Phenotyping of plants: Quantitative Analysis of Structure and Function
Technologies and Concepts

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ICG-3: Phytosphere
Plant phenotyping: quantifying plant structure and function for grand challenges

Breeding

Functional genomics

Agricultural production

Horticultural production

Identification of heritable traits

Acute plant status

Biodiversity

Global Change

Field environment

Plant Phenotyping
Quantitative Analysis of Plant-Environment-Interaction

Environment
Dynamic interaction
Genome

Performance of and products from plants
The genome is the toolbox for endogeneous developmental patterns

.....and responses to dynamic environments

...and their interaction
The Phenotyping Triangle

- **Defined genetic material**: Heritable traits; defined genetic conditions
- **Modelling and Simulation**: Sensorics to analyse dynamic and heterogenous plant and environmental properties
- **Environment**: Simulation or Monitoring of relevant (=heterogenous and dynamic) environmental conditions
- **Sensorics**: Sensorics to analyse dynamic and heterogenous plant and environmental properties
Phenotyping

Environment
- Constant
- Dynamic

Genomes
- Natural variation
- Transgenic

Bioinformatics

Structure and Architecture
- Root and shoot system geometries

Physiology
- Growth
- Photosynthesis
- Water relations
- Nutrient acquisition

Biochemistry and Omics
- Metabolites and Proxies
- Proteins
- Transcripts

Integration Across Scales

Implementation
The Phenotyping Concept

Defined genetic material

Heritable traits; defined genetic conditions

Modelling and Simulation

Environment
Simulation or Monitoring of relevant (=heterogenous and dynamic) environmental conditions

Sensorics
Sensorics to analyse dynamic and heterogenous plant and environmental properties
Challenge: What is the proper environment to obtain relevant phenotyping data?

Temporal frequencies
- Annual
- Daily
- Minutes
- Seconds and faster

Spatial frequencies
- Micrometer
- Millimeter
- Meter
- Kilometer
Phenotyping of roots .... a special challenge

Roots live in a special environment

- Spatial patterns
- Temporal patterns
- Chemical structured environment
- Mechanical properties

Soil environment

Environmental conditions highly important

Fig. 2 Micrograph obtained by cryoscanning electron microscopy observation of the rhizosheath of buckwheat (Fagopyron esculentum) sampled in situ in field-grown plants. Development of long root hairs extending in a large macropore is clearly visible. (Reproduced by kind permission of Margaret E. McCully.)

Watt et al. 2005
Phenotypes are highly responsive to the history of spatial and temporal interactions

Phenotypes “accumulate” over time

Structures are the “memory” of plants

Talk by Hendrik Poorter

Example: Long-term effects in forest trees
Environmental heterogeneity does play a role

- Spatial and temporal heterogeneity are essential
- Phenotyping in relevant environmental scenarios (relevance, transfer to field conditions)
Detailed mechanistic Bioinformatics Environments
- Constant
- Dynamic Genomes
- Natural variation
- Transgenic Phenotyping

Structure and Architecture
Root and shoot system geometries

Physiology
- Growth
- Photosynthesis
- Water relations
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Biochemistry and Omics
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INTEGRATION ACROSS SCALES
Challenge: Integration across scales – Example: Root Structure and Function

Root tip

Root system

Root system function

3D structure and function

Root – soil interaction model
Mechanisms: spatio-temporal root growth

Dynamic maps of root growth

Rapid response root growth to light changes

Nagel et al. (2006) PCE
High throughput root system analysis

Throughput: 300 plants/ 12 Min

Automated analysis of properties of
- Main root
- lateral root
- total root system
- growth
- etc.
Root growth in soil-based rhizotrons

![Graph showing root length growth]

- Root length visible (cm)
- Root length harvest (cm)

\[ R^2 = 0.91 \]
\[ y = 2.9 \times x \]
Non-invasive Quantification of Root processes and structures

30 cm, 4.5 Tesla

10 cm, 7 Tesla

50 cm, 1.5 Tesla
Combining two non-invasive methods: MRI-PET

MRI (4.7T) + PlanTIS (PET)

$^{11}\text{CO}_2$

Reconstruction

3D-Coregistration

MRI = Magnetic Resonance Imaging

PET = Positron Emission Tomography

PlanTIS = Plant Tomographic Imaging System (a PET system dedicated to plants)

Talk by Sigfried Jahnke
Complex 3D-datasets of structure and function + time

Maize root system (see Fig. 4c)
Grey: MRI imaging (isosurface)
Colours: PET imaging; import of 11C-tracer

Time: 0 min

Sugar beet storage root (see Fig. 2h-k)
MRI imaging, sagittal sections

Structure and Function of organs in real soil
Growing roots at different root temperature
Root structure and function models

Growth parameters

- Growth at root tips at every time step where growth rate depends on branching orders and resources.
- Curvature of root defined by:
  - rate of change for growth angle
  - distribution function for direction change
  - gravitropism parameter

Branching parameters

- Branching lag
- branching probability
- fixed branching angle
- radial distribution
Multiscale Approaches at the leaf level

Talk by Achim Walter
The Phenotyping Concept

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Challenge:
Novel technologies are available, have to be developed and have to be integrated

(Hyper-)spectral methods

Chl-Fluorescence

Thermography

Plot and stand

Photosynthesis, water relations and indirect impacts (e.g. biotic stress)
Challenge: Novel technologies are available, have to be developed and have to be integrated

Mobile NMR

Novel detection principles

- Hardware development
- Software development
- Applications in
  - Plant sciences
  - Medical sciences
  - Soil and geosciences
Challenge:
Novel technologies are available, have to be developed and have to be integrated

Growth and photosynthesis

Sensor Fusion

Chlorophyll-Fluorescence - hyperspectral imaging – thermal imaging
Implementation of a complete phenotyping pipeline

- Experimental Design and Planning
- Measurements
  - Time series
  - Multi-modal
  - Large amounts of data
- Data storage
- Data assimilation and Modelling
- Experimental Design and Planning
Multidisciplinarity is key

- engineering
- equipment
- electronics and sensor development
- physics – chemistry
- robotics
- (bio-) informatics
Integration of non-invasive analysis into fully automated systems

Intensive cultures

ScreenHouseR

Non-invasive sensors

Robot

Field
Deutsches Pflanzen Phenotypisierungs Netzwerk

Module 5: Education
- Junior Scientists
- Senior Scientists

Module 4: Communication
- Developers
- Users

Module 2: Access
- Academia
- Industry

Module 3: Phenotyping Technologies
- Sensorics
- Environmental Sim.
- Informatics
- Robotics
- Assay-Development

Module 1: DPPN-Infrastructures
- High Throughput Phenotyping
- Deep Phenotyping
- Field Phenotyping
International Plant Phenomics Initiative

Agenda for an IPPI

• Develop a prospering landscape of phenotyping activities
• Identification of synergies and options for collaboration
  • „informed“ development and use of infrastructure
  • development of large, joint projects
• Communication
  • within the phenotyping community
  • with stakeholders
  • with keepers
• Setting quality standards
• Fostering education and exchange of protocols

Proposed Instruments

• International Plant Phenotyping Conference (biannually – next Jülich 2011)
• Topic-specific workshops
  • White paper on plant phenotyping workshop (Jülich November 2009)
  • E.g. high-throughput workshop
  • Integration with bioinformatics...
• Staff exchange/ trainee options
• Opinion papers/ contact point
• Workgroups
  • Quality standards/ ontologies/ common data format,
  • Reference geneotypes....
• Summerschools
• Mix advisory boards
Key messages

Adequate phenotyping requires systematic approaches and goes beyond „buying a machine“

- Relevant environmental conditions
- Phenotyping chains
  - lab-to-field
  - mechanistic - high throughput – field
- Multi-mode - multi-scale – multi-disciplinary
- Integrated systems

Close interaction of users and developers is key

Plant Phenotyping can have an analogue impact on plant sciences as non- and minimal invasive technology in medicine
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