Root Phenomics: Cheap, Fast ... and Good?

Christopher Topp
Donald Danforth Plant Science Center
Six feet

Root interactions

N = few

Weaver and Voigt Botanical Gazette 1950
Impact opportunity?
Better field phenotyping of roots


http://rps.psu.edu/indepth/roots.html

www.dpi.nsw.gov.au
Phenotyping is vastly more dimensional than genotyping

There is not, and will not be, one all encompassing phenotyping tool
Phenotypes are many. And depend on context.

**Phenotypes**

- Gene expression
- Protein levels
- Metabolite levels
- Cells
- Tissues
- Organs – (roots, shoots, flowers)

  - Physiological: carbon allocation / vascular function
  - Behavior / environmental response
  - Plasticity
  - Growth rates
  - Macro and micro architecture

Et al.
Phenotypes are many. And depend on context.

**Space/Time**

- Dynamic interactions
- Development
- Maturation/ Flowering time
- Relative growth of organs
- Circadian effects
- Tradeoff constraints
Phenotypes are many. And depend on context.
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- Incredible wealth of untapped information in natural variation
- Extremely powerful genetic resources have been developed
What phenotypes do we want to measure?
And in which contexts?

Sampling many levels of many factors and their interactions:
Requires high sampling and high throughput!!!
We can leverage existing technologies in industrial engineering, robotics, computer vision/AI

Rick van de Zedde – Wageningen UR
‘High Resolution’ genetic resources are designed to rapidly associate phenotypes with the genes controlling them.

Several generations of intermating →

Several generations selfing →

High throughput genotyping →
Root phenomics: major questions

1. How can we image roots?

2. What phenotypic variation exists and how can we quantify it?

3. What genetic and environmental factors condition root architecture, and what tradeoffs exist?

4. How do local (2D) growth decisions “add up” to global 3D shape?

5. What biological function does phenotypic variation have?
Automated rhizotron
Nagel Fun. Plant Biology 2012

X-ray Computed Tomography

MRI and PET
Schurr et al Plant Journal 2009

Optical Tomography

precision and accuracy

Genes driving advantageous root traits

high throughput

environmental complexity

Shovelomics
http://rps.psu.edu/indepth/roots.html
Optical Projection Tomography (OPT) platform for root phenotyping in 3D

Imaging time: ~5 minutes / plant

Tim Horn – mechanical engineer extraordinaire
Randy Clark – bio-engineer
Alex Bucksch and Joshua Weitz – physics and computer science
3-dimensional modelling of root architecture

traits analyzed in 3D
1. median root number
2. maximum root number
3. root system volume
4. convex hull volume
5. solidity
6. surface area
7. bushiness
8. total root length
9. root system volume
10. specific root length
11. number of branches
12. et al.

Rootwork - Zheng et al ICCV 2011
RootReader3D - Clark et al Plant Phys 2011
Image-based phenotyping allows the genetic basis of new ‘traits’ to be identified.
Illinois Long-term selection experiment

In >100 years of selection for seed protein content, Nitrogen uptake capacity was also strongly selected for.

modified from Moose et al. TIPS 2004
Identifying the genetic basis of root architecture: integrated root phenotyping with high-resolution germplasm

Root phenotyping methods

1. 3D gel imaging
2. X-ray CT in pots
3. Excavated root crowns:
4. minirhizotrons

High-resolution germplasm with important agronomic traits
Characterizing potentially efficient high Nitrogen uptake root architectures in maize

*# of root tips

\[
\begin{array}{c|c|c}
\text{Genotype} & \text{IHP} & \text{ILP} \\
\hline
\text{Number Root Tips 3D} & \\
\hline
0 & 50 & 100 & 150 \\
\end{array}
\]

\* = P < 0.05; Wilcoxon

IHP
High N uptake

ILP
Low N uptake
Field excavated maize roots
DIRT Pipeline: image based phenotyping of field excavated root samples:

Alex Bucksch and Joshua Weitz
Jonathan Lynch and Eric Nord, Jimmy Burridge, Larry York

http://www.bucksch.nl/index.php/using-joomla
Converging lab and field phenotyping on high-resolution germplasm

3D gel imaging

DIRT pipeline

IPSRI 152 - high

IPSRI 77 - low

IPSRI 152 - high

IPSRI 77 - low

PC1 38.1%

PC2 19.7%

PC1 26.9%

PC2 17.2%
Intermediate phenotyping by X-ray CT: realistic soils x controlled environment
High-throughput X-ray computed tomography (X-ray CT) for comprehensive 3D shoot and root imaging in soils

Daniel Goldman and Daria Moanenkova (GA Tech Physicists)
~ 10 day old rice root in fine sand particles
Micron resolution structures using X-ray CT

Mark Anastasio and Trey Garcon – WashU Biomedical Engineering

Dan Chitwood – DDPSC
Capturing growth dynamics is key to understanding how roots interact with the environment.
fully automated imaging table built into a controlled growth environment for high temporal resolution data (24/7 imaging)
Maize
6 hours growth
3 DAP
Growth model algorithm to quantify changes in RSA over time

4-Point Congruent Set for Shape Alignment

Geometric Tree

Branch Matching and Time Propagation

Olga Symonova and Herbert Edelsbrunner, IST Austria
3D time series analysis software:

For each root at each time point:
- length
- width
- Volume
- root angle
- root curvature
- etc.

Hebert Edelsbrunner and Olga Symonova

bi-hourly data set
25 reconstructions
How do roots respond to environmental challenge?
Positron Emission Tomography (PET): to image Carbon allocation and other dynamic physiological processes

Plant PET System

Funded by a NSF MRI Grant DBI-1040498

A cucumber plant labeled with $^{11}\text{CO}_2$

Yuan-Chuan Tai, Qiang Wang, Sergey Komarov, Aswin J Mathews, Ke Li, Jie Wen, Joseph A O’Sullivan

Washington University
Department of Radiology
Department of Electrical and Systems Engineering
B73 – 3 dap

30 min

60 min

80 min
B73 – 4 dap
OPT-PET: physiological dynamics
OPT-PET: morphological and physiological dynamics

Day 05
Day 06
Day 07
OPT-PET can be used to quantify baseline levels of carbon allocation: growth.
Opportunity – molecular imaging over a large field of view
Bottlenecks and opportunities:

Plant phenomics is relatively nascent; we lack expertise in tool development, data processing and analysis

Groups with the relevant expertise:

medical and industrial imaging (engineers, physicists, computer scientists)

1. embed plant phenotyping in medical schools
2. leverage production agriculture for science
3. technology moves fast - focus on open source tools

This will happen at some level on a case by case, grant by grant basis, but a concerted institutional effort is required for large sustained payoffs
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