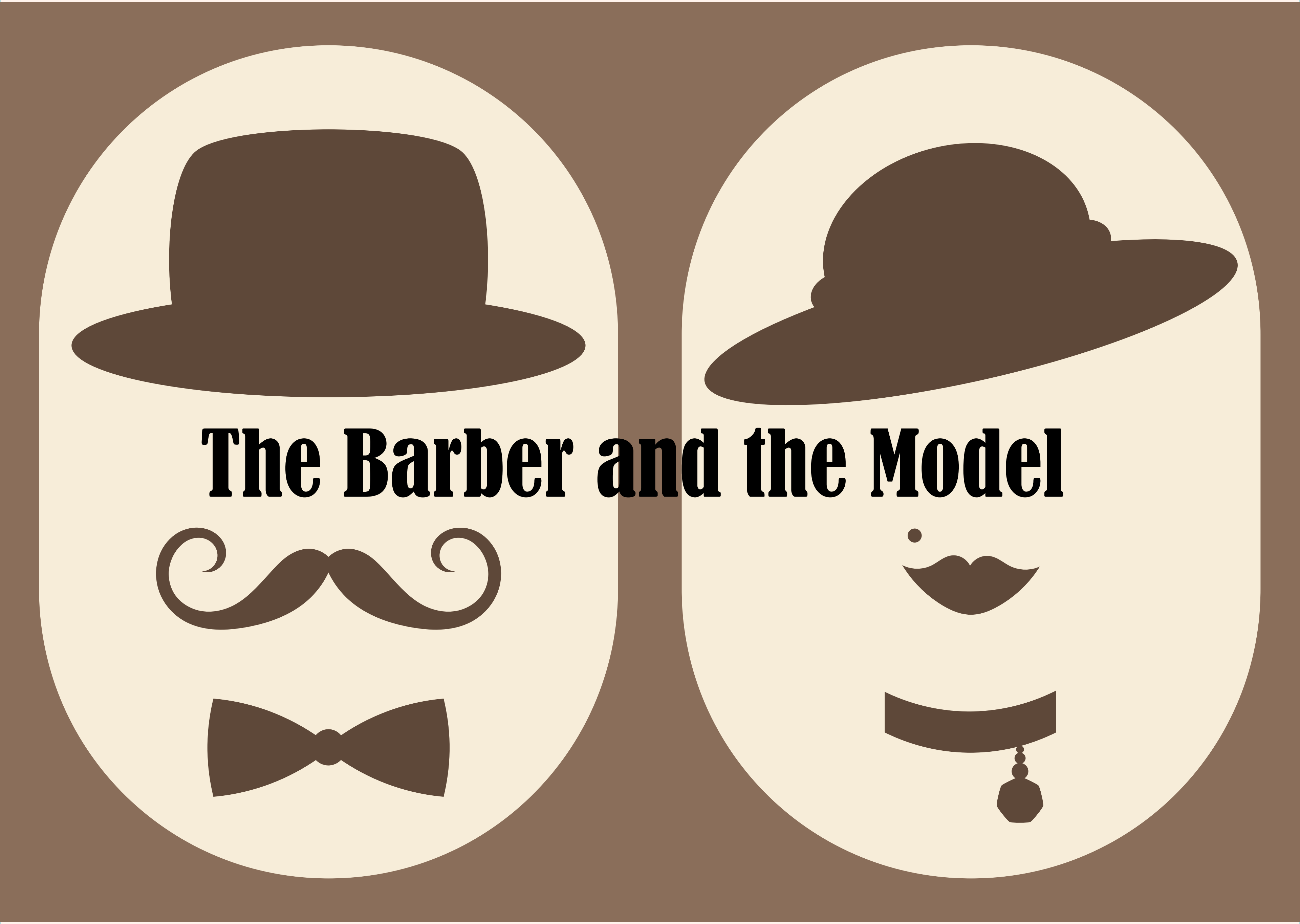
Photo: Richard Lund


The Barber and the Model

Dr. Barber and the Phosphorus Uptake Model

Dr. Stan Barber

Simulation Model for Nutrient Uptake from Soil by a Growing Plant Root System[1]

N. Caassen and S. A. Barber[2]

ABSTRACT

Mathematical models of nutrient uptake by plants are useful for investigating the effect of various soil and plant factors on nutrient flux to plant roots. The objective of this research was to develop a model based on theoretical considerations of the processes of nutrient uptake by plant roots growing in soil and then to test the model experimentally. The soil and plant factors used in the model were to be measured independent of final nutrient uptake.

The model for flux by mass flow and diffusion to the root was patterned after that of Nye and Marriott. The absorption kinetics of the root were assumed to follow Michaelis-Menten kinetics. The Nye-Marriott model gives the nutrient concentration at the root with time. From this accumulated uptake per cm^2 of root surface with time was calculated. Rate of root growth was assumed exponential for the growth of the young plant. Uptake per cm^2 of root with time was combined mathematically with rate of root growth to get total uptake with time by the plant. The present program assumes root hairs do not affect uptake and that roots do not compete for nutrients.

A computer program was written for solution of the mathematical model. The factors required in the model from the soil are: effective average diffusion coefficient, initial nutrient concentration in solution, and buffering capacity. For the plant they are: the relation between nutrient concentration in solution and net influx into the root, water influx, root radius, initial root length, and rate of root growth.

The model was tested for measuring K uptake by corn (*Zea mays* L.) from eight different soil-K combinations. The corn was grown in a growth chamber and K uptake was measured for the period of plant growth from 4 to 10 and 13 days. The calculated uptake, y, was correlated with observed uptake, x, by the equation $y = 0.155 + 1.566 \times$ ($R^2 = 0.87$) where y and are µmoles of K/plant. Calculated uptake was overestimated by about 50%, possibly because competition occurred between roots for soil K and K was not absorbed by the root as fast at night as in the day.

The model should be useful for investigating the principles of nutrient absorption by plant roots from soil which can be used for developing more efficient systems of fertilizer application.

Additional index words: Potassium, *Zea may* L., Diffusion, Mass-flow, Buffering capacity.

NUTRIENT absorption by plant roots growing in soil depends on (i) the morphology and rate of growth of the root system, (ii) the nutrient absorption characteristics of the root system, and (iii) the nutrient supply characteristics of the soil. In order to investigate the effect of these factors in an organized way it is helpful to have a mathematical model based on fundamental principles that organizes the mechanisms involved in the process of ion uptake by plant roots growing in soil.

Mathematical models have been proposed for measuring nutrient fluxes to plant roots. These have been reviewed by Olsen and Kemper (1967), Barley (1970), and Helyar and Munns (1975). Only the model of Brewster et al. (1975) has been used to relate predicted uptake to that observed during plant growth. The objective of this research was to develop a model based on theoretical considerations of nutrient uptake from soil and then to test the model experimentally. The model was to calculate uptake for those nutrients where mass-flow and diffusion are the main mechanisms of supply and supply by root interception is minimal.

DEVELOPMENT OF THE MODEL

Equation [1] from Nye and Marriott (1969) was the equation used to describe the flux of nutrients to the root by mass-flow and diffusion.

$$\frac{\partial C_l}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r D \frac{\partial C_l}{\partial r} + \frac{v_0 r_0 C_l}{b}\right) \quad [1]$$

where r is the radial distance from the root axis, r_0 is the root radius, C_l is the ion concentration in soil solution. v_0 is the inward flux of water at the root surface, D is the differential diffusion coefficient in the soil, b is the differential buffer power, dC/dC_l, where C, the total diffusable K, was considered to be exchangeable plus solution K, and t is the time of uptake which is also the age of the root segment.

The initial boundary conditions describing the condition before flux occurs are:

$$t = 0,\ r > r_0,\ C_l = C_{li}$$

where C_{li} is initial ion concentration in the soil solution.

The second boundary condition relates the flux, i.e., rate of net influx, In, of the solute into the root to the solution concentration at the root surface. It can be described by Michaelis Menten kinetics after subtracting a term for efflux, E, as described by Claassen and Barber (1974).

$$In = \frac{Imax\ C_{l_0}}{Km + C_{l_0}} - E \quad [2]$$

where C_{l_0} is the ion concentration in soil solution at the root surface, Imax is the rate of influx at infinite concentration, and Km is the Michaelis constant

Accordingly, the second boundary condition is:

$$t > 0,\ r = r_0,\ Db\frac{\delta C_l}{\delta r} + v_0 C_l = \frac{Imax\ C_l}{Km + C_l} - E$$

As described by Nye and Marriott (1969), Imax and Km are assumed independent of v_0. D is assumed independent of v, water flux toward the root. Roots are assumed to be smooth cylinders with uniform uptake kinetics. Root hairs are not considered in the present model. D and b are assumed independent of concentration which implies that there is a linear relation between C and C_l over the range of interest. If this is not so, the values assigned to b and D should be averages for the concentrations considered. This was done in this research. No allowance for a change in Imax, Km, or E with age is made. However, if known, they can readily be included. In the test of this model, the plants were not older than 17 days and thus, most of the

[1] Journal Paper No. 6222. Purdue Univ. Agric. Exp. Stn., Lafayette, IN 47907. Contribution from the Dep. of Agronomy. This research was supported in part by the Tennessee Valley Authority and by United States Energy Research and Development Administration under Contract AT (11-1)-1495. Received 29 Mar. 1976.

[2] Former graduate assistant, Purdue Univ., now research agronomist, Fusagri, Cagua, Venezuela, and professor of agronomy, Purdue Univ., respectively.

Episode 1:

Where oh hair have you gone?


American

Nutrient movement TO roots:

$$\frac{dC_l}{dt} = \frac{d}{dr}\left[D \frac{dC_l}{dr} + v \frac{Cl}{b} \right]$$

Total nutrient uptake by the root system:

$U_n = U_o + \sum_{i=0}^{m-1} U_i$

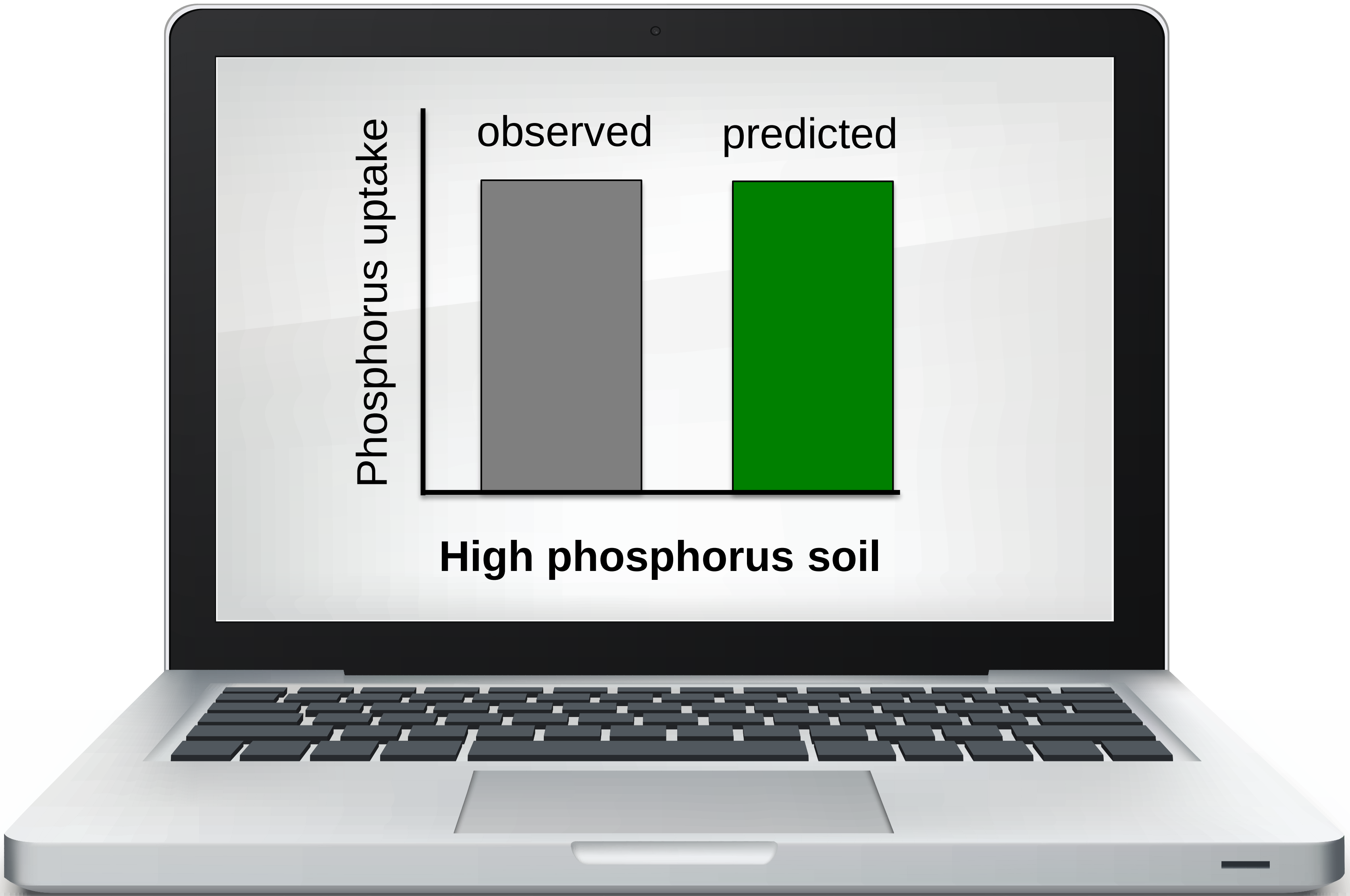
Nutrient uptake per unit root surface area:

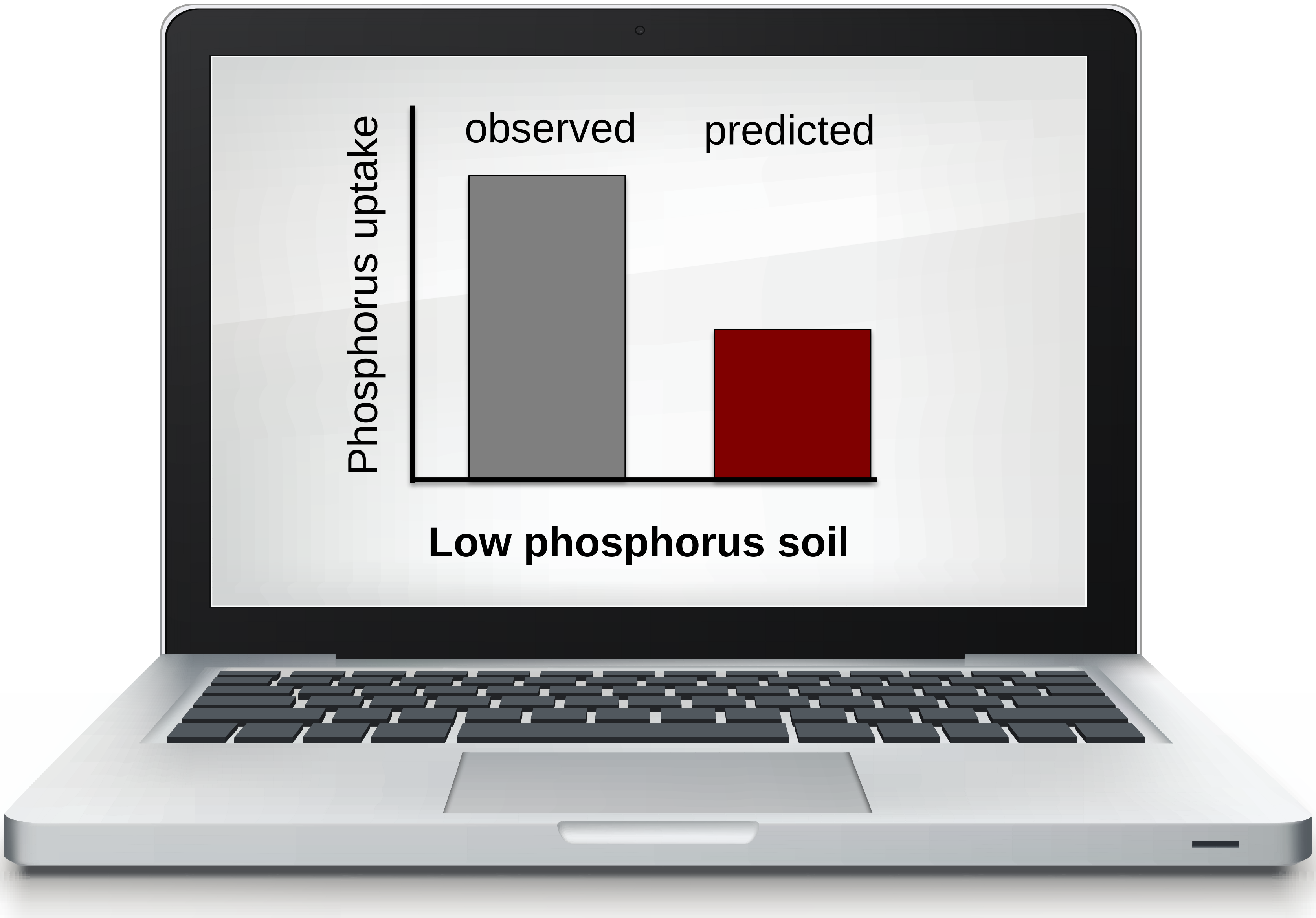
$In = \frac{I_{max} C}{K_m + C} - E$

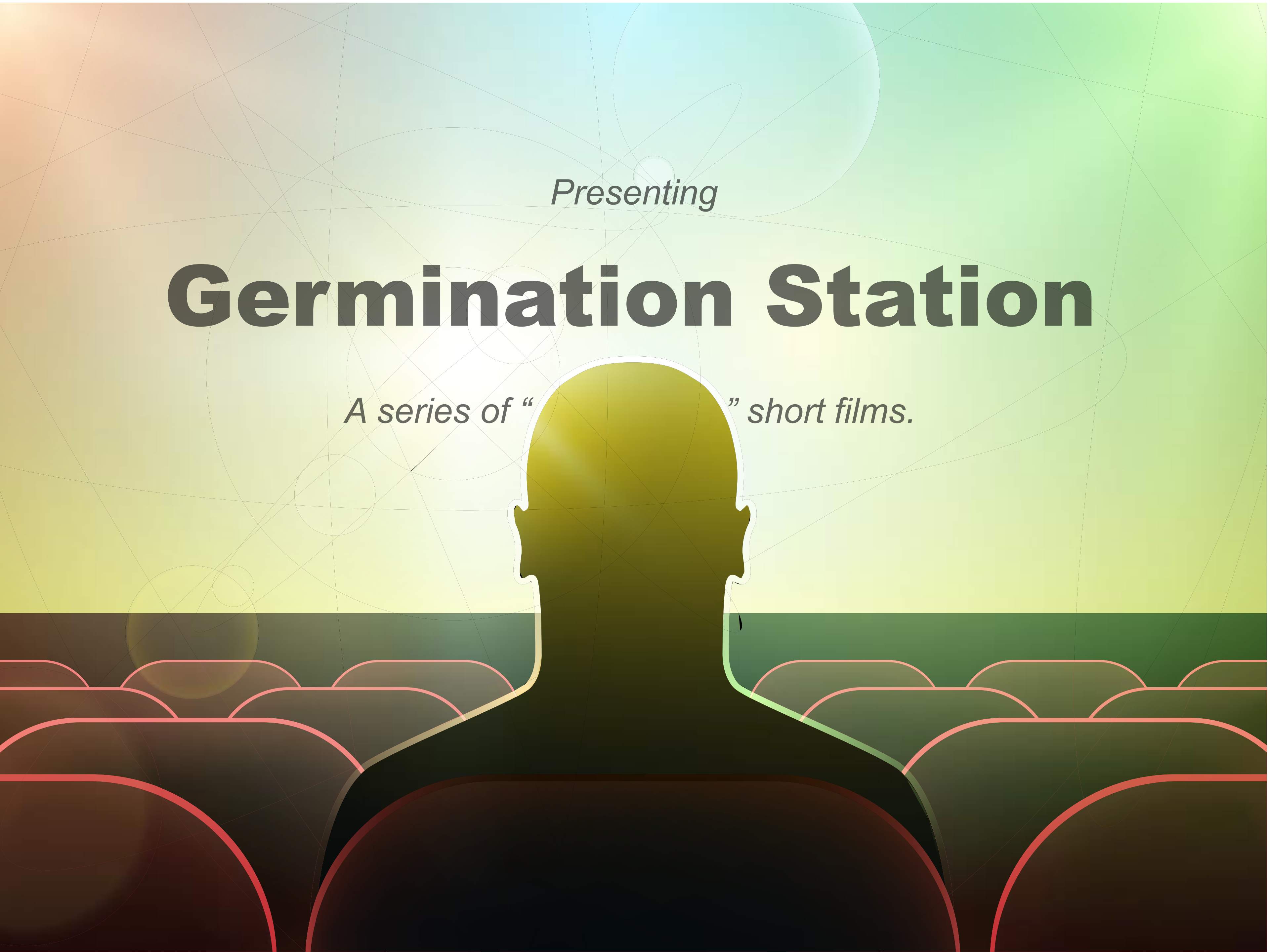
Total nutrient movement TO roots:

$V_m = \sum_{i=1}^{m} \ln \frac{C \Delta t_i}{C_o}$

Root = cylinder


observed
predicted
Phosphorus uptake
High phosphorus soil


Phosphorus uptake
observed
predicted
Low phosphorus soil


Presenting
Germination Station
A series of “ ” short films.

Root Hairs

Nutrient movement TO roots:

$$\frac{dC_l}{dt} = \frac{d}{dr}\left[r\, D \frac{dC_l}{dr} + v\, r\, Cl \right]$$

Total nutrient uptake by the root system:

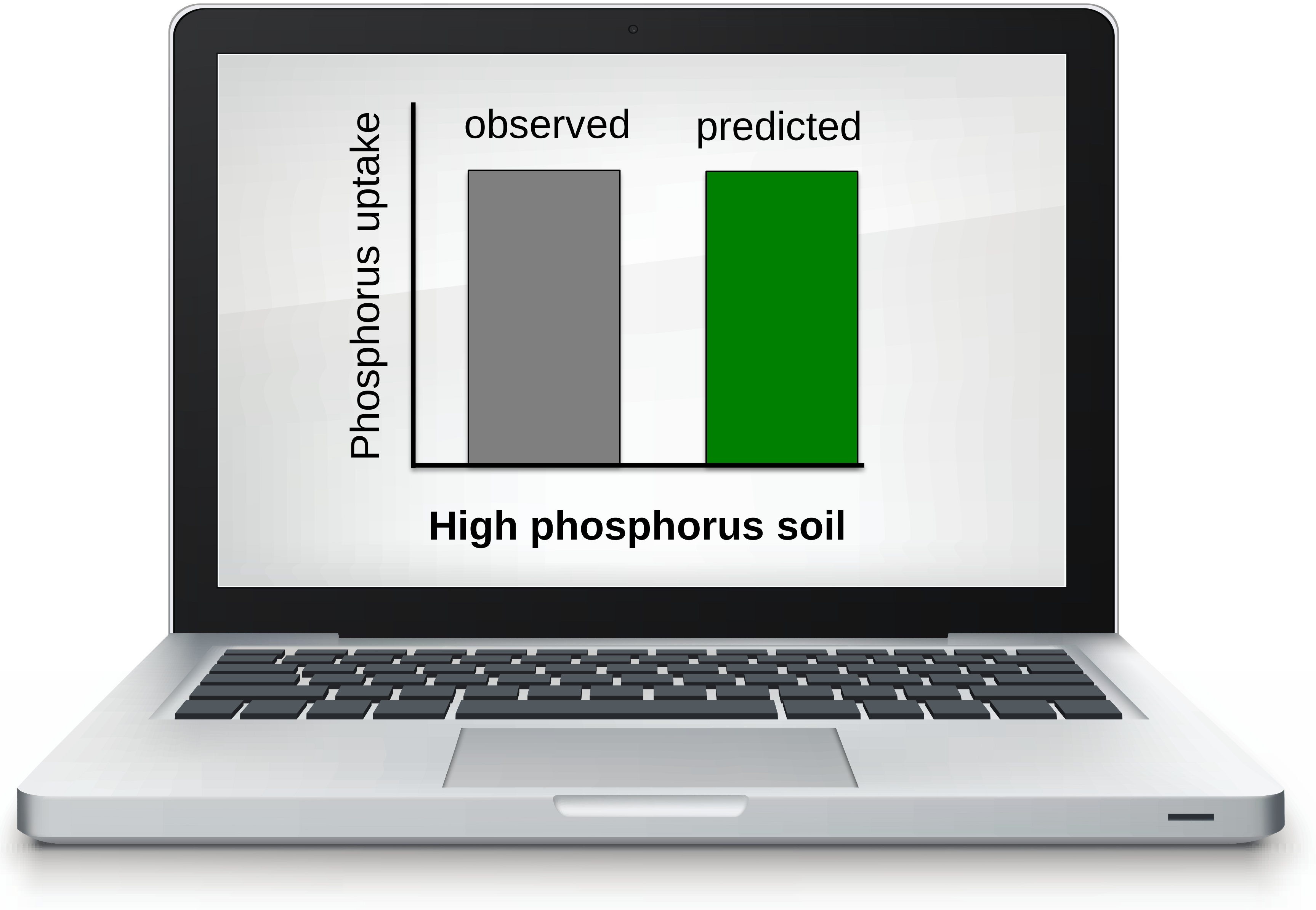
$$U_m - U_o = \sum_{i=0}^{m-1} U_i$$

Nutrient uptake per unit root surface area:

Total nutrient movement INTO roots:

V_m I_{max} C_b Δt_i K_m C_{lo} E

Root cylinder


observed
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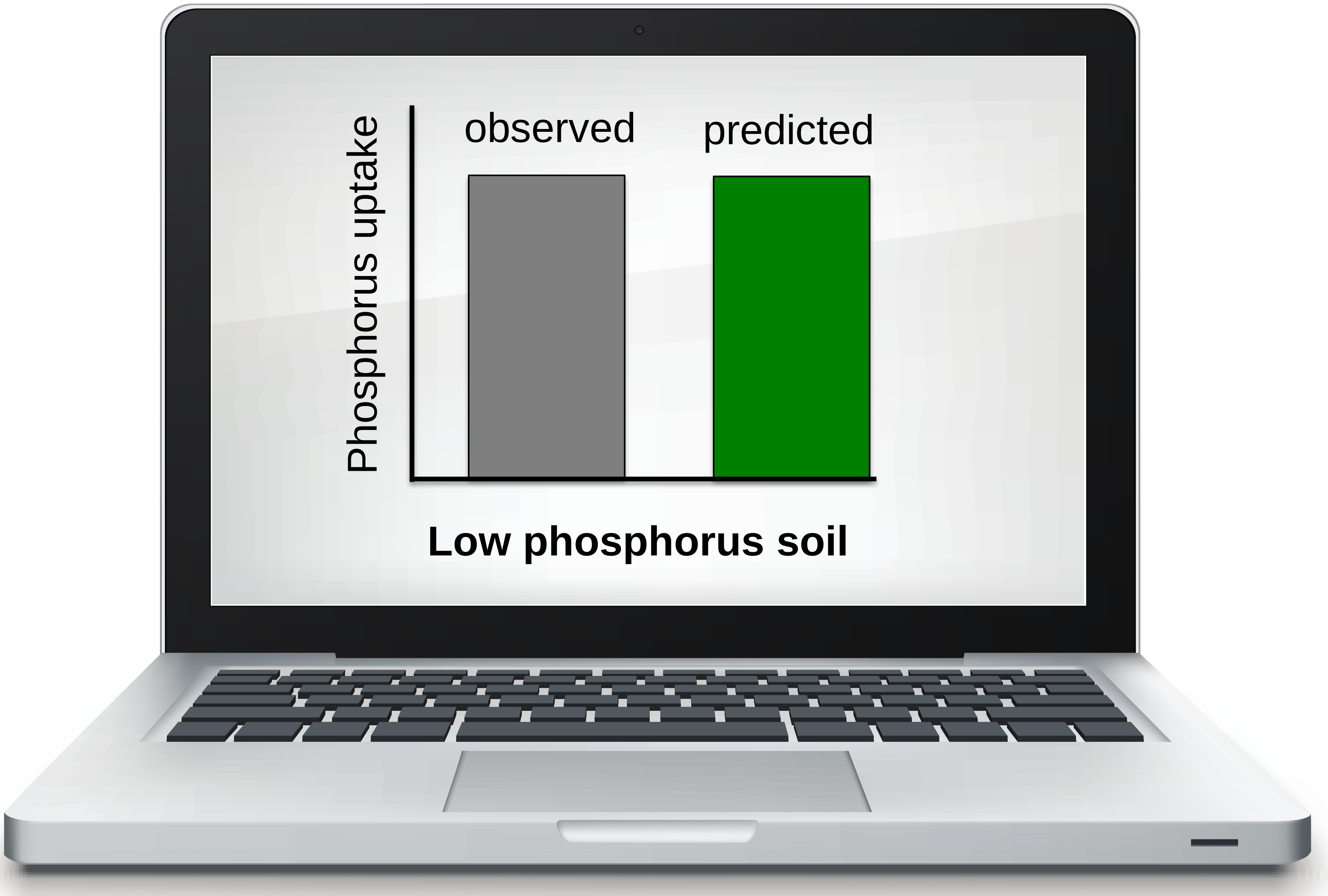
observed
predicted
Phosphorus uptake
Low phosphorus soil

Studies Referenced

- The first try:

  Schenk, M.K. and S.A. Barber. 1979. Root characteristics of corn genotypes as related to P uptake. Agron. J. 71:921-924.

- The second try:

  Itoh, S. and S.A. Barber. 1983. A numerical solution of whole plant nutrient uptake for soil-root systems with root hairs. Plant Soil 70:403-413.

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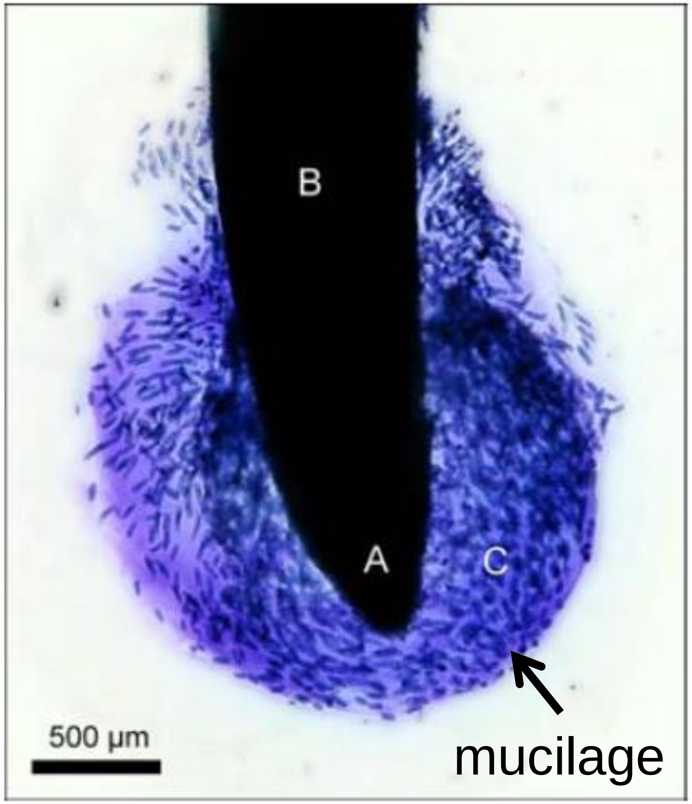
Root Exudates

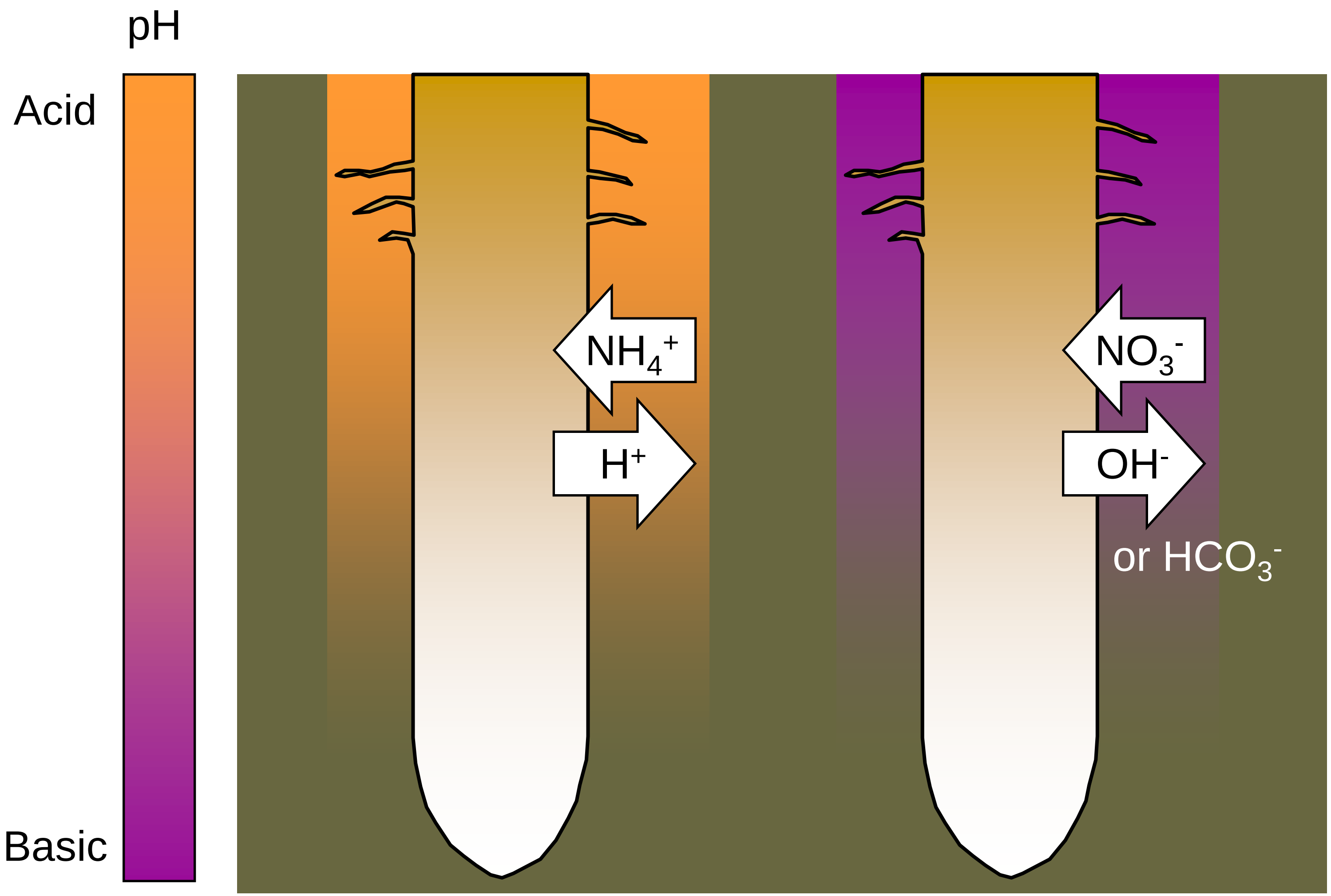
Root Exudates

- Root exudates are biologically active compounds that are released by plant roots. They serve a variety of functions:
  - Attract or repel organisms
  - Selectively inhibit fungal and bacterial growth
  - Stimulate the microbial community around the root
  - Form complexes with metals that keep them from damaging the root tip
  - Reduce friction between root and soil



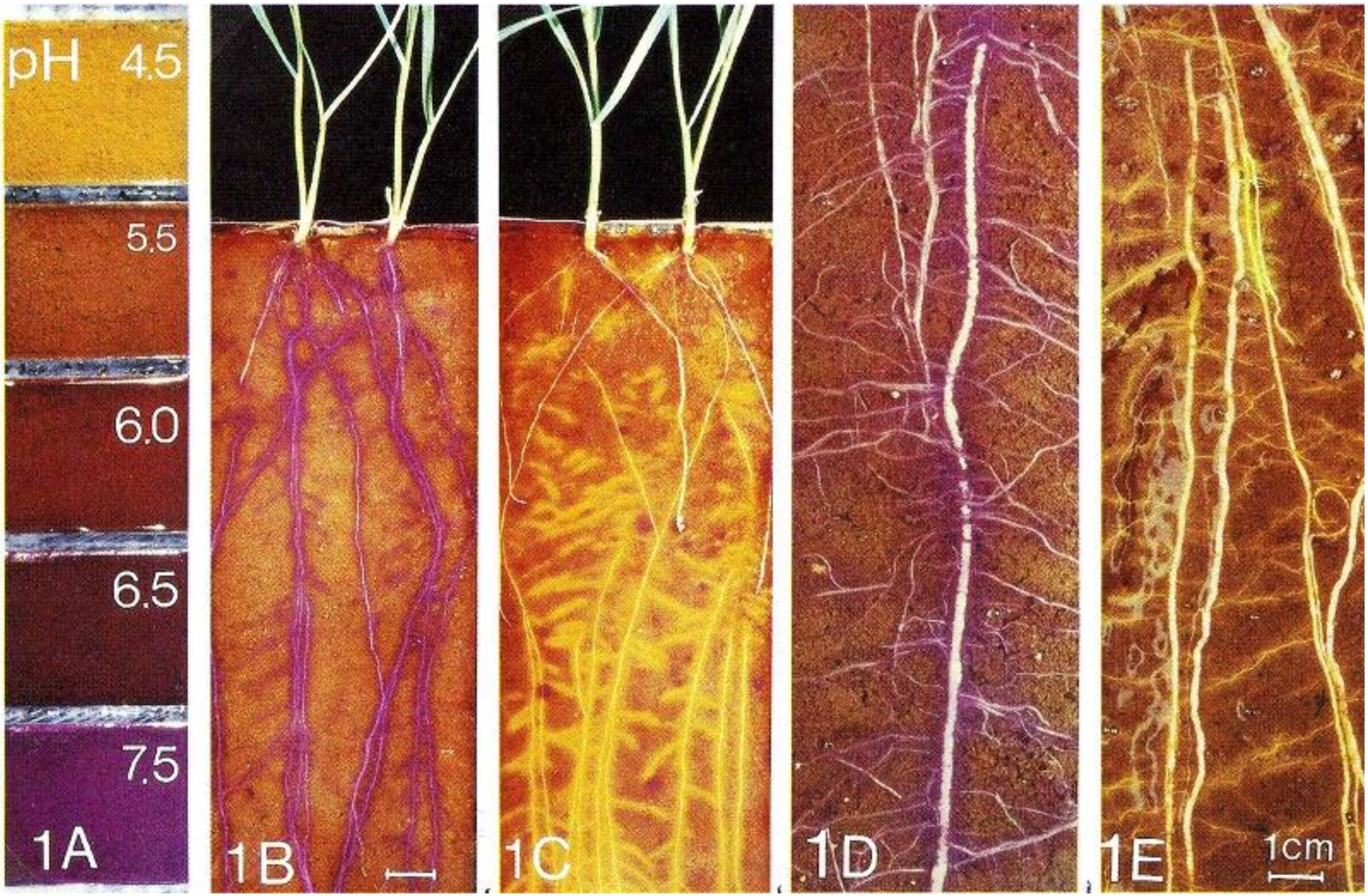
Baetz, U. and E. Martinoia. 2014. Root exudates: The hidden part of plant defense. Trends Plant Sci. 19(2):90-98.
Jones et al. 2009. Carbon flow in the rhizosphere: Carbon trading at the root-soil interface. Plant Soil 321:5-33.

Ammonium and nitrate: rhizosphere pH differences



Marschner, 2002

Wheat – 2wks   Corn – 8 wks



Scale **NO_3-N** **NH_4-N** **NO_3-N** **NH_4-N**

200 kg N per ha

Rōmheld

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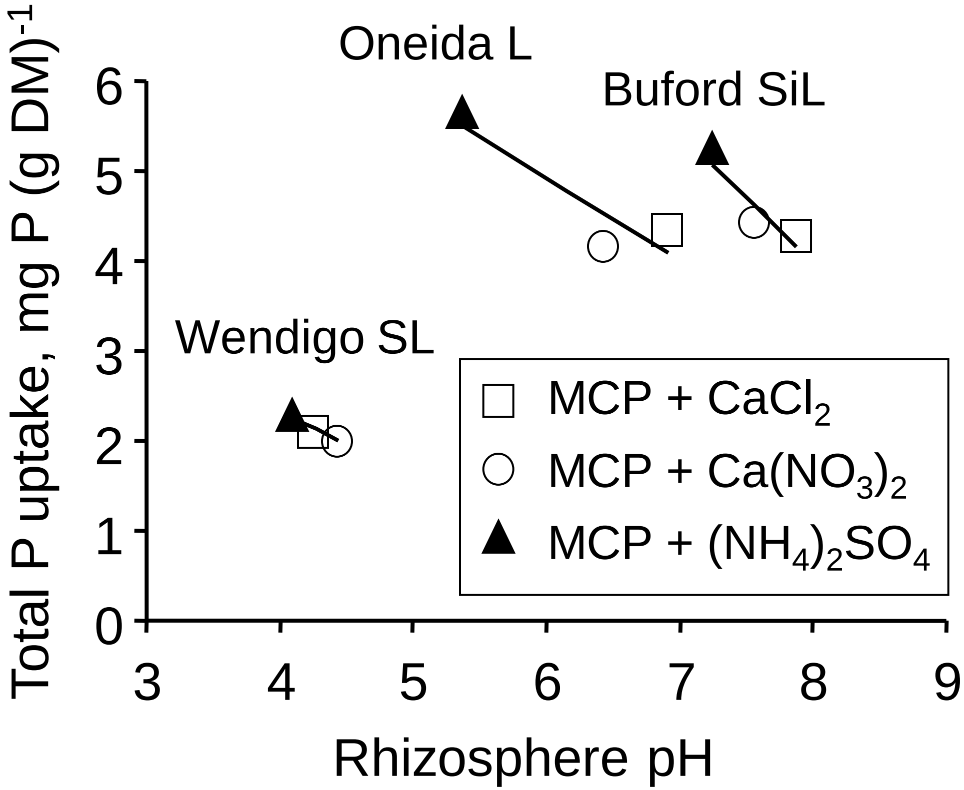
Lower Rhizosphere pH Increases P Uptake by Corn

- 11 day old corn
- Ammonium source reduced rhizosphere pH and increased P uptake

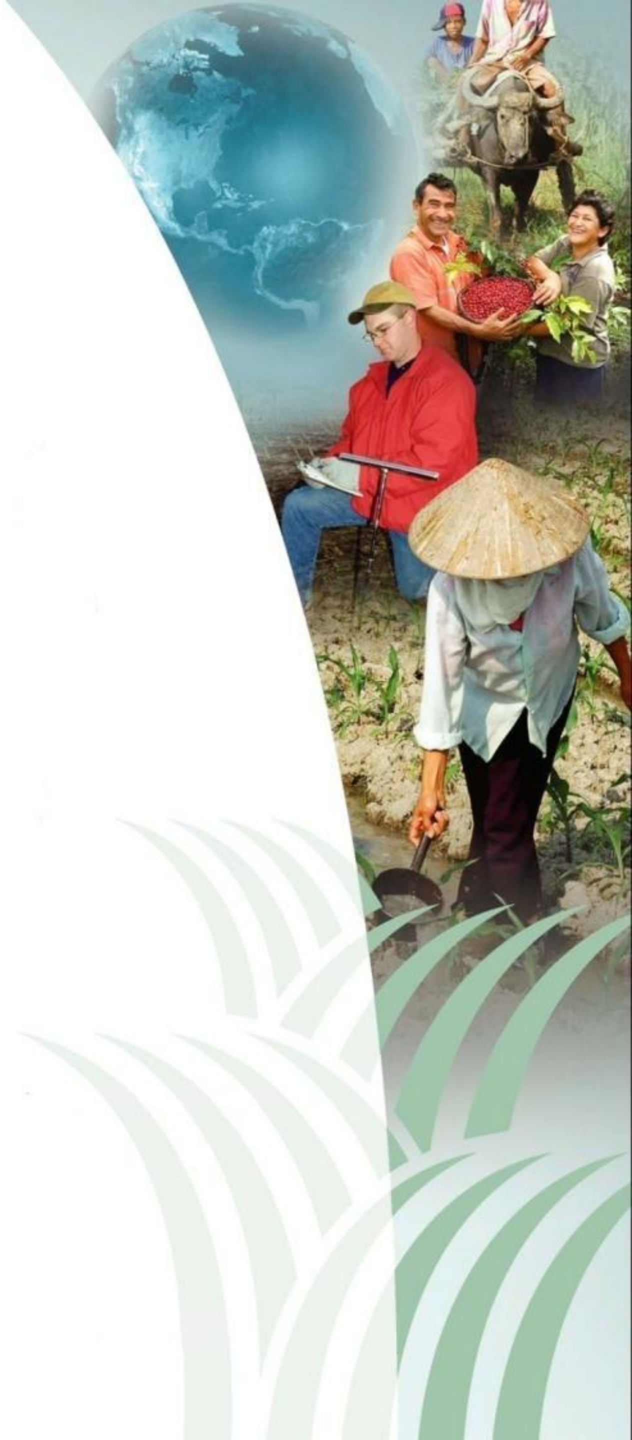


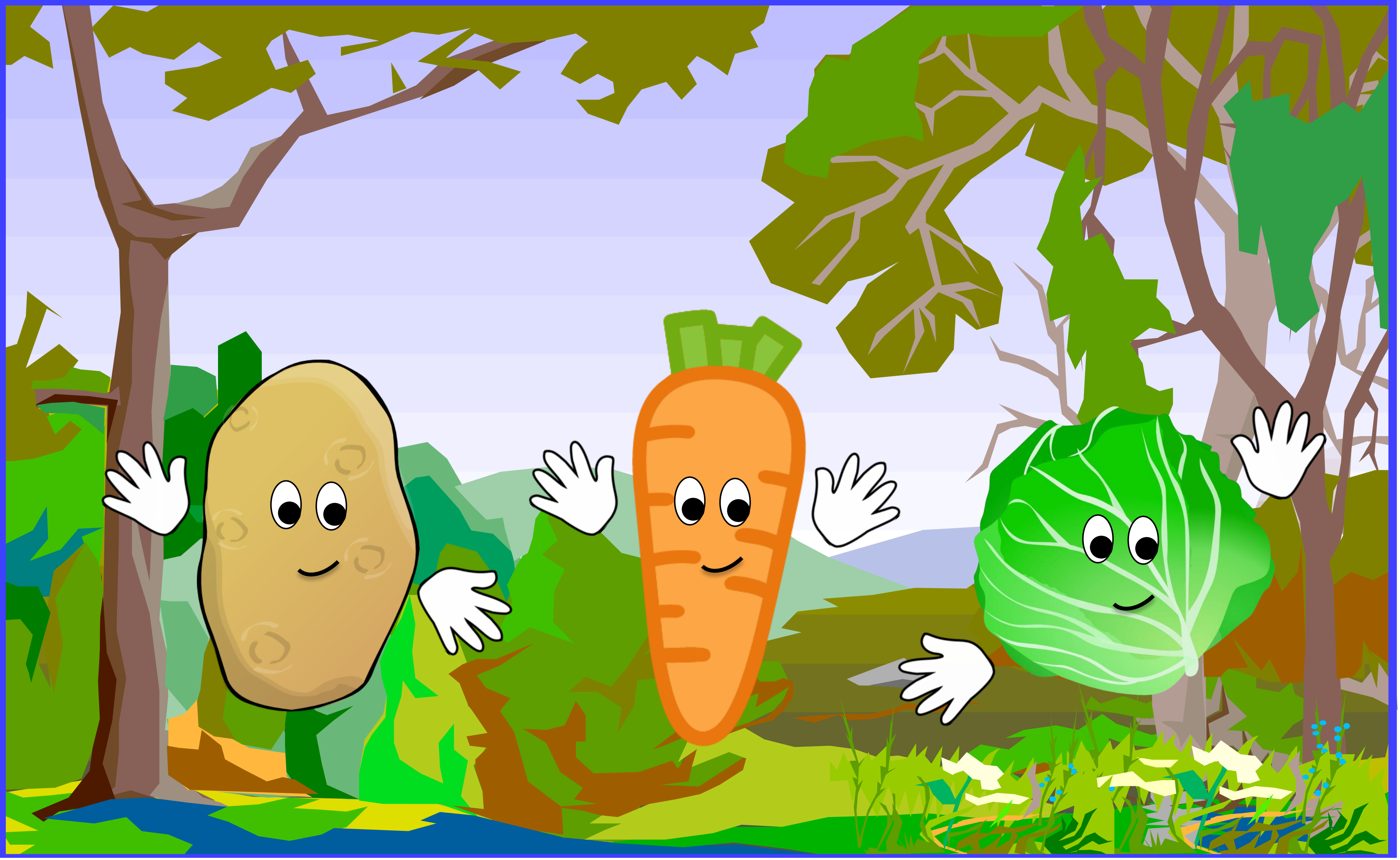
Soon, Y.K. and M.H. Miller. 1977. Soil Sci. Soc. Am. J. 41:77-80

The Three Vegetables Gruff

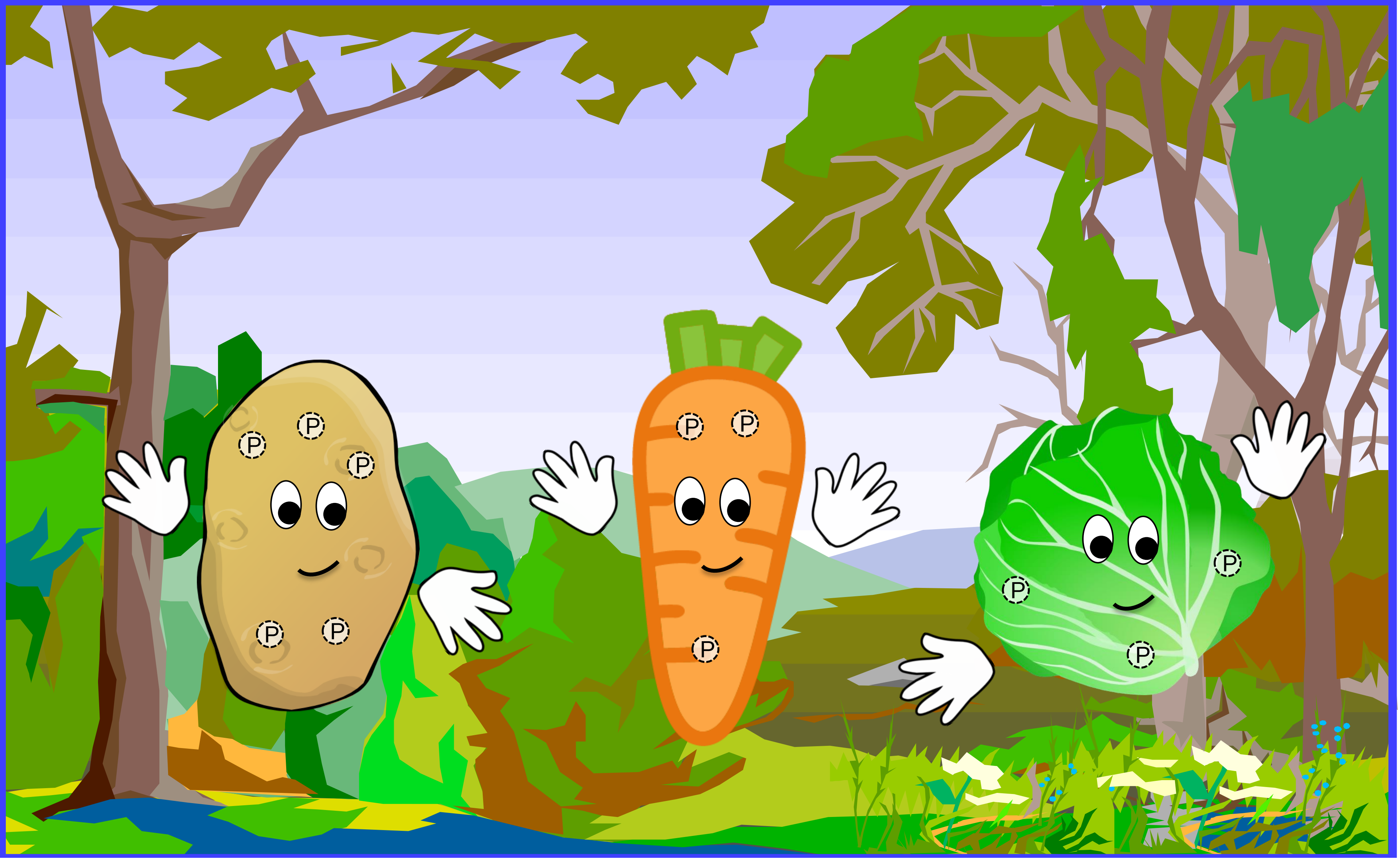
– OR –

Why Some Plants Differ In Their Ability to Take Up Phosphorus

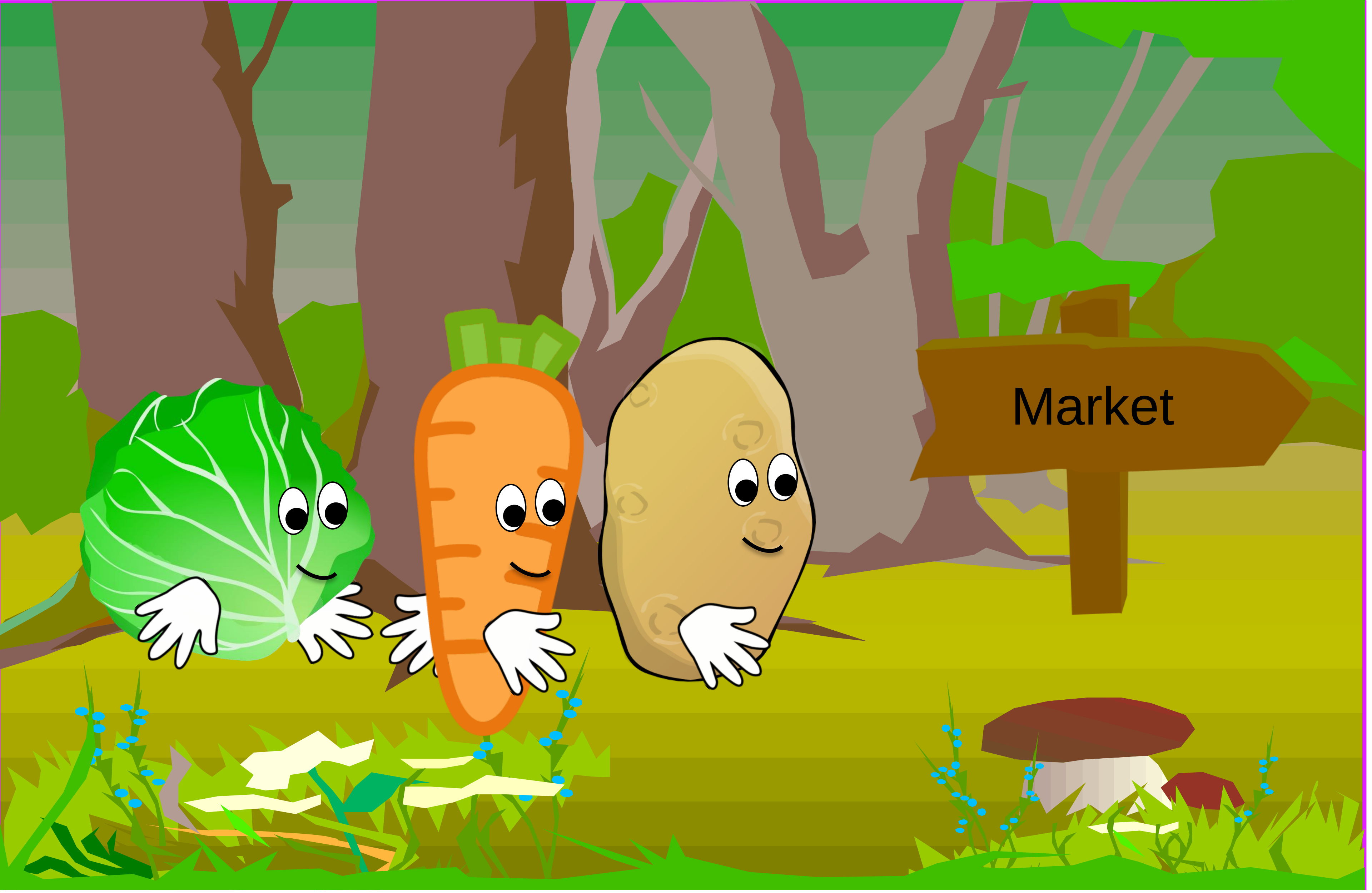




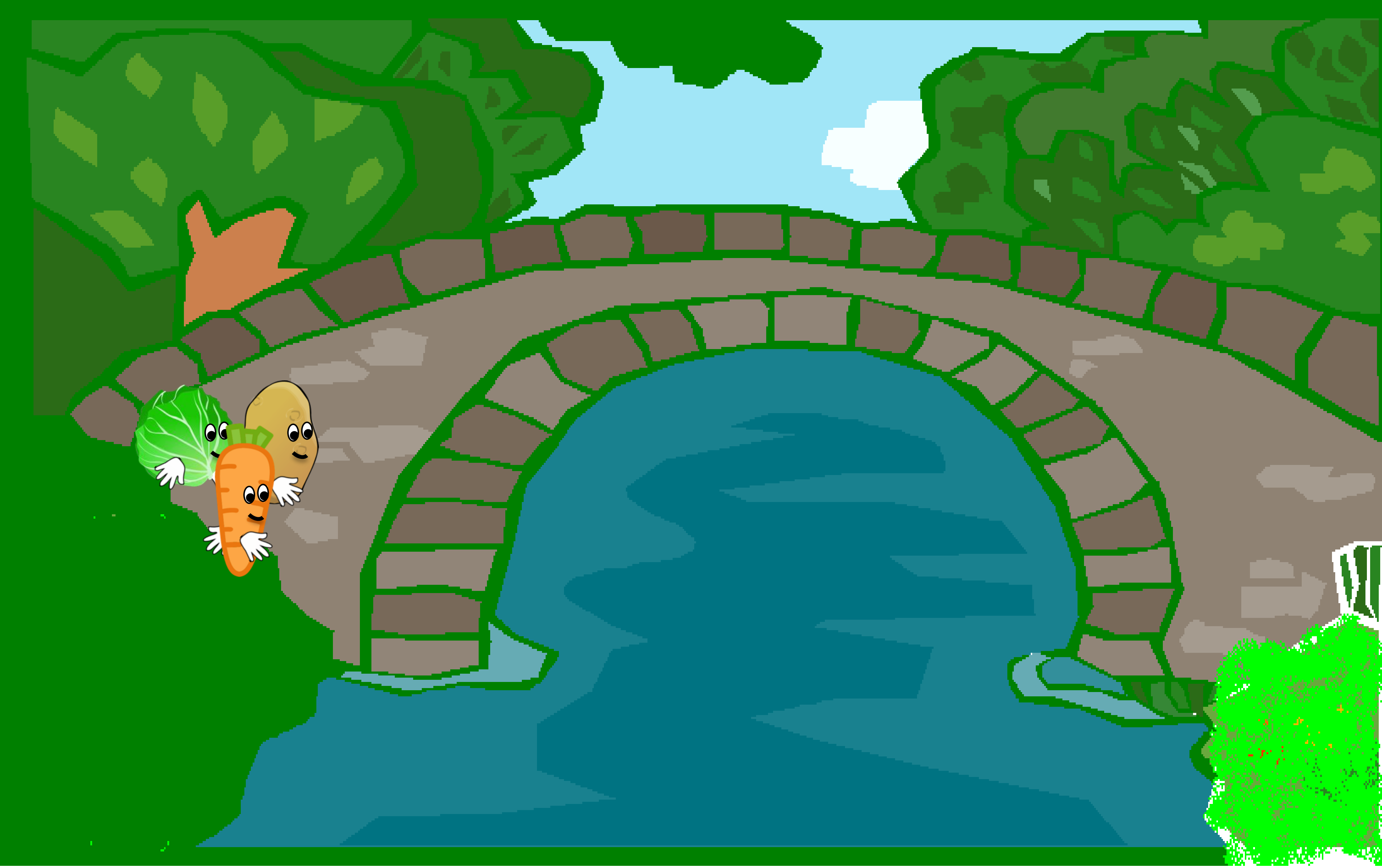
Once upon a time, there were three vegetables: Potato Gruff, Carrot Gruff, and Cabbage Gruff.



They each had nutrients inside them that came from the soil.
One nutrient in particular was phosphorus.



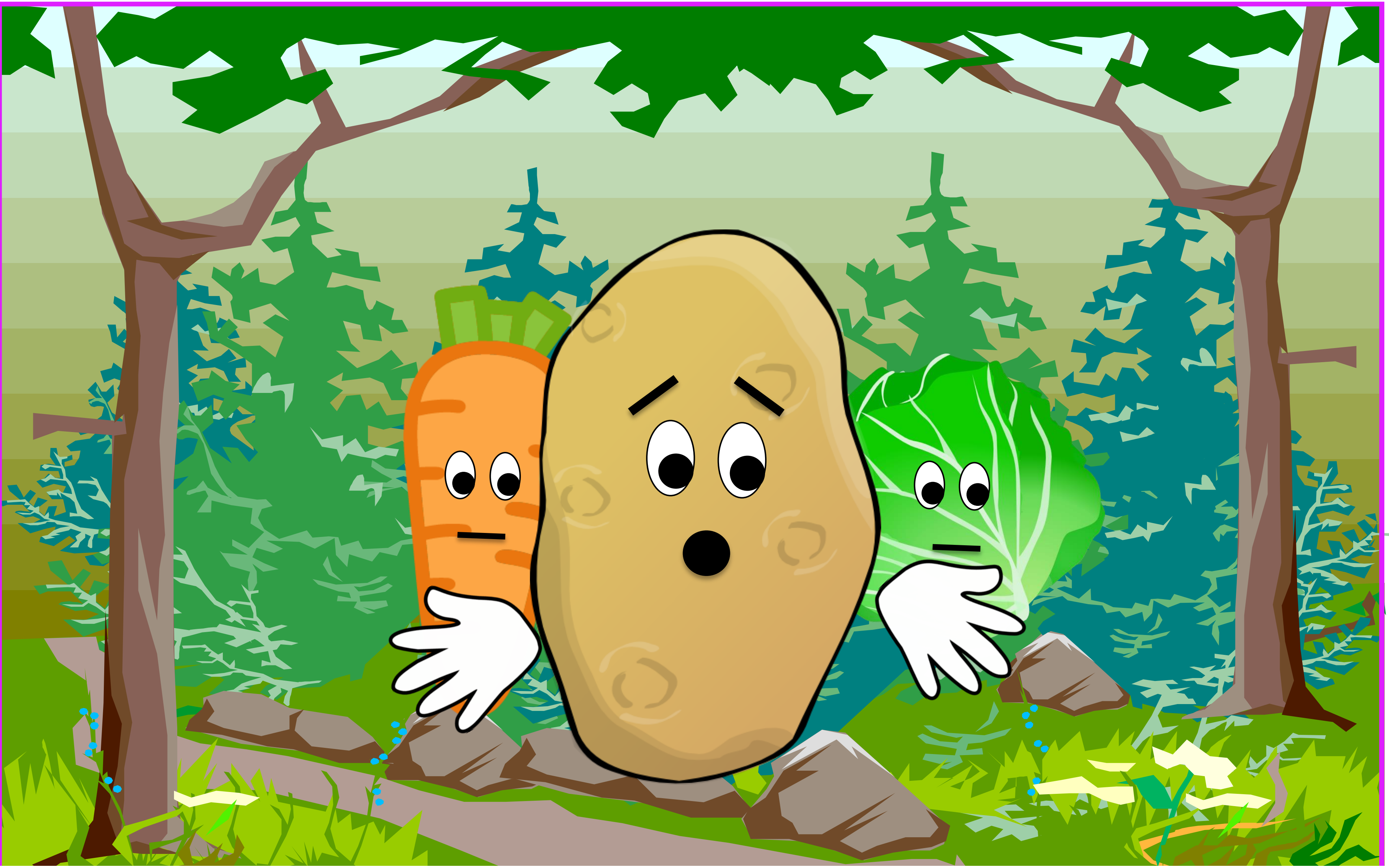
They were on their way to the market. No vegetables had come to the market in some time. No one knew why.



As they walked happily along, they came to a bridge.

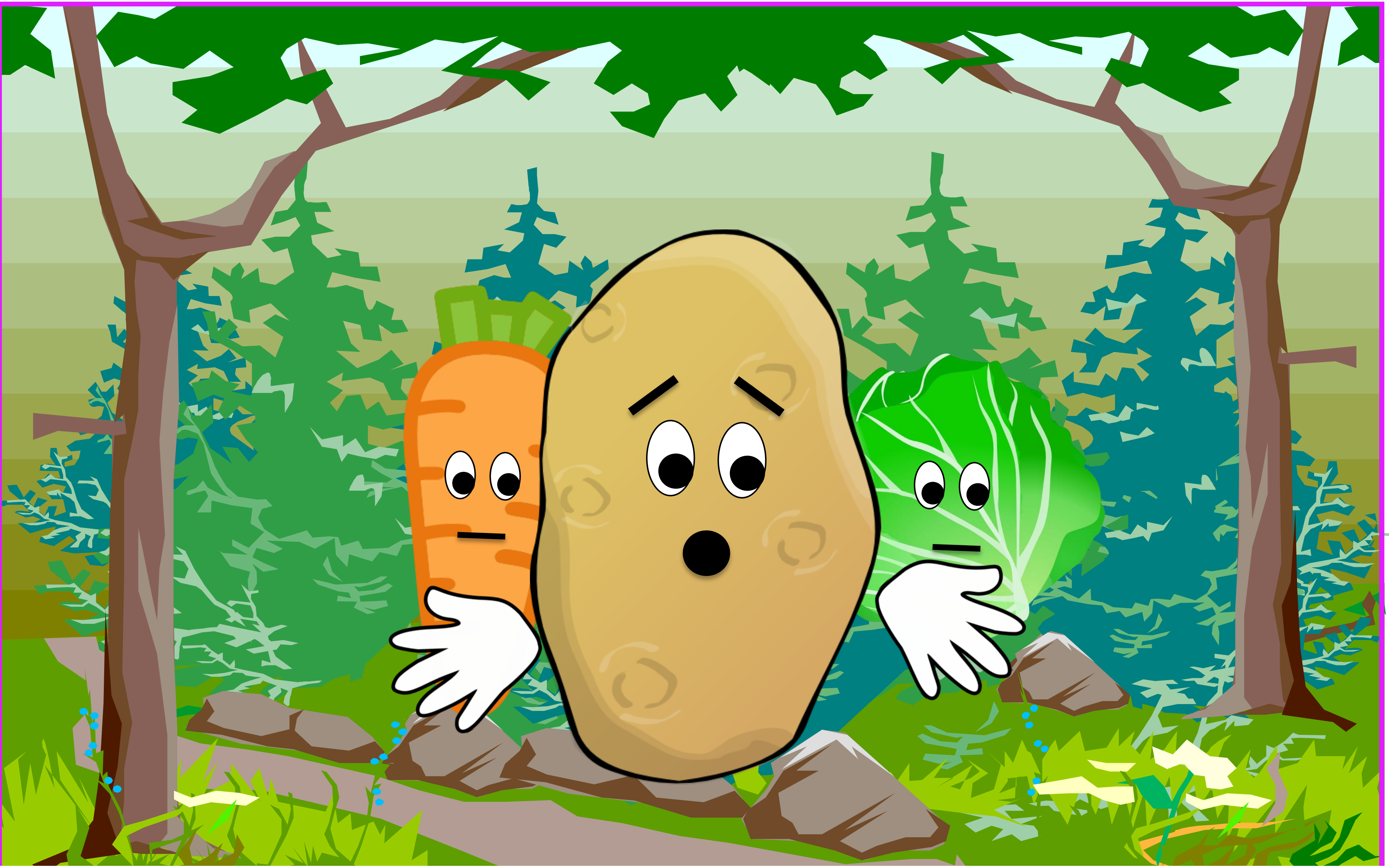
Suddenly, a troll appeared!

“**S***top!” yelled the troll. “You cannot pass!” I need your phosphorus to* keep my teeth strong! I must eat all of you!



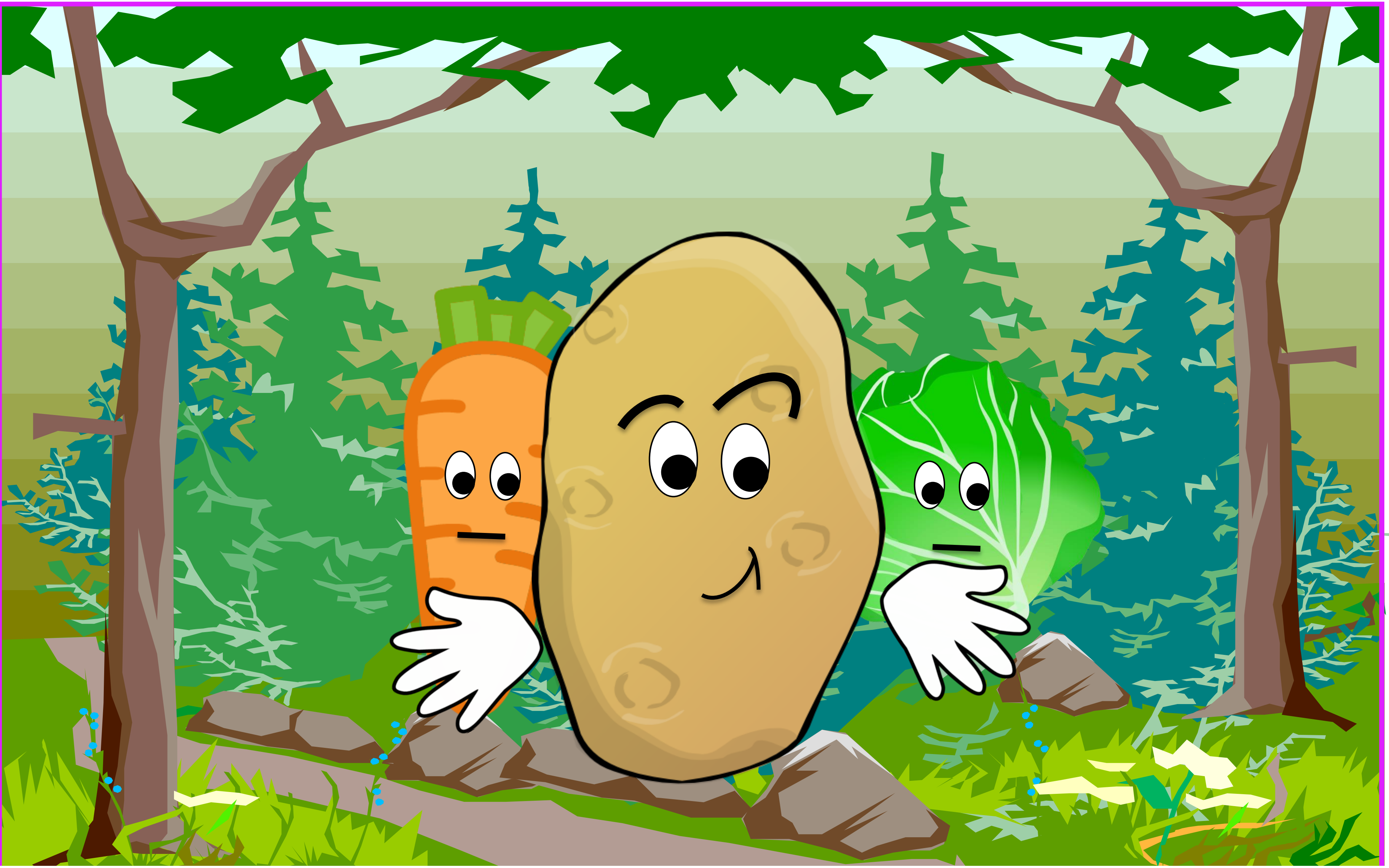
But we must go to the market! Isn't there some way we can pass?

"If I CAN'T guess how much phosphorus you have, then you may pass.



But what if you CAN guess how much phosphorus we have?

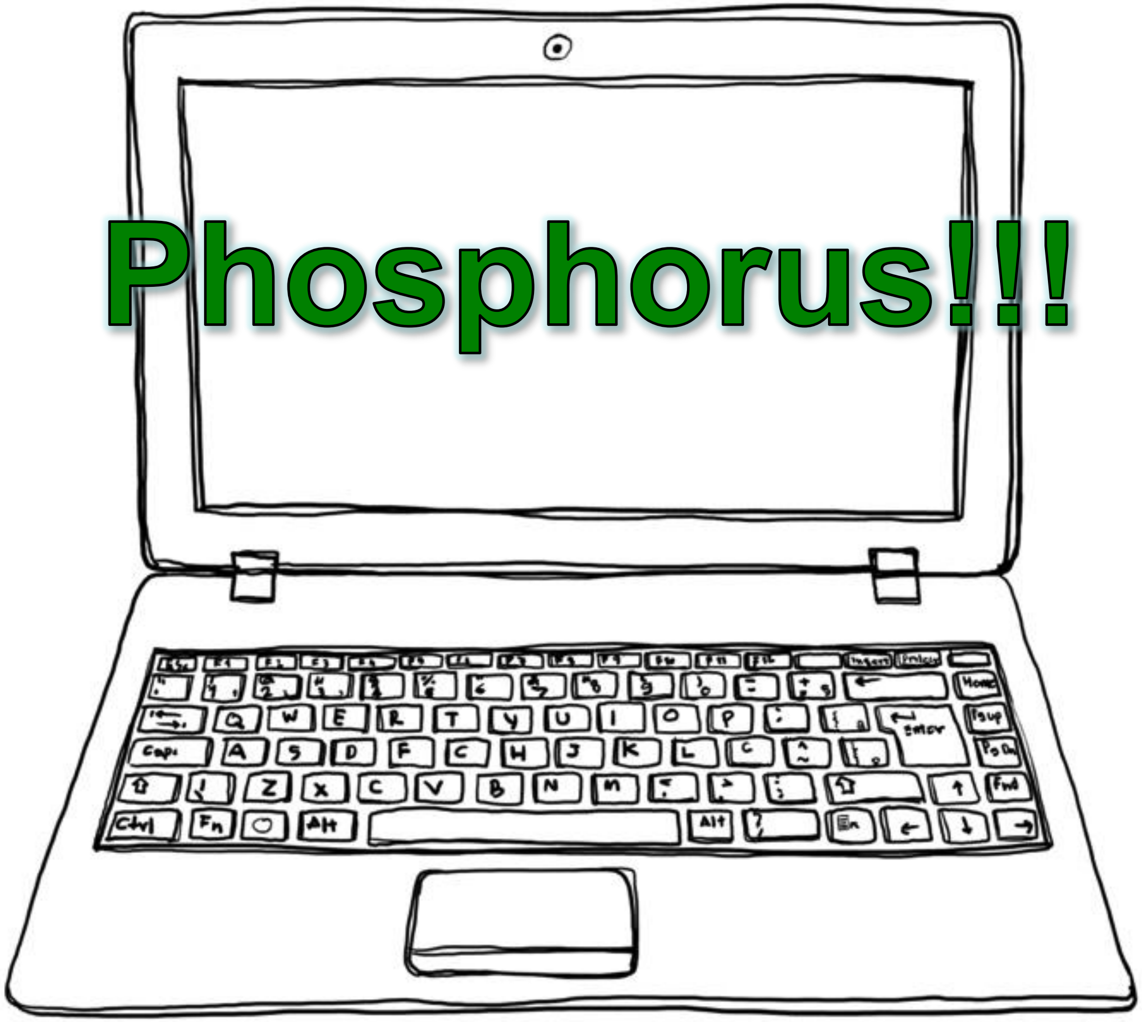
Then I will gobble you up!



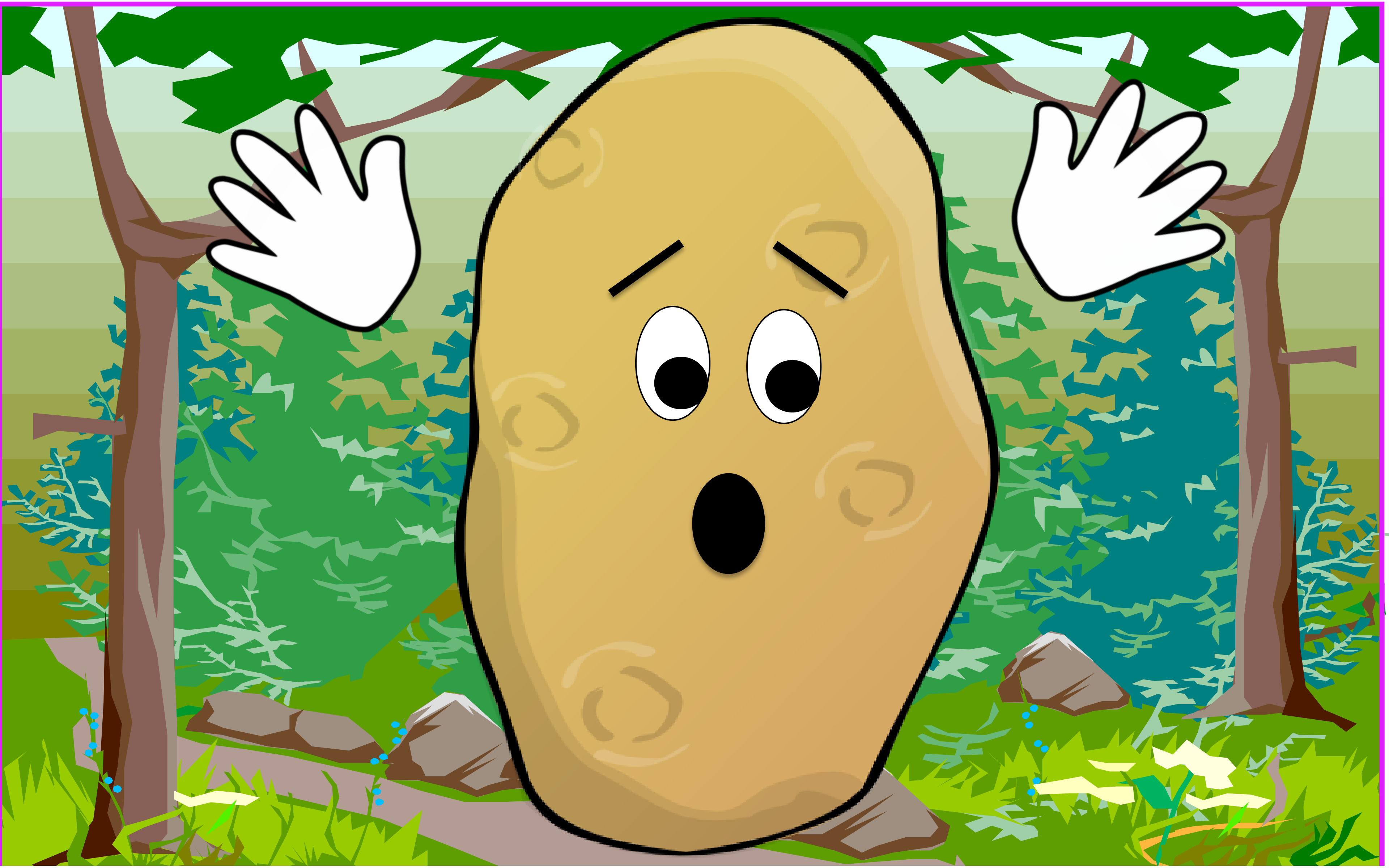
Potato Gruff was confident. How could the troll ever guess how much phosphorus he had? Phosphorus in vegetables cannot be seen! *"You're on!" said Potato Gruff.*

But this was a smart troll. He looked at Potato Gruff's roots. He looked at Potato Gruff's size. He guessed Potato Gruff's age. And then…

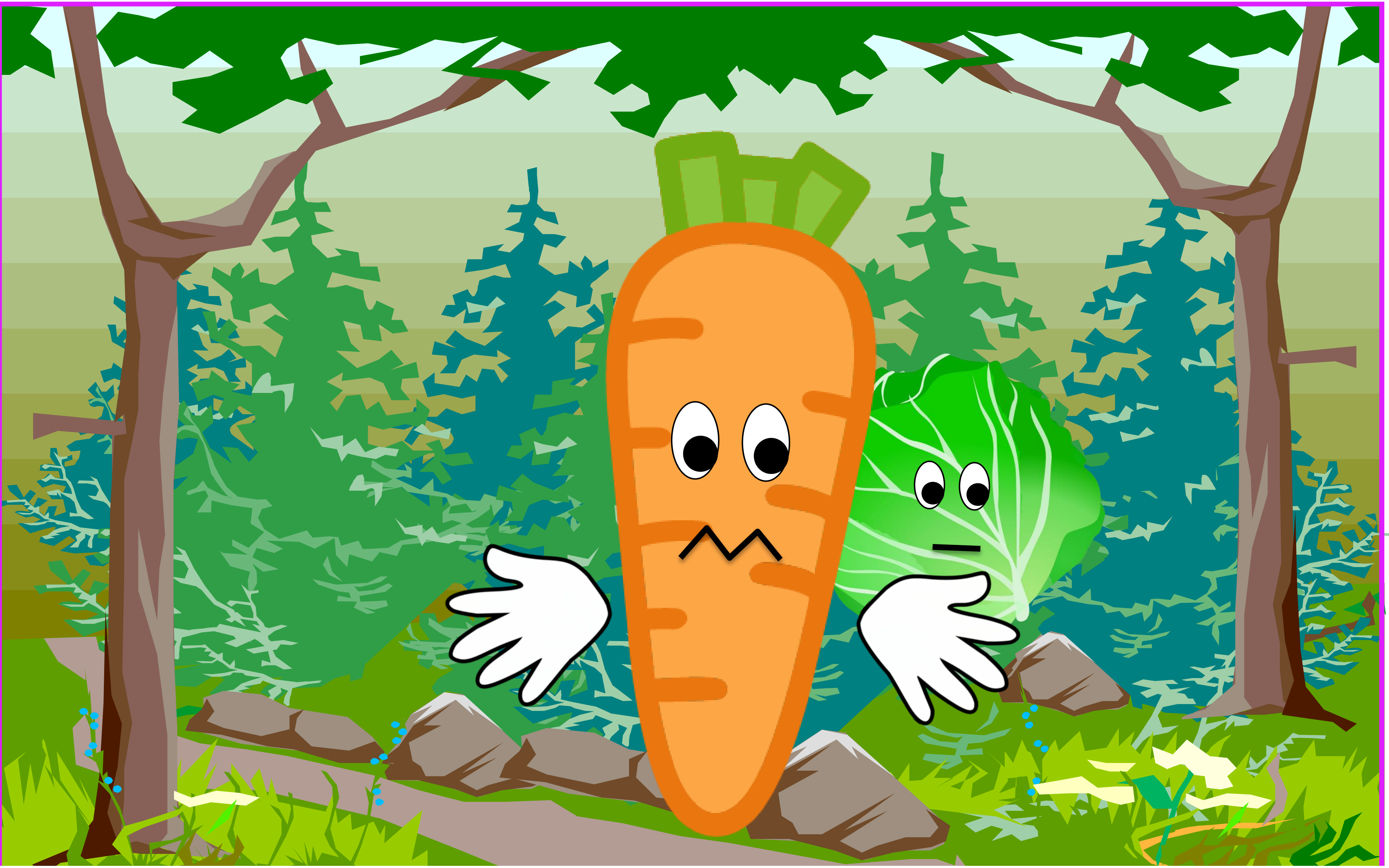
He ran a computerized phosphorus uptake model that guessed how much phosphorus there was!



The computer whirred and shook and shook and whirred and then spit out an answer!



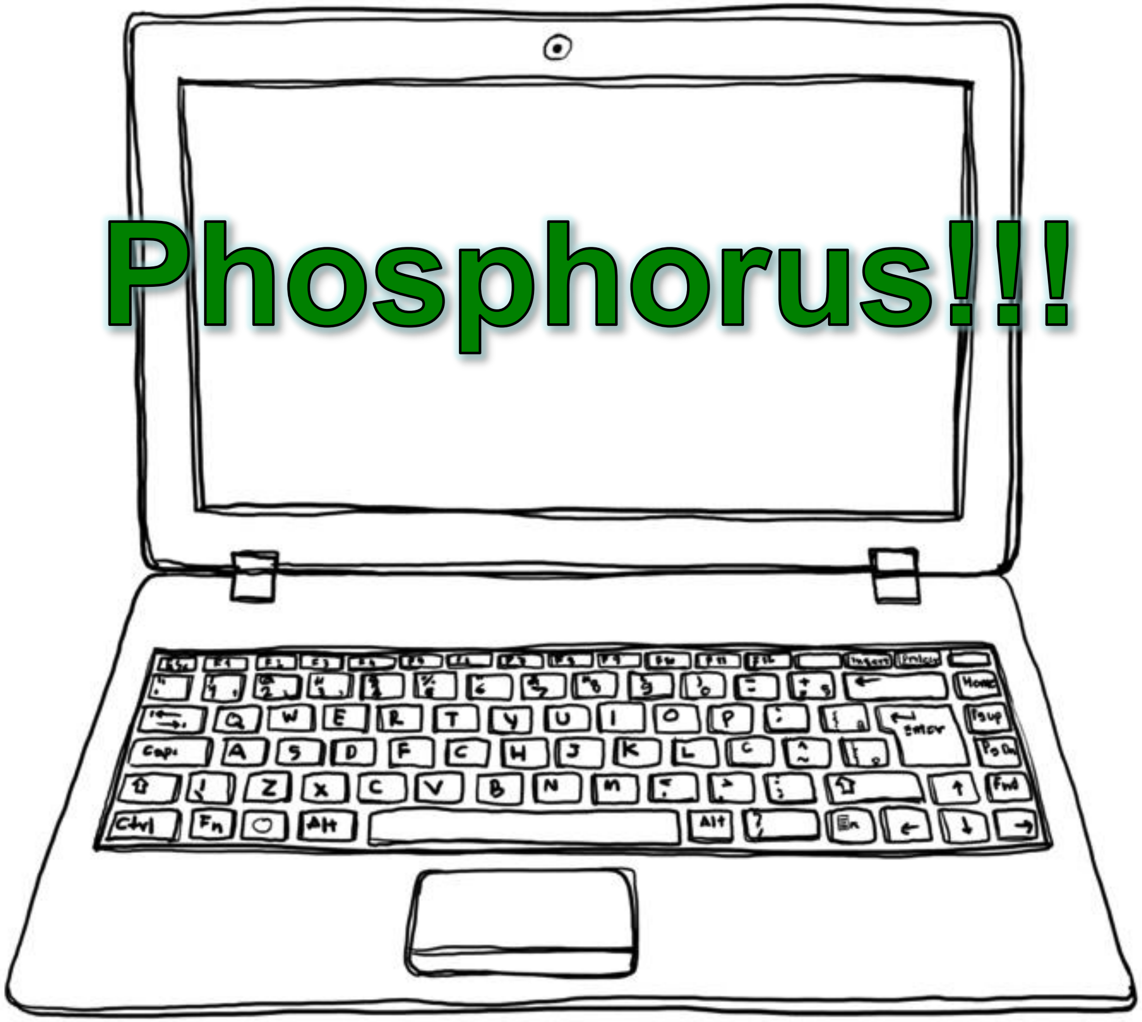
AND IT WAS RIGHT! And the troll gobbled up the potato!



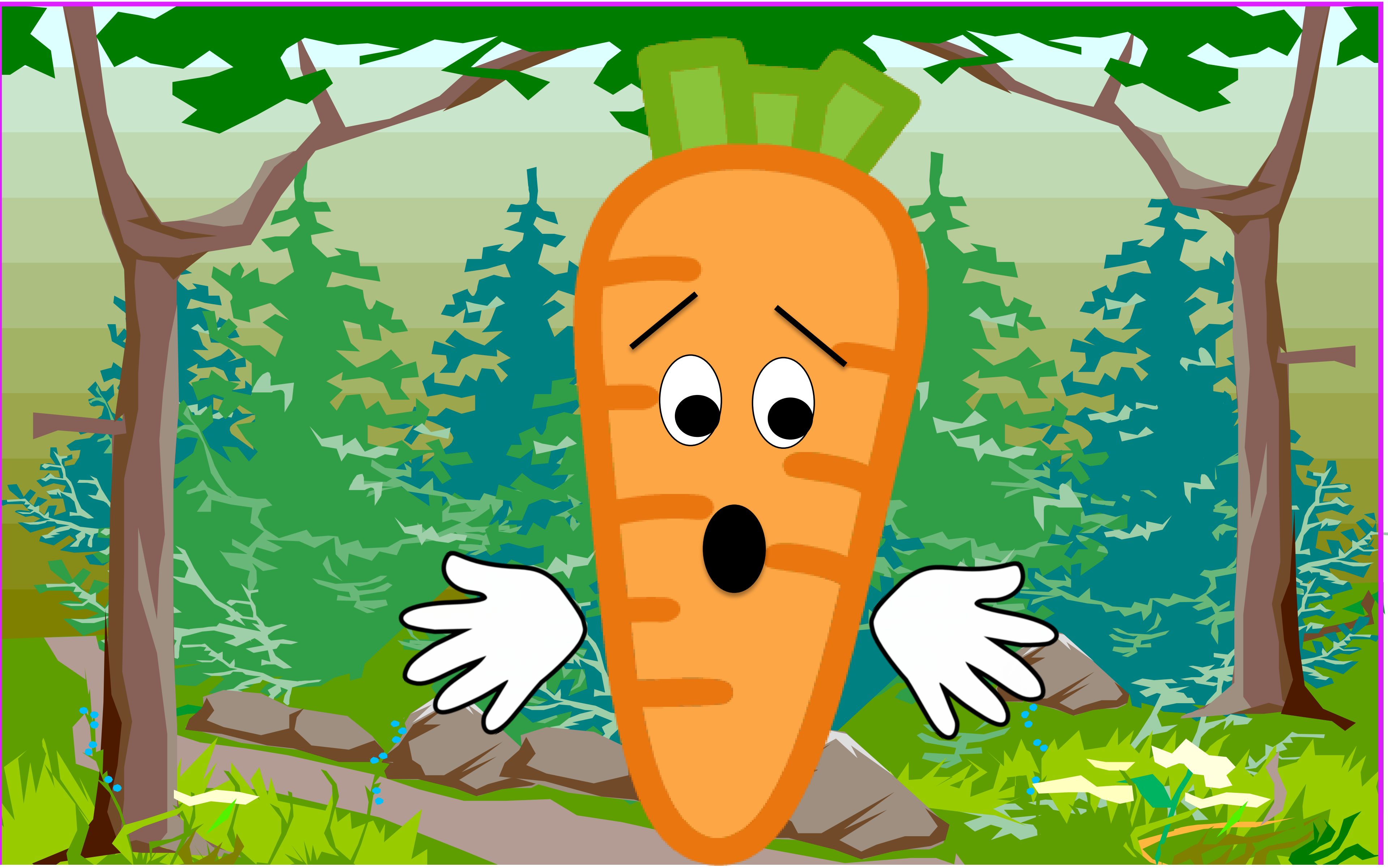
Carrot Gruff was next. He was trembling in his roots.

The troll looked at Carrot Gruff's roots. He looked at Carrot Gruff's size. He guessed Carrot Gruff's age. And then…

Ran the computer model again!



The computer whirred and shook and shook and whirred and then spit out an answer!



AND IT WAS RIGHT! And the troll gobbled up the carrot!

And now our story has come to a head. Only Cabbage Gruff was left! He was so scared, he just wanted to leaf!

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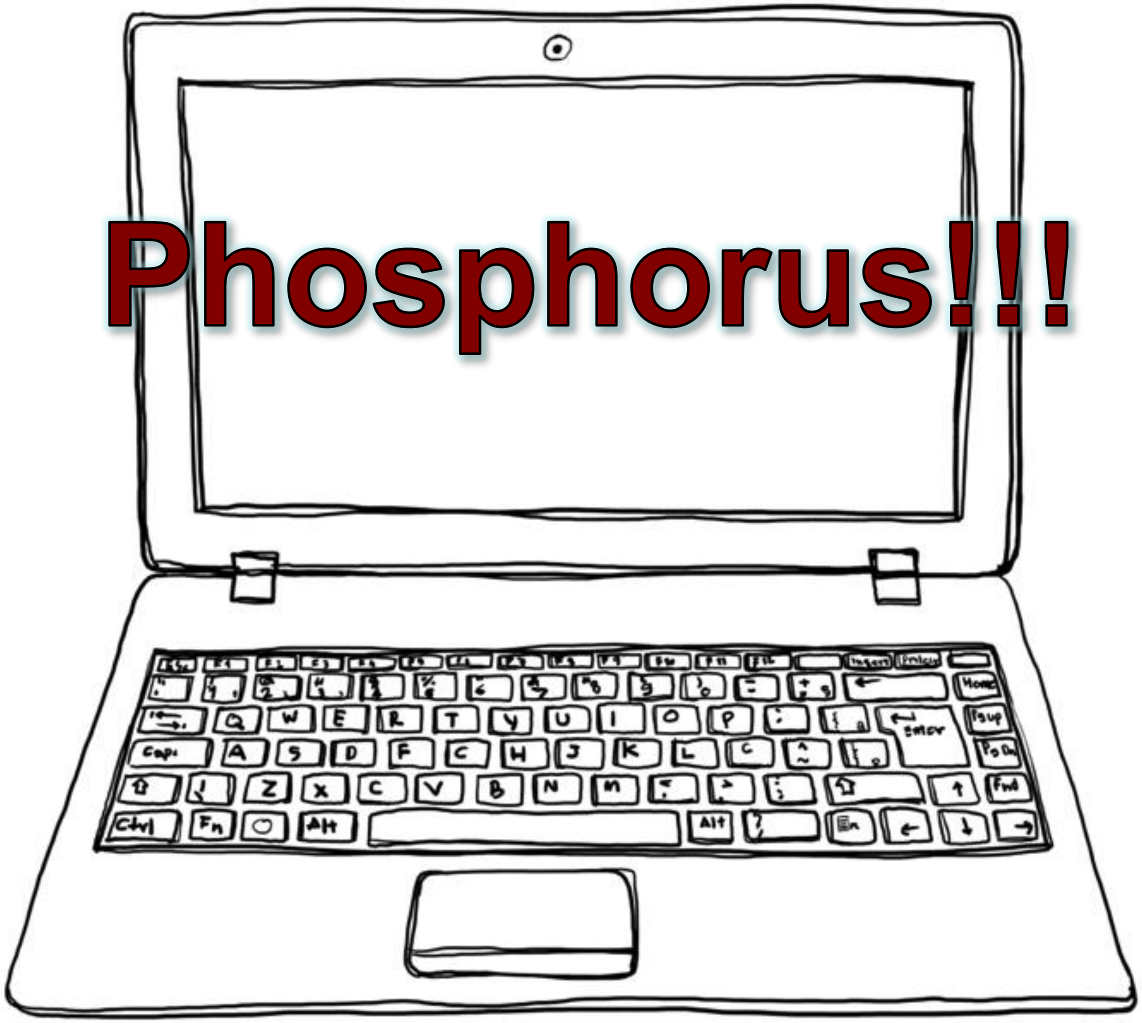
But then, Cabbage Gruff… grinned!

The grin angered the troll. “Oooh! I can’t wait to eat YOU, you cocky cabbage!”

The troll looked at Cabbage Gruff's roots. He looked at Cabbage Gruff's size. He guessed Cabbage Gruff's age. And then…

Ran the computer model!



The computer whirred and shook and shook and whirred and then spit out an answer!

Only this time, the model was WRONG! Cabbage Gruff had over twice as much phosphorus as the model predicted!

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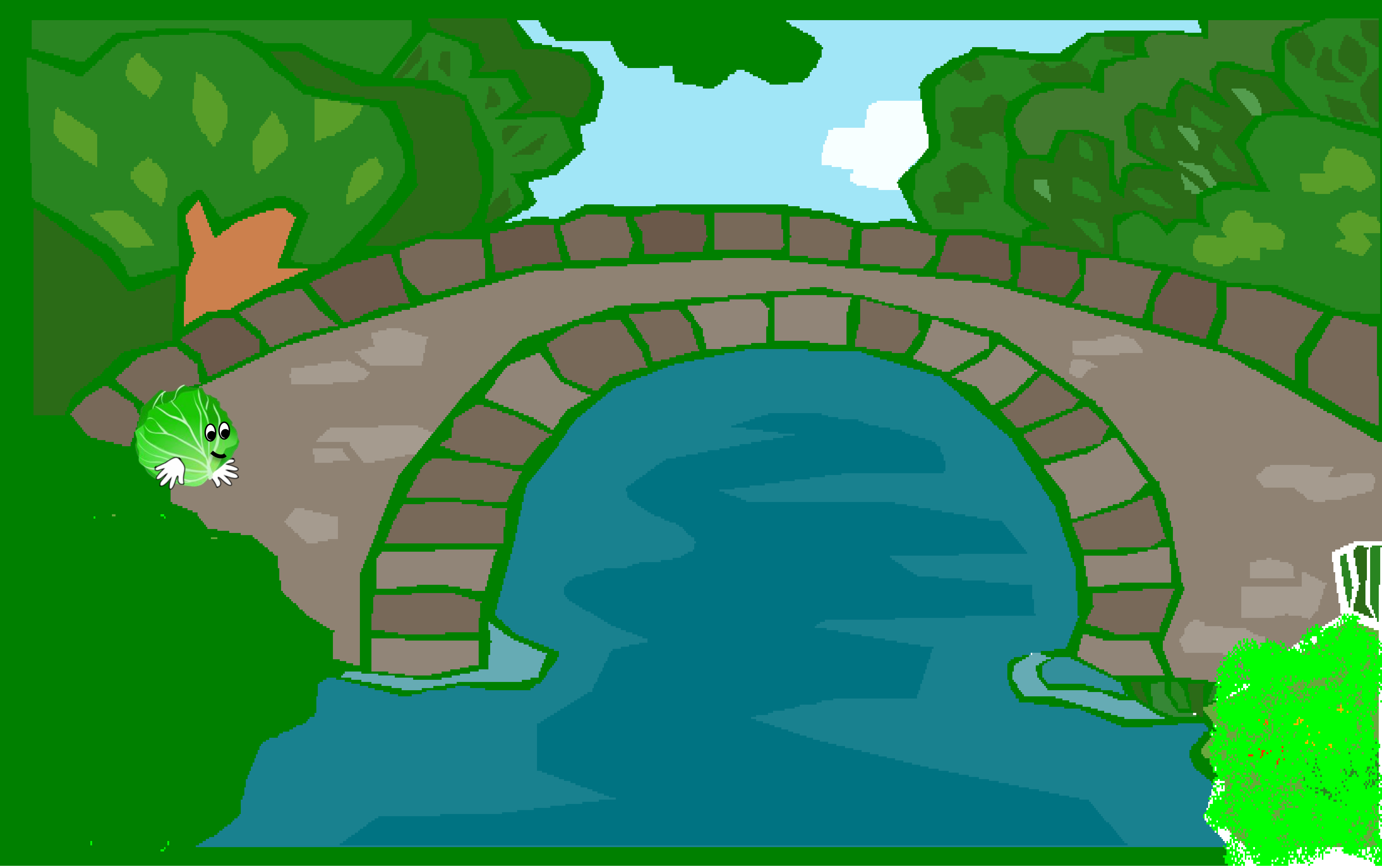
The troll became so angry, he exploded!



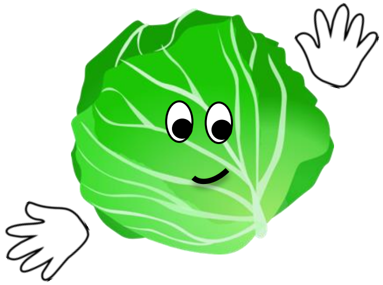
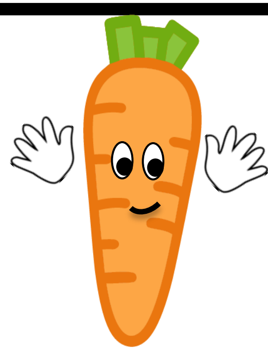
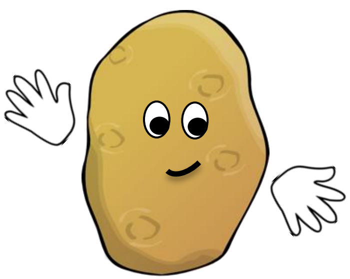
C*abbage Gruff safely crossed the bridge…*

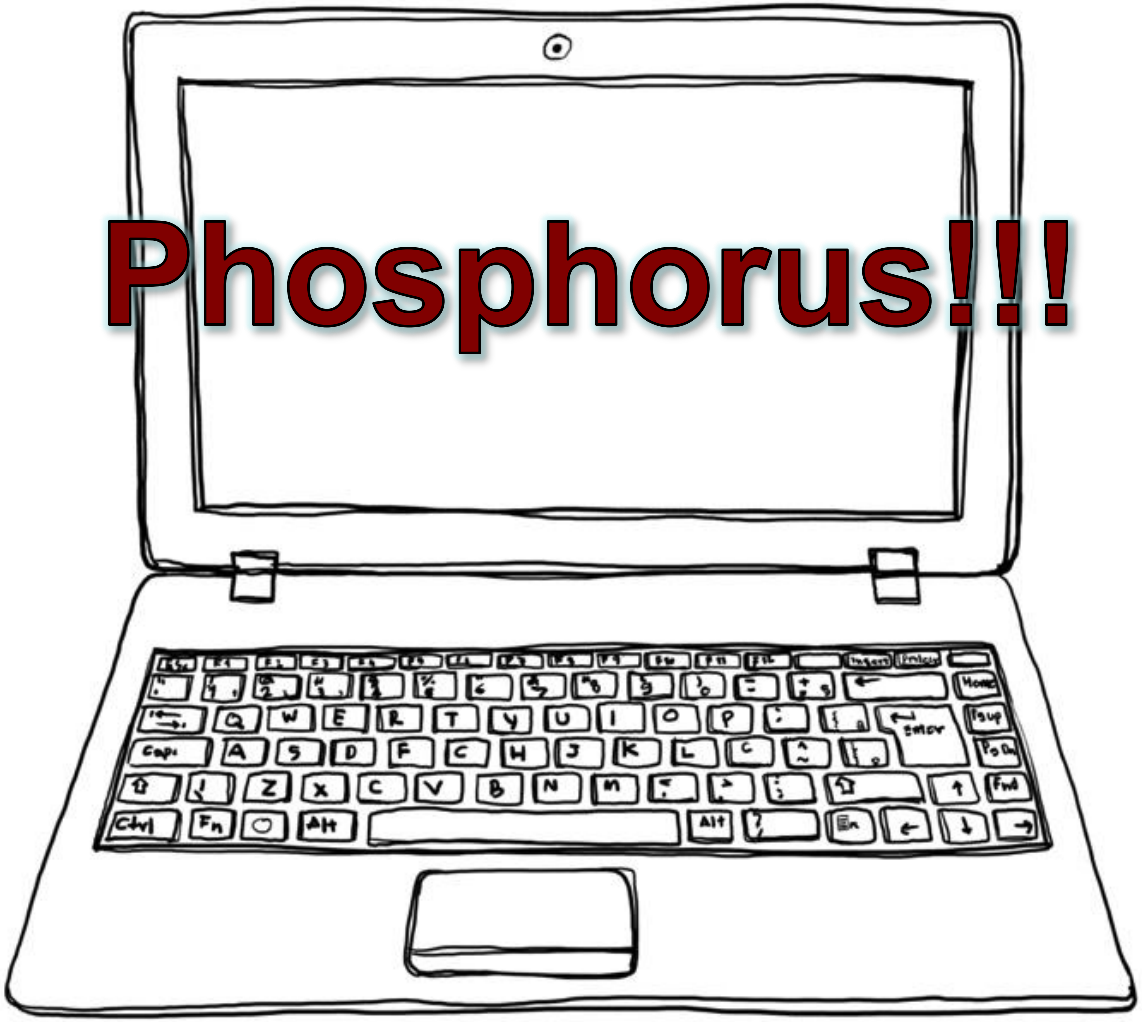
And got to the market! The store owner was very pleased!

How did you make it here? I haven't seen any vegetables for days!

Cabbage Gruff told the whole story.

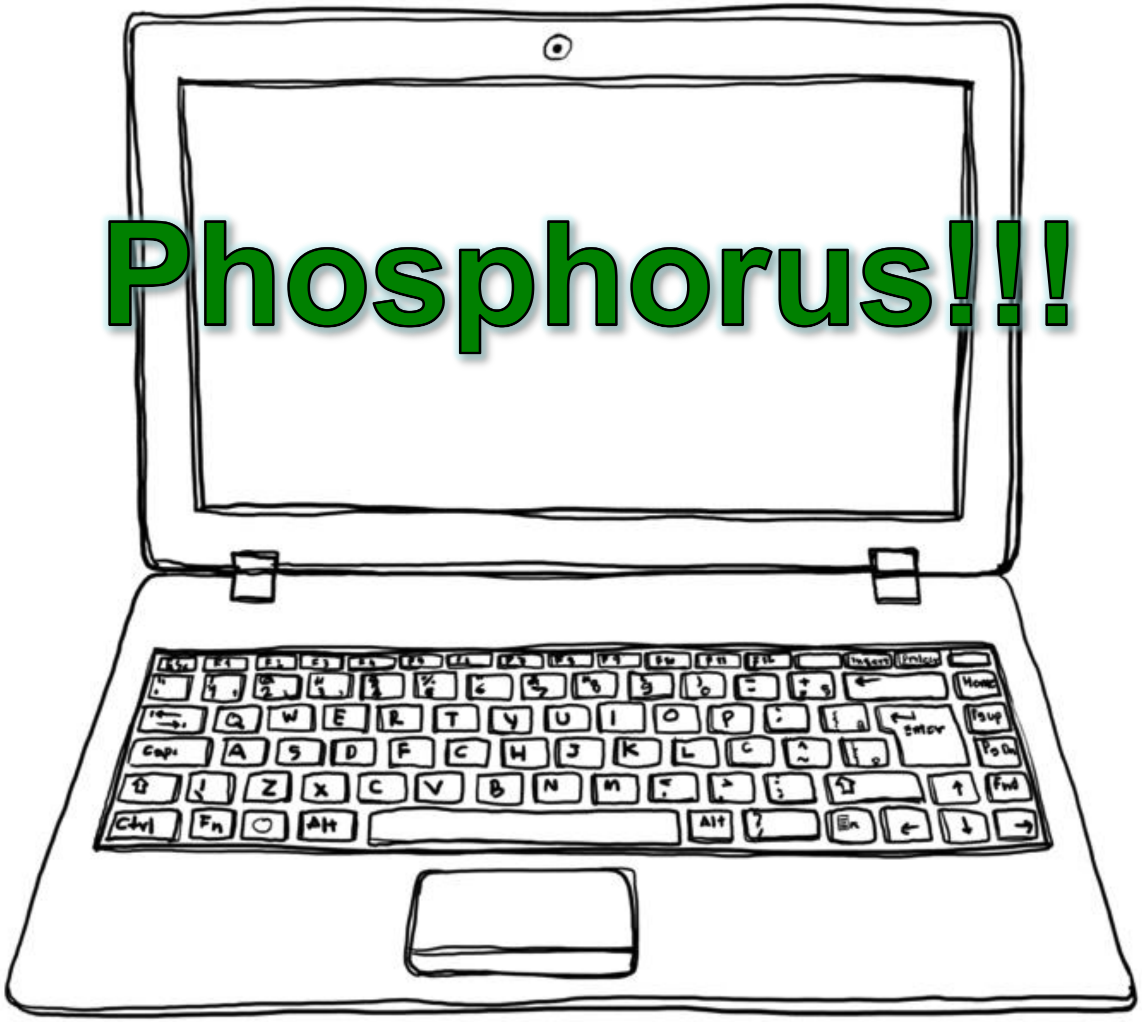
H*ow could you be so confident that the troll's guess would be too low?*

	root → citrate	Exchanges with P, making P more available to roots and increasing P uptake
	root → malate	10 times less effective than citrate in making P available to roots
	root → succinate	Does not make P more available to roots



The computer model did not account for the citrate coming from *Cabbage Gruff's roots, so it understimated phosphorus uptake!*

Phosphorus!!!



For Potato Gruff and Carrot Gruff, their compounds did not increase P uptake, *so the model's guess was more accurate.*

W*ell, you're not a cocky cabbage, you're a clever cabbage! Please* come into my store!

Cabbage Gruff was very proud of his shelf and lived happily ever after.

Studies Referenced

- Three vegetables gruff storyline:

  Dechassa, N., M.K. Schenk, N. Claassen, and B. Steingrobe. 2003. Phosphorus efficiency of cabbage *(Brassica oleraceae* L. var. *capitata*), carrot (*Daucus carota* L.), and potato (*Solanum tuberosum* L.). Plant Soil 250:215-224.

- *The cabbage's secret weapon:*

  Dechessa, N. and M.K. Schenk. 2004. Exudation of organic anions by roots of cabbage, carrot, and potato as influenced by environmental factors and plant age. J. Plant Nutr. Soil Sci. 167:623-629.

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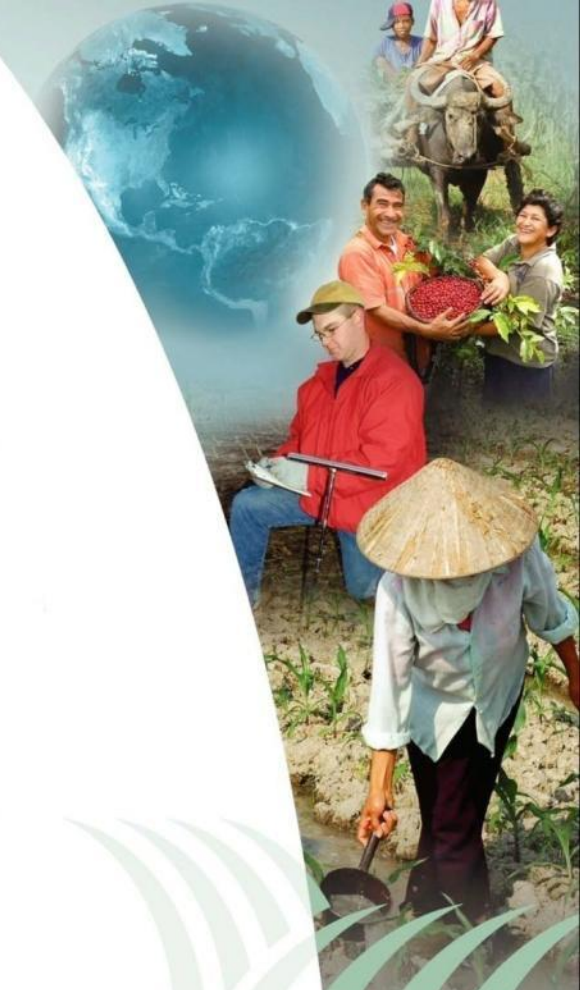
Mycorrhizal Symbiosis

- OR –

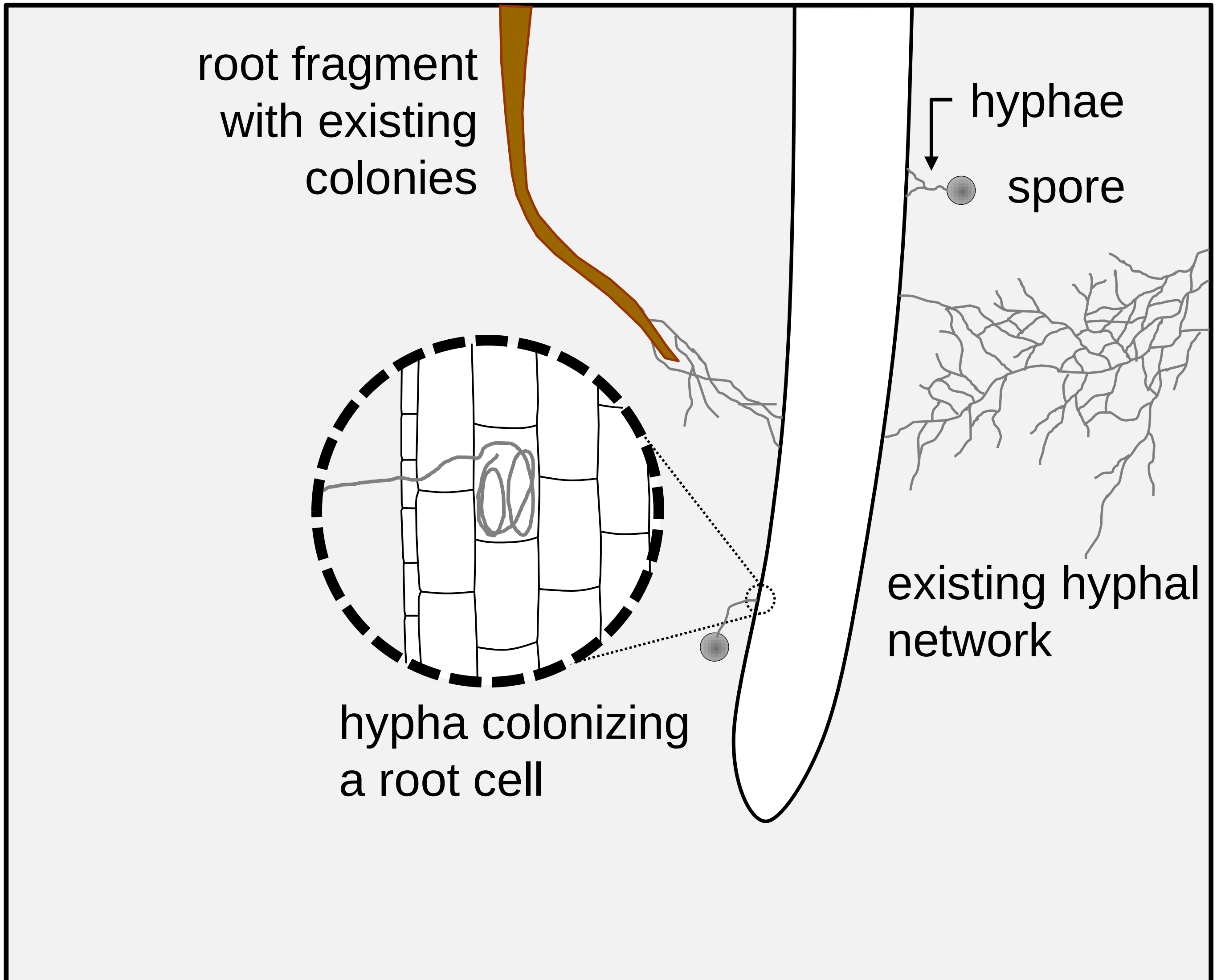
Being a Good Host



Ancient Fungae

Devonian Age (400 million years ago)

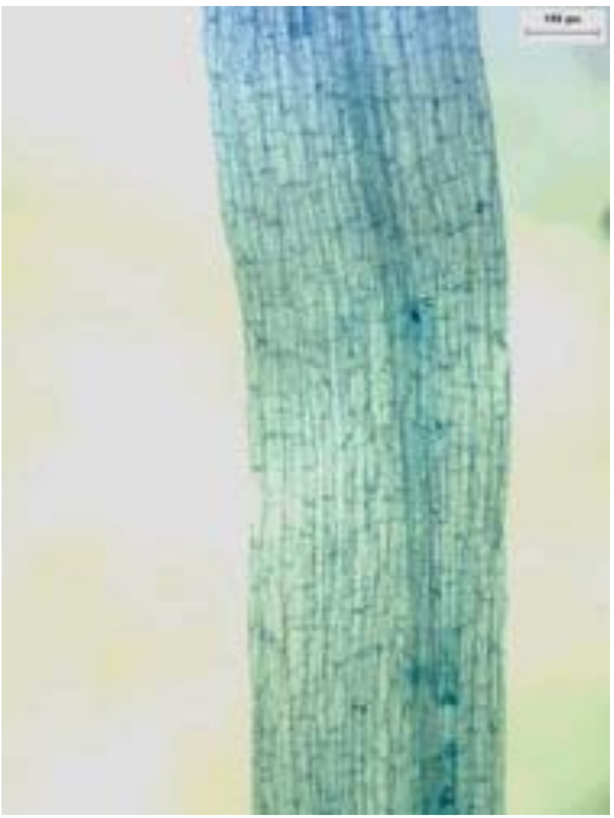
Pathways for Mycorrhizal Colonization



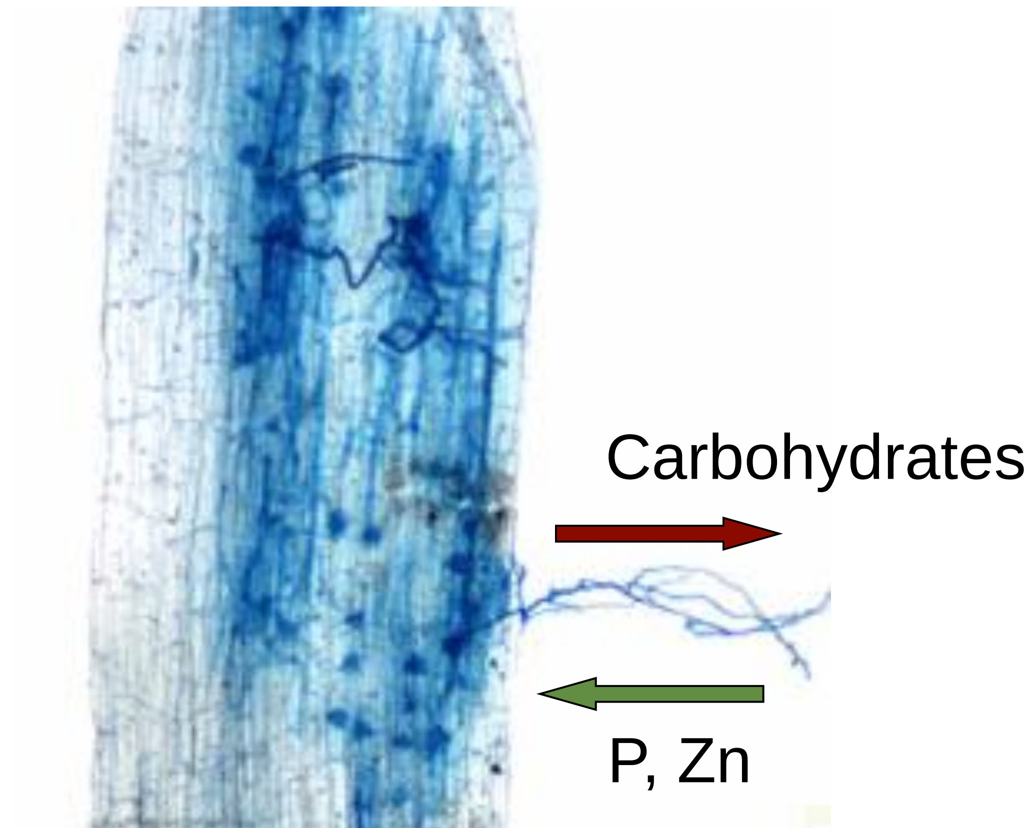
Smith, S. and D. Read. 2008. Mycorrhizal symbiosis. Academic Press, New York, NY.

Symbiosis: Being a Good Host

Without mycorrhizae



With mycorrhizae

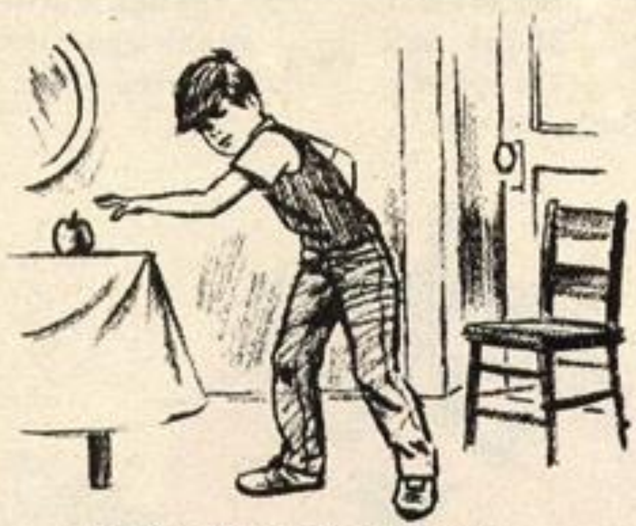


M.A. Monreal, Agriculture and Agri-Food Canada

Goofus and Gallant

Goofus bosses his friends.

Gallant asks, "What do you want to do next?"



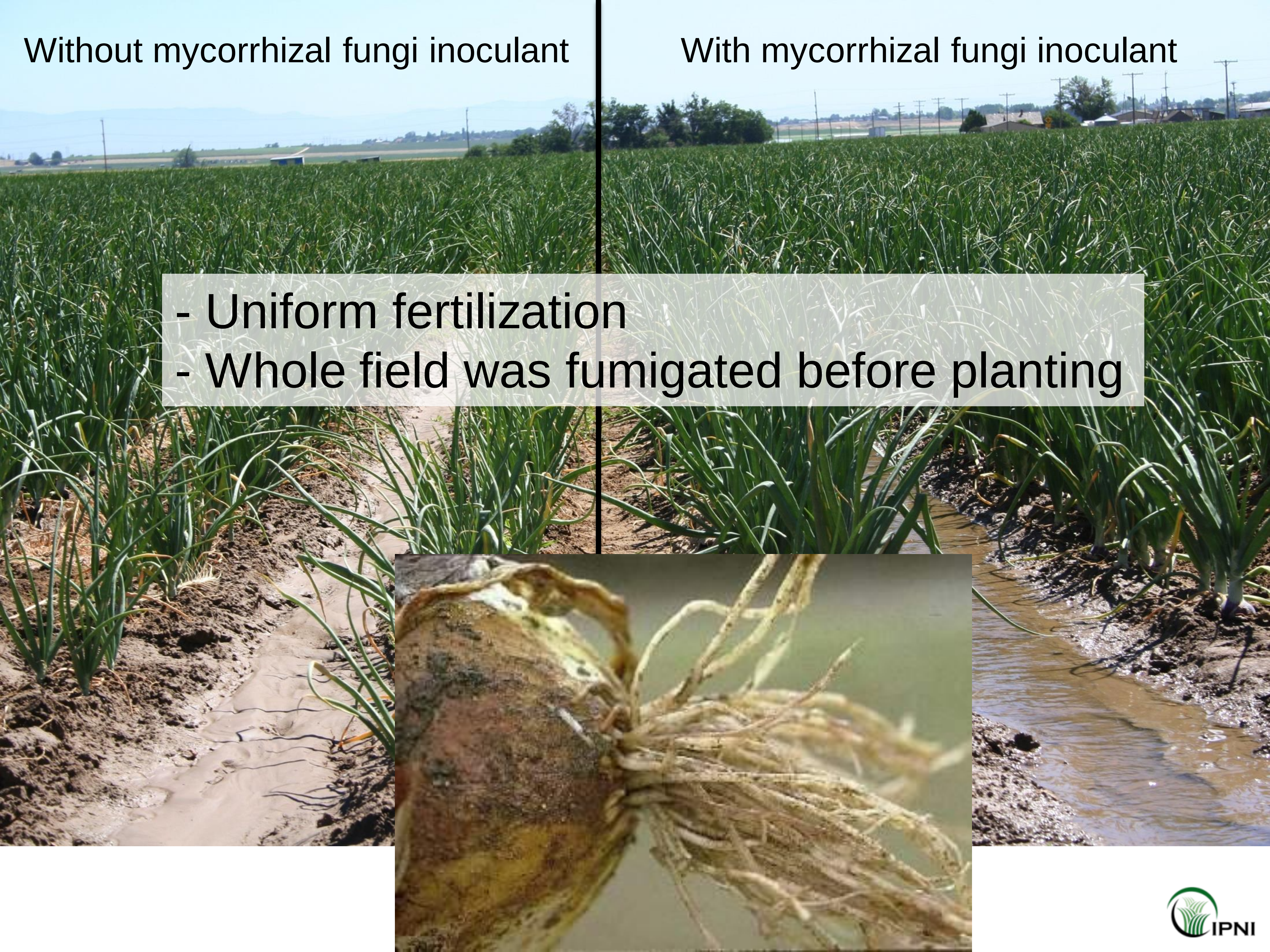
Goofus takes the last apple.

Gallant shares his orange.

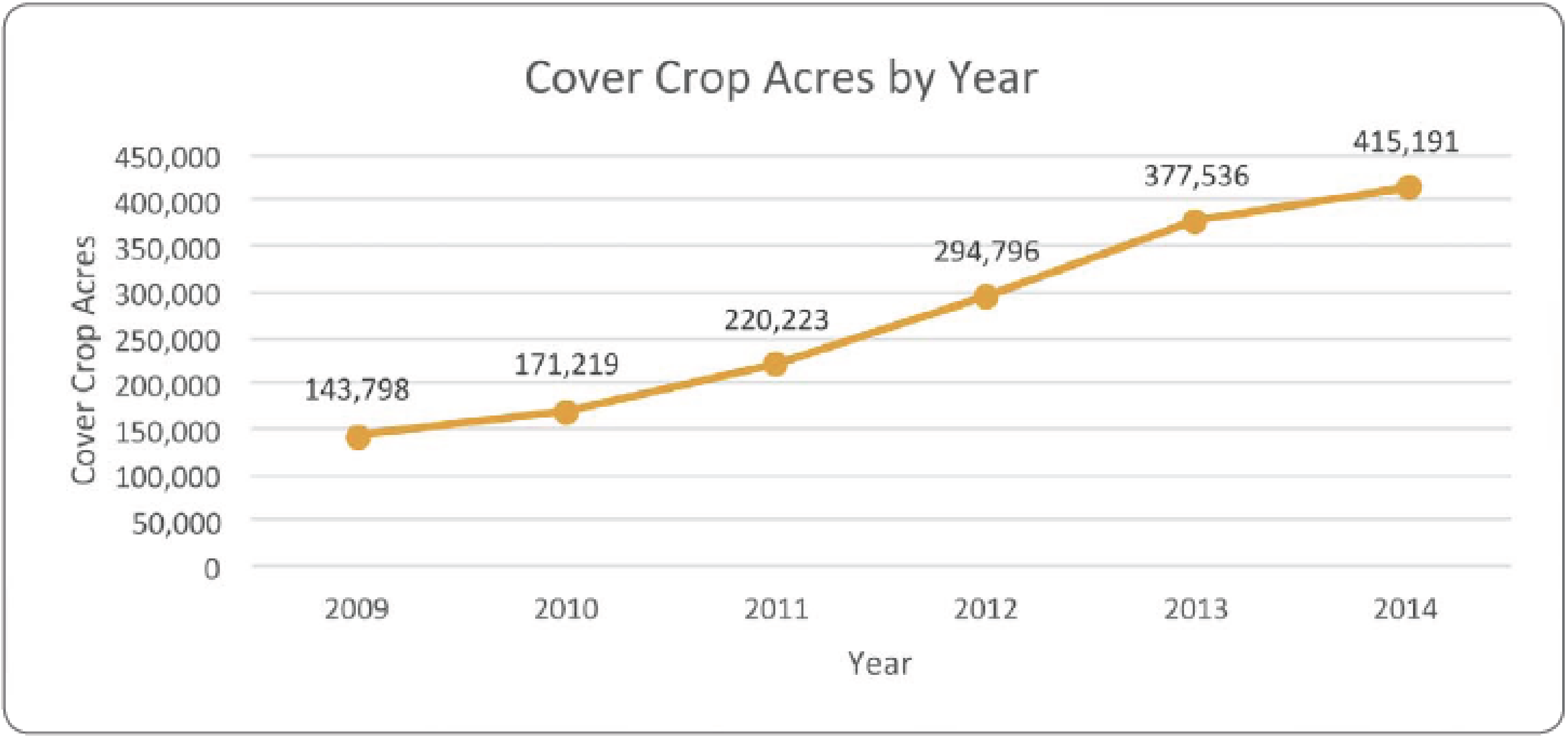
Good Host or Bad Host?

Goofus Crops
Sugar Beet
Many *Brassicas*
Broccoli
Canola
Daikon radish

Gallant Crops
Alfalfa
Corn
Cotton
Onion
Potato
Most others…

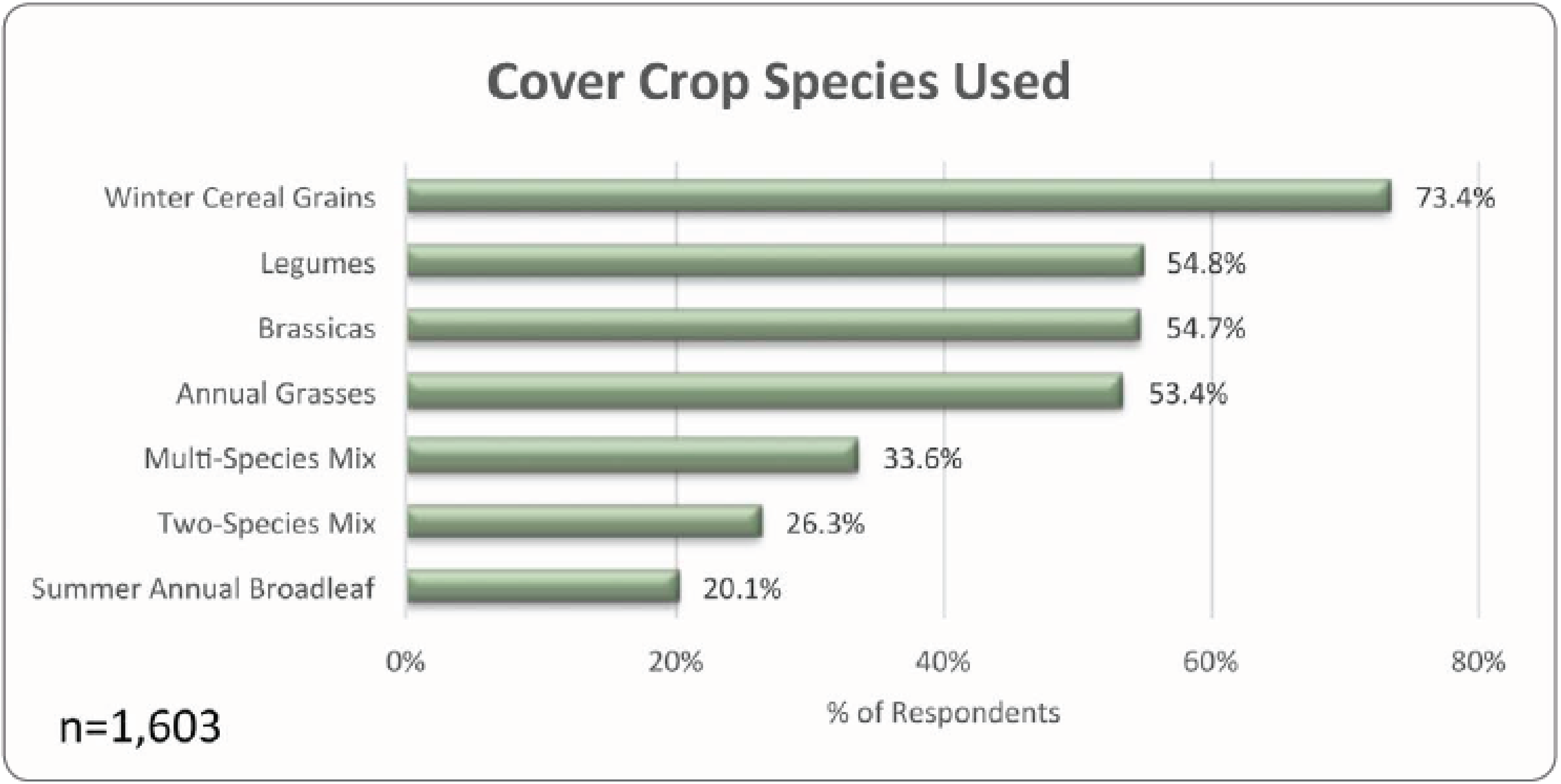

Without mycorrhizal fungi inoculant
With mycorrhizal fungi inoculant
- Uniform fertilization
- Whole field was fumigated before planting

Cover Crop Use Is Increasing



Conservation Technology Information Center. 2014. Report of the 2013-2014 cover crop survey. CTIC and SARE.

Cover Crop Species



Conservation Technology Information Center. 2014. Report of the 2013-2014 cover crop survey. CTIC and SARE.

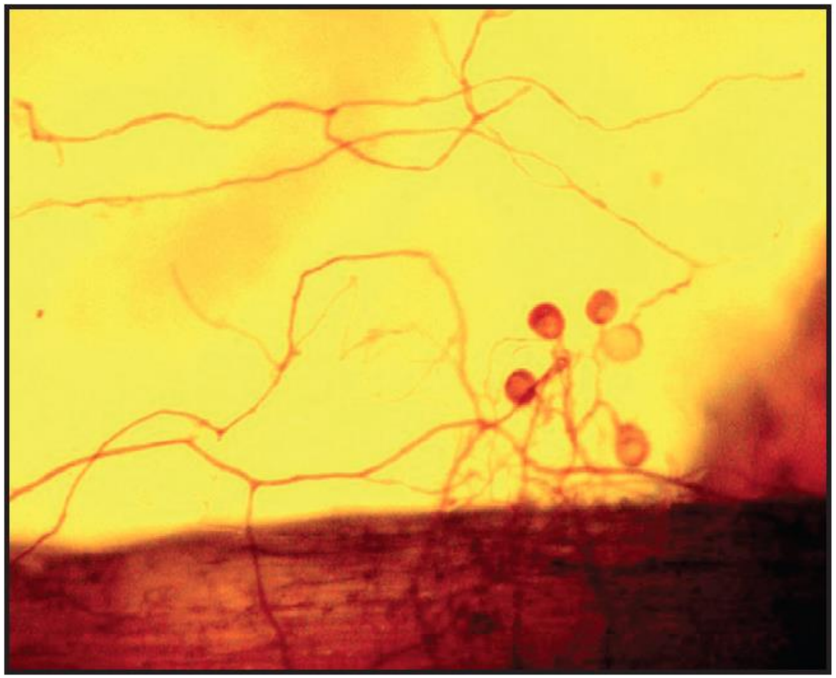
Cover Crops:
What Are the Impacts on Mycorrhizae?

Goofus Crops
Sugar Beet
Many *Brassicas*
Broccoli
Canola
Daikon radish

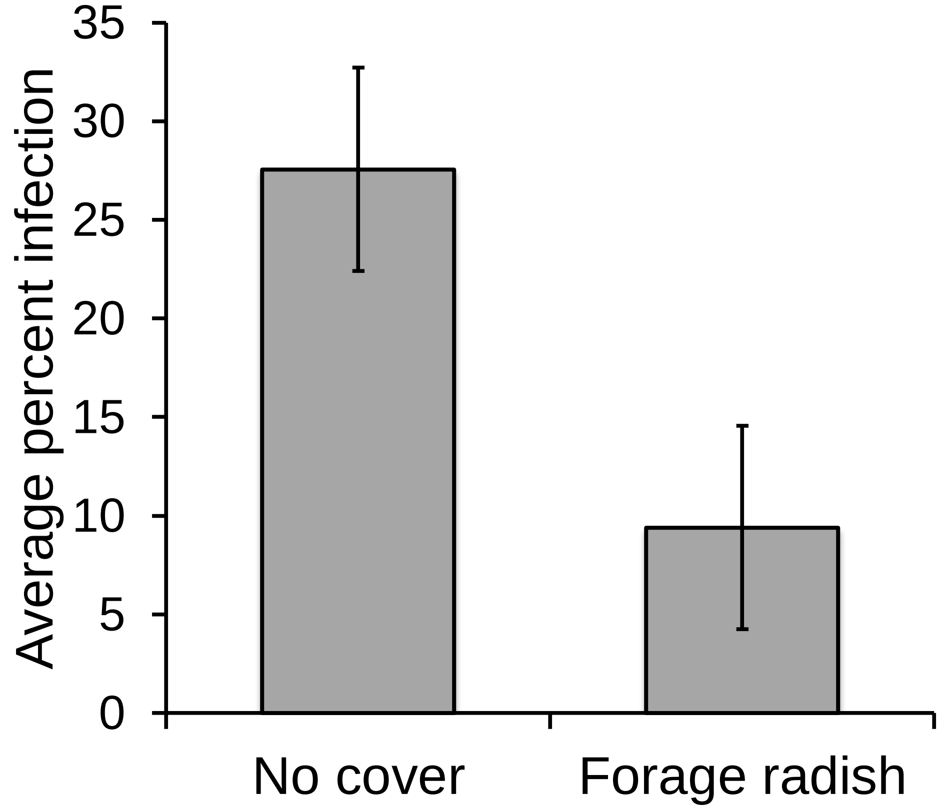
Photo: ask.extension.org

Mycorrhizal Infection of Soybean Roots:

Percent Infection Following a Forage Radish Cover Crop



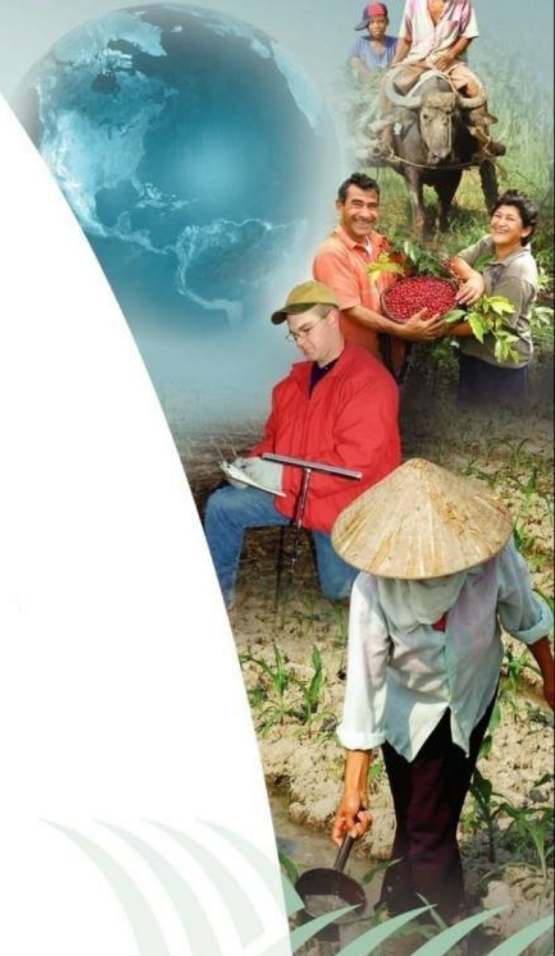
Mycorrhizal infection
of a soybean root



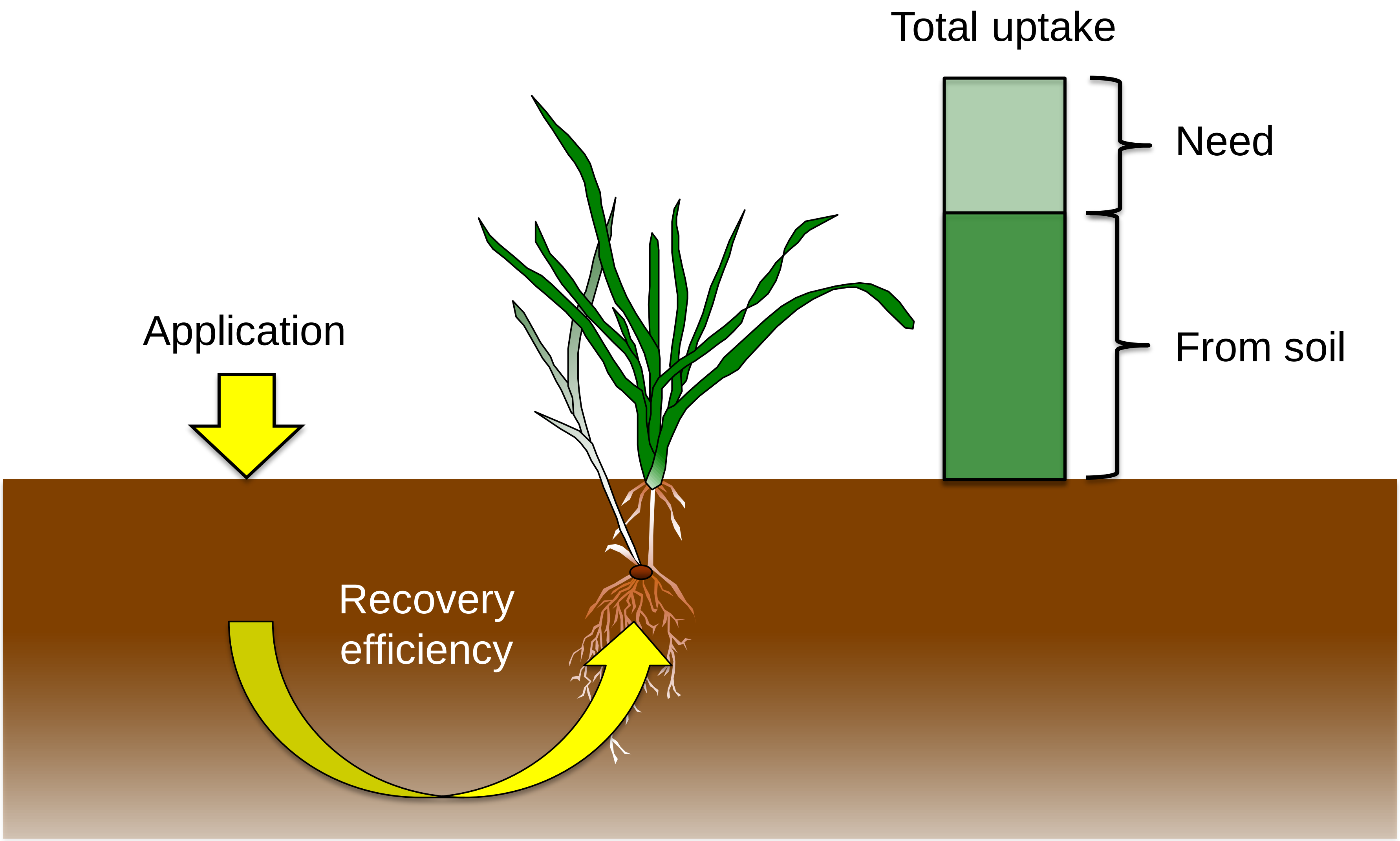
Hill, J. 2006. Soybean roots following *Brassica* cover crop. J. Nat. Resour. Life Sci. Educ. 35:158-160.

INTERNATIONAL PLANT NUTRITION INSTITUTE

How Do Root-Soil Interactions Affect Our Fertilizer Rate Decisions?



Components of a Nutrient Recommendation



Stanford, G. 1973. J. Environ. Qual. 2:159-166

Foundational theory of N rate recommendations for cereals

$$\text{Fertilizer rate} = \frac{(\text{total uptake} - \text{uptake from soil})}{\text{crop recovery efficiency}}$$

total uptake $\uparrow$ = fertilizer rate $\uparrow$

uptake from soil $\uparrow$ = fertilizer rate $\downarrow$

crop recovery efficiency $\uparrow$ = fertilizer rate $\downarrow$

Stanford, G. 1973. J. Environ. Qual. 2:159-166

What Have We Done in the Last Hour?

- Went to the theater to watch roots grow
- Listened to a hair-raising tale
- *Answered a little girl's question about root hairs*
- Heard a pitch for a sitcom about Barber and his phosphorus model
- *Read "The Three Vegetables Gruff" (citric acid is cool)*
- Learned about Goofus crops and Gallant crops
- Leaned how root-soil interactions could affect a fertilizer rate decision

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