PLANT PHENOTYPING: TECHNOLOGIES AND TARGETS

13. MARCH 2024I ULI SCHURR (U.SCHURR@FZ-JUELICH.DE),
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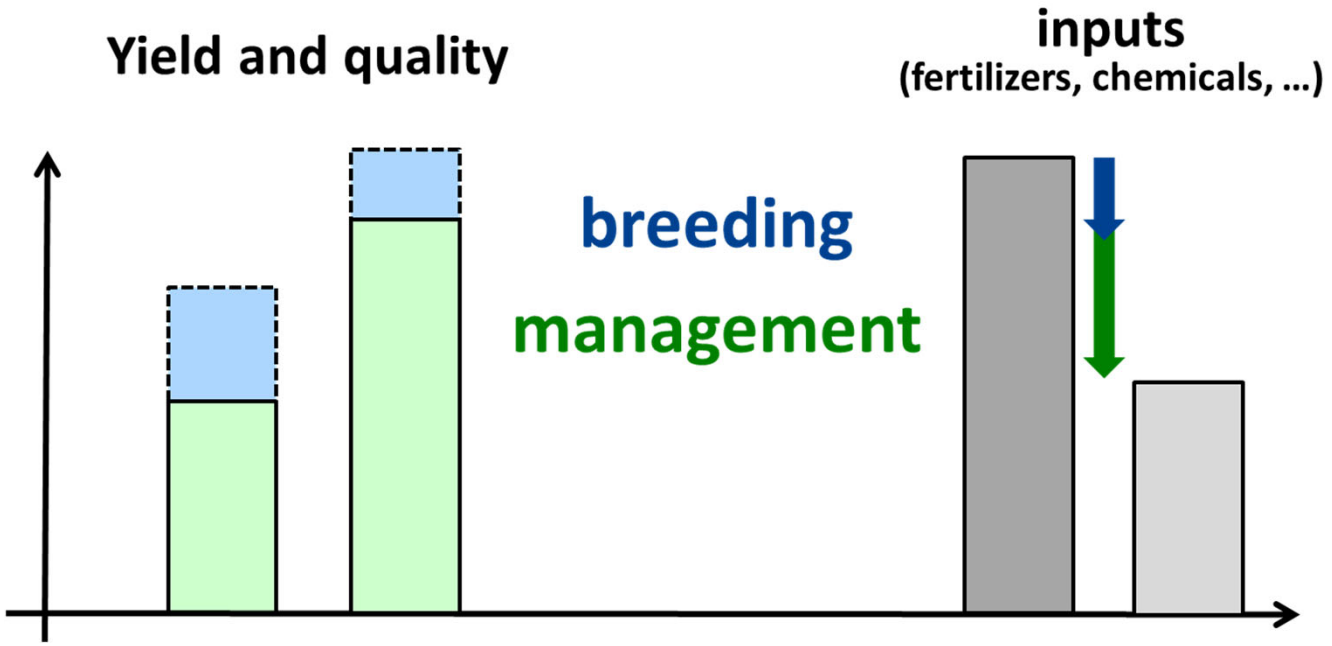
Challenges for Agriculture in the 21st century

Breeding and crop management

Quantitative, innovative data and solutions for breeding and crop management

- ➡ understand
- ➡ design
- ➡ manage



DIGITAL INNOVATION IN AGRICULTURE

PHENOROB

developing digital technologies

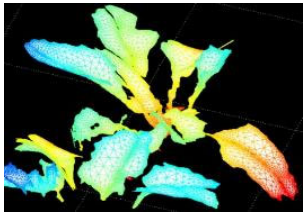

monitoring

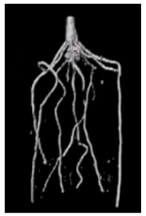

robots

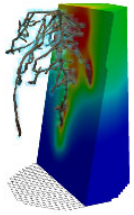

intervention

data sciences

understanding plant and soil

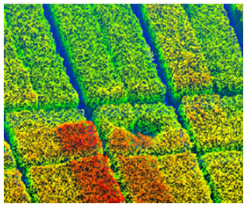


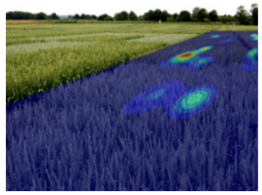


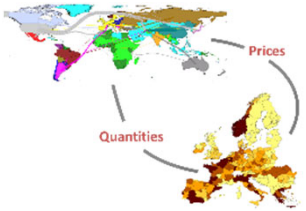


non-invasive phenotyping plant-soil interaction

integrating in environment and economy







assessing, modeling, and optimizing implications

Technology scales


remote sensing


affordable digital technology

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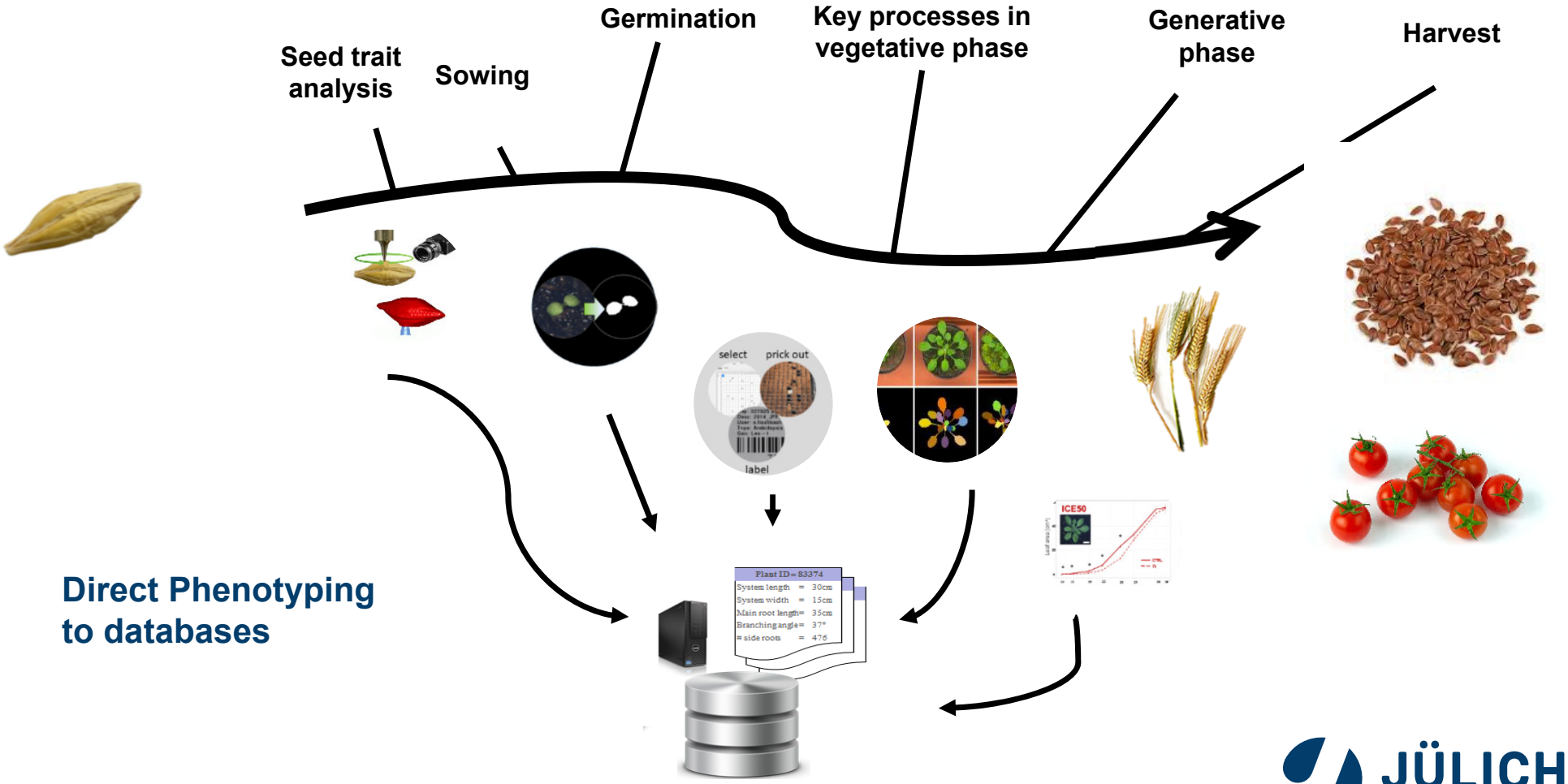
PHENOTYPING TROUGHOUT THE LIFE CYCLE



Direct Phenotyping to databases

TECHNOLOGIES COVER THE SEED-TO-PLANT LIFECYCLE

Seeds

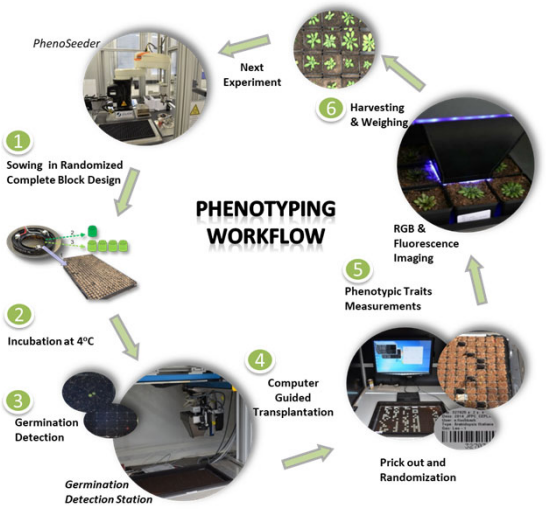
Seedling Establishment

Vegetative growth

Yield and harvested product

Phenotyping seeds and fruits

SEED PHENOTYPING – WHY?



Optimizing the phenotyping pipeline

- Reducing statistical variance in starting material (seed batches)
- Characterising the harvest

Seed physiology

- Seeds properties
- germination
- …..

Characterising germplasm

- Quantify seed characteristics in seed banks
- …..

Seed testing for seed industry

- Quality of seed progeny in commercial environment
- …..

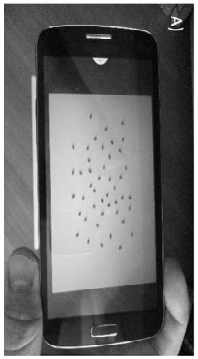
MODES OF SEED PHENOTYPING – BULK VS DETAIL

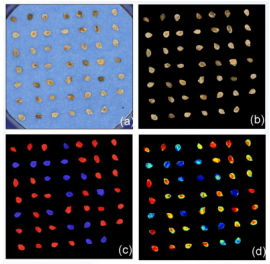
Bulk seed properties

Bulk seed Individual

CNR

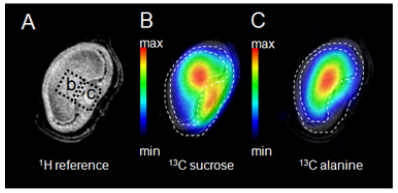
Seed individual and sorting





Extrem Detail

Fraunhofer CT



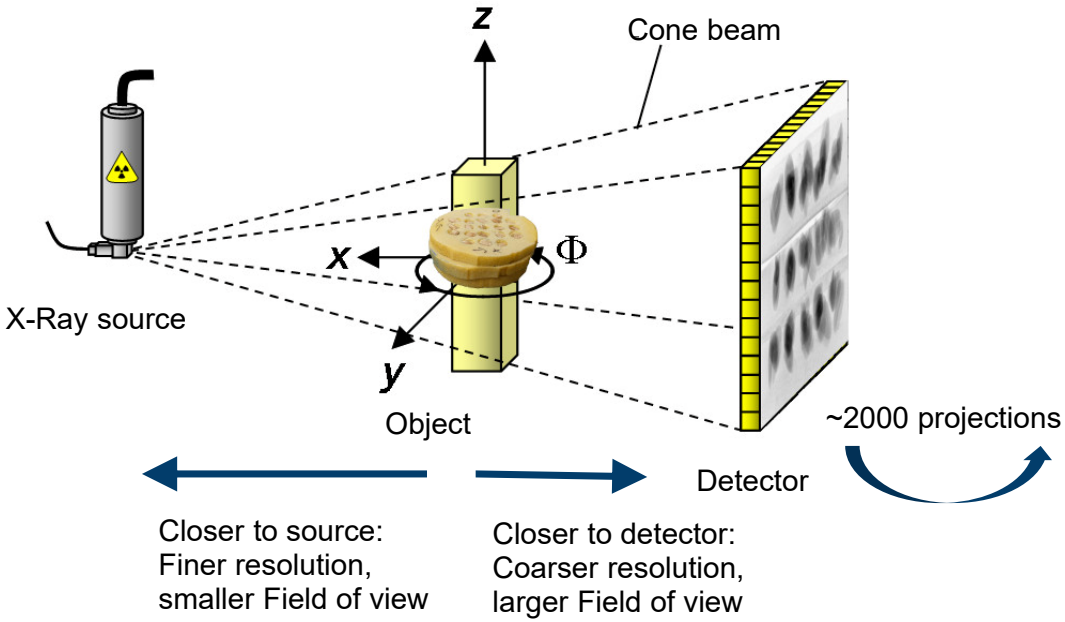
IPK High Resolution MRI

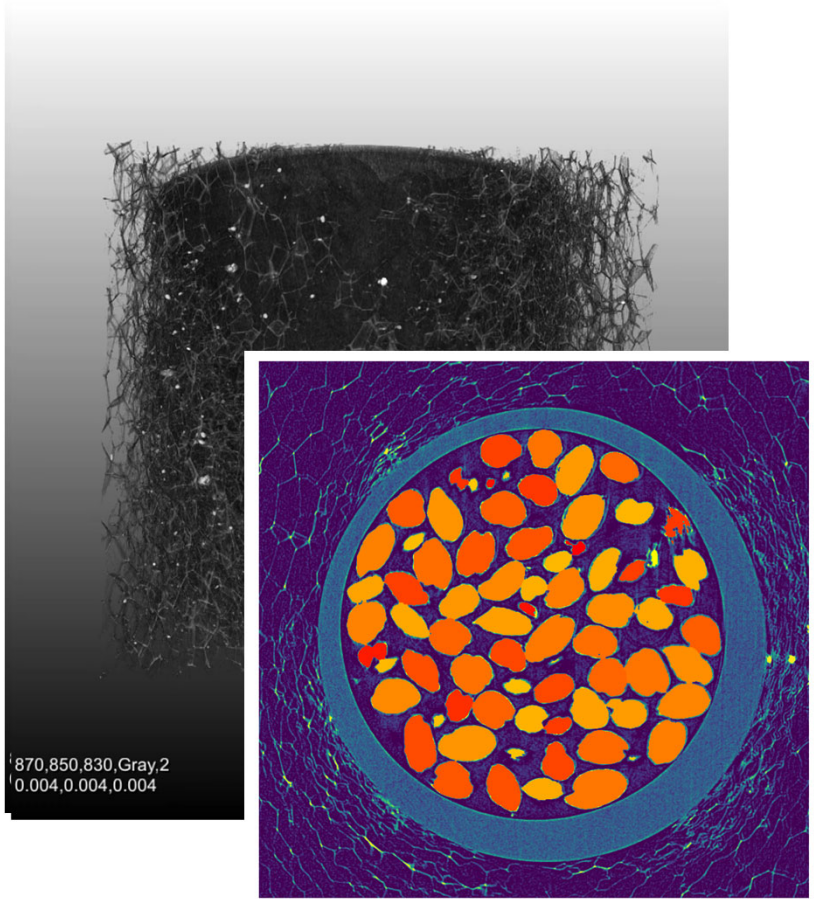
Throughput

Information

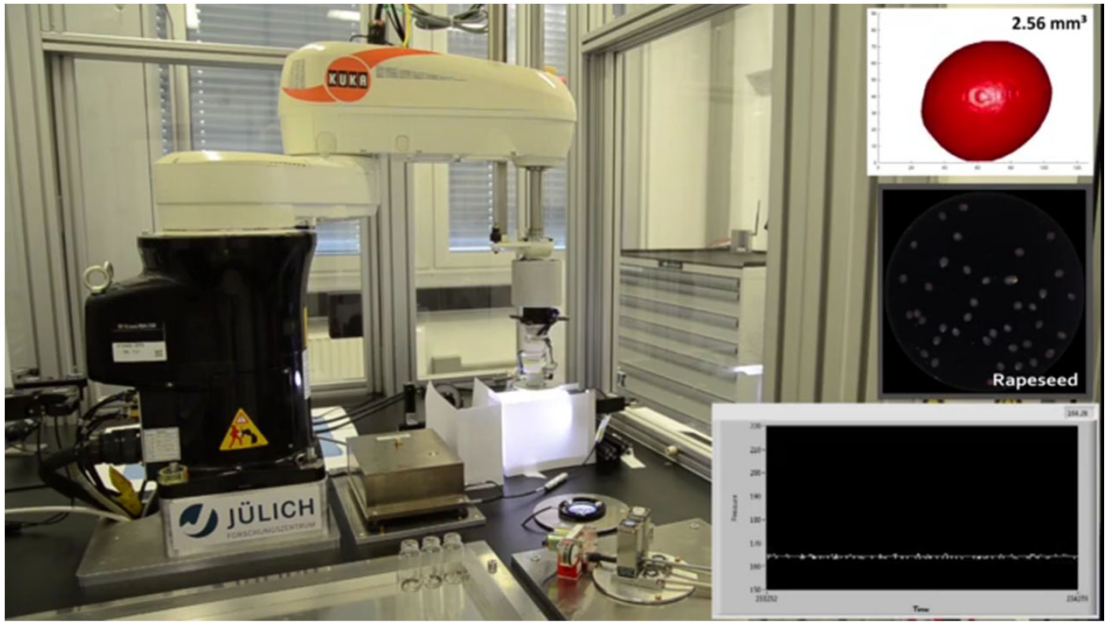
Seed batch analysis for single seed traits by CT

https://de.wikipedia.org/wiki/Kegelstrahl-Computertomographie





INDIVIDUAL SEEDS ANALYSIS: HIGH THROUGHPUT (PHENOSEEDER)



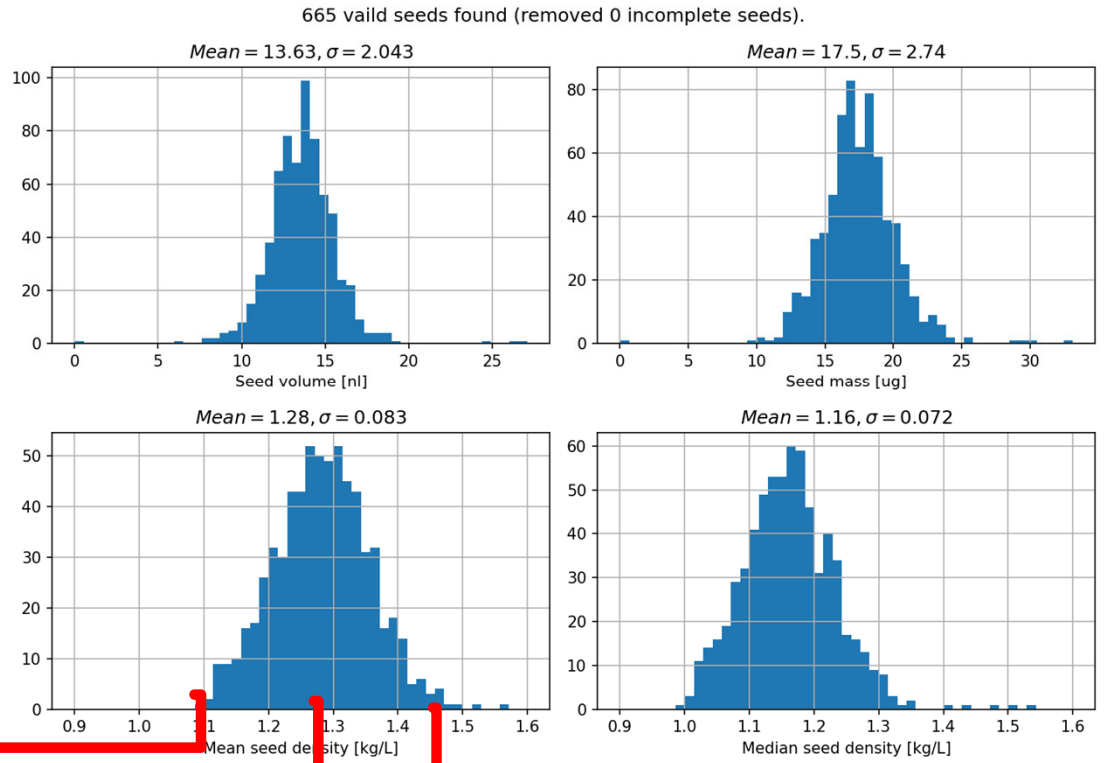
Traits

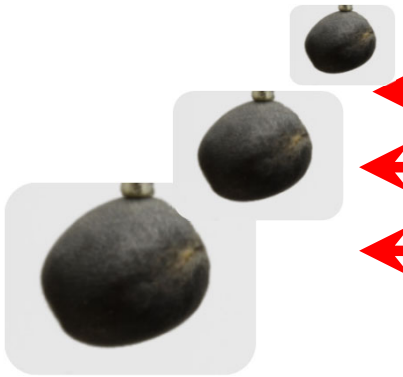
- Projected area
- Volume
- Mass
- Density
- Colour
- (3D) shape

Species

Arabidopsis thaliana (~ 700 ≠ genotypes)
Zea mays
Hordeum vulgare
Triticum aestivum
Phaseolus lunatus
Sorghum bicolor
Oryza sativa
Cardamine chenopadifolia
Solanum quitoense
Brassica napus
Nicotiana tabaccum
Boechera spatifolia
B. stricta, B. pallidifolia B. polyantha
B. divaricarpa
Sida hermaphrodita
Cardamine chenopodifolia
Arabis alpina, A. hirsuta, A. ciliate
…. And more

Analyse bulk properties, quantify trait categories and pick individual seeds for further analysis

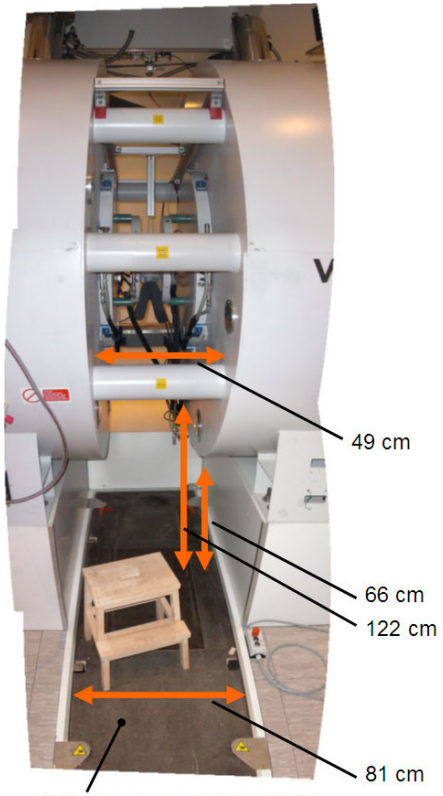




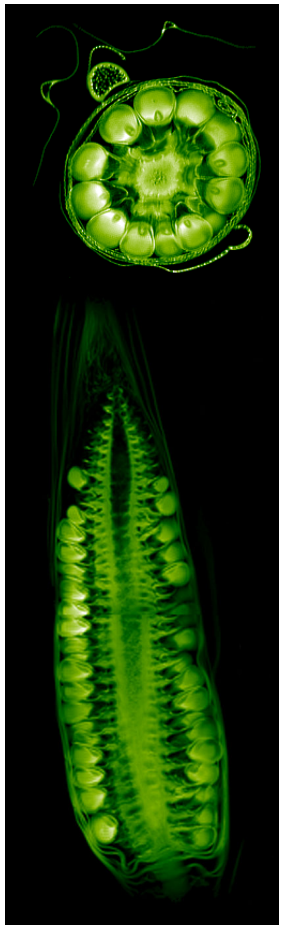
Jahnke, S. *et al.* (2016) 'phenoSeeder - A Robot System for Automated Handling and Phenotyping of Individual Seeds', *Plant Physiology*, 172(3)

PHENOTYPING OF SEED DEVELOPMENT AT THE LIVING CROP

SEED STRUCTURE IN VIVO

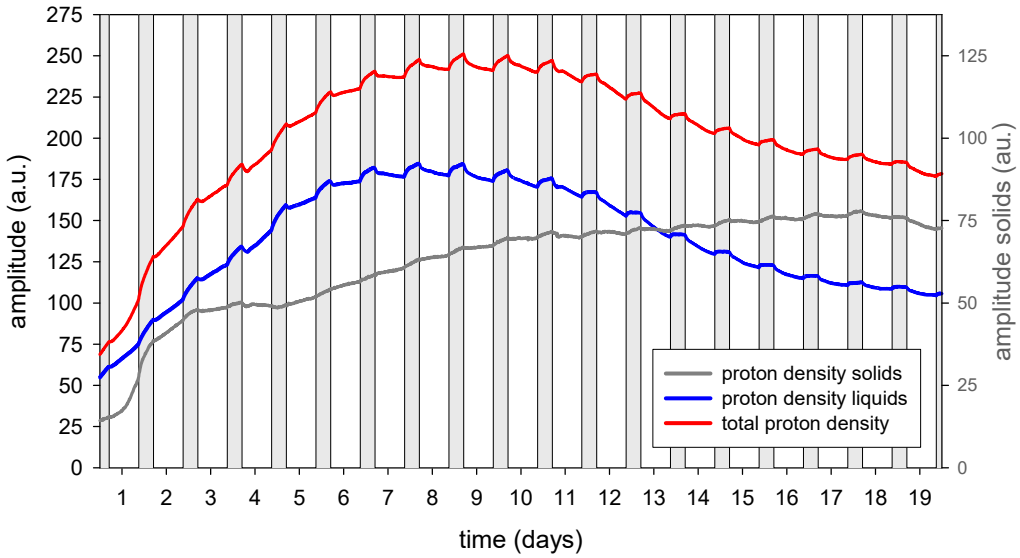


Elevator platform, can be lowered 2.4 m
Max tree height standing up: 3.6 m
Max tree height with tipping: 4.5 m



SEED FUNCTION IN VIVO

Seed filling
(high temporal resolution)



Phenotyping roots and shoots

PHENOTYPING OF ROOTS …. A SPECIAL CHALLENGE

Roots live in a special environment

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

Environmental conditions highly important

Soil environment

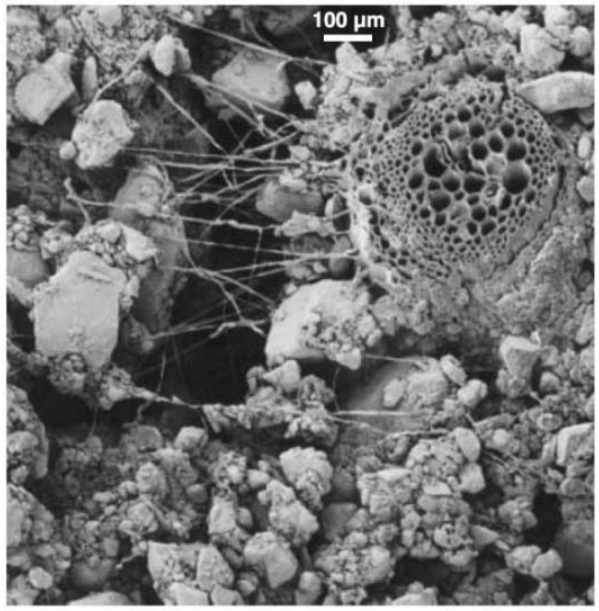


Fig. 2 Micrograph obtained by cryoscanning electron microscopy observation of the rhizosheath of buckwheat (*Fagopyron esculentum*) sampled *in situ* in field-grown plants. Development of long root hairs extending in a large macropore is clearly visible. (Reproduced by kind permission of Margaret E.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

Watt et al.2005

UNIQUE ROOT IMAGING SYSTEMS
HIGH-THROUGPUT AND DEEP PHENOTYPNG

INTEGRATING SCALES

Plant level → **Plant community** → **Field Performance**

Root system architecture

Root performance
large containers

Destruktive root samplng

1.) Characterisation of basic root traits

2.) Screening for resource use-efficiency

3.) Validation of root system characteristics

DEEP-PHENOTYPING OF SPATIAL AND TEMPORAL DYNAMICS OF ROOTS

Structure
Root **S**ystem **A**rchitecture

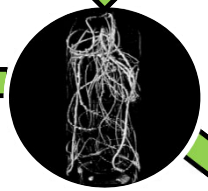
MRI
Magnetic **R**esonance **I**maging

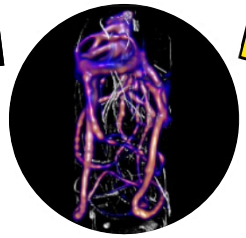
Function
Assimilate **A**llocation

CYPRES
Cyclotron for **P**lant **Res**earch

PET
Positron **E**mission **T**omograph

Trait calculation





3D-Traits Co-registration

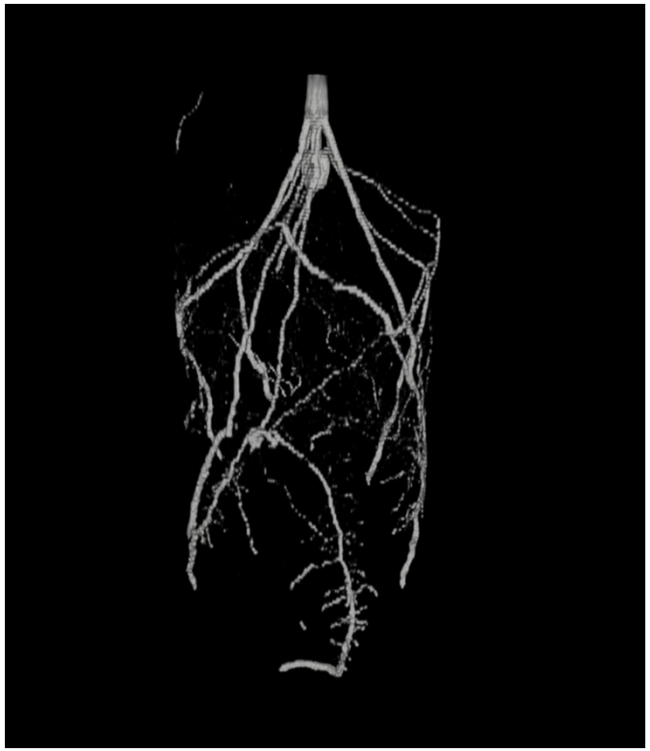
Trait calculation

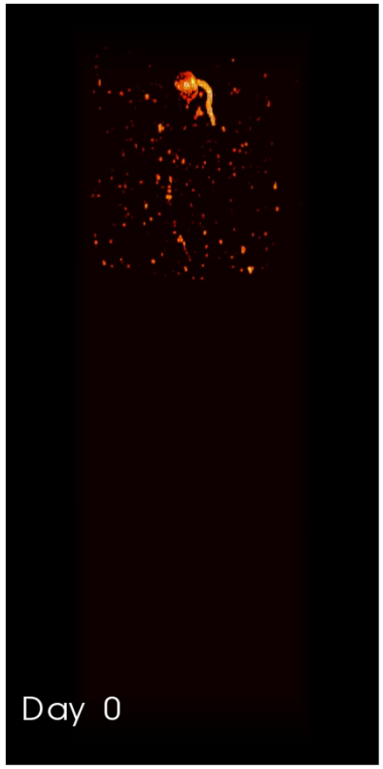
Non-invasive, live imaging of structure,growth and carbon transport on root systems in real soil

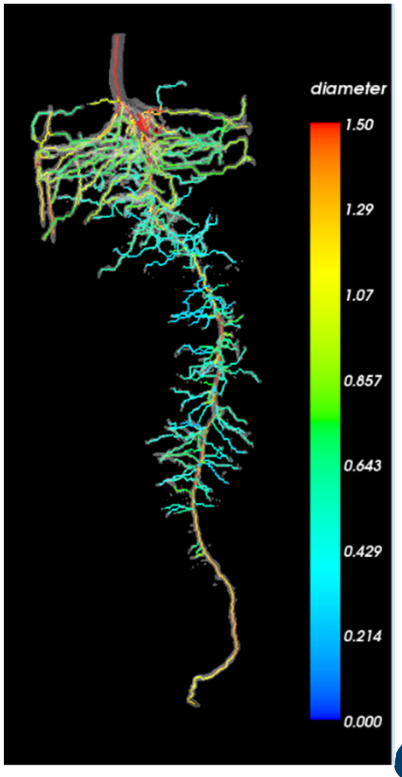
Short-term dynamics
(minutes and hours)

Day-to-day
dynamics

Quantitative,
non-invasive
morphology







Zea mays

HIGH-THROUGHPUT SCREENING IN RHIZOTRONS GROWSCREEN RHIZO III

- 850 – 1000 rhizotrons
- Automated transport
- Automated imaging

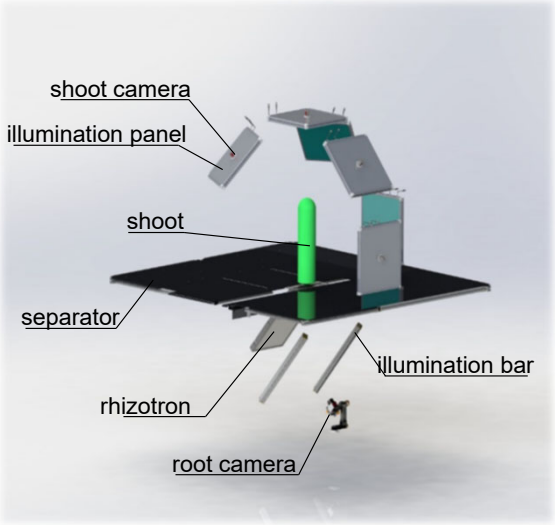


Image acquisition

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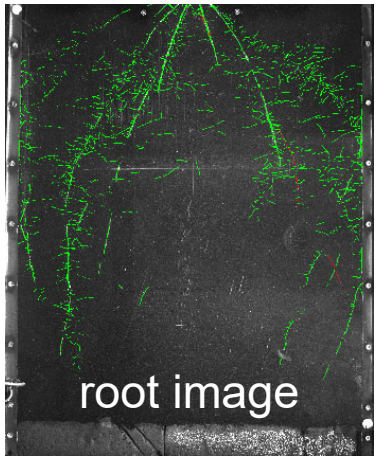
HIGH-THROUGHPUT SCREENING IN RHIZOTRONS GROWSCREEN RHIZO III

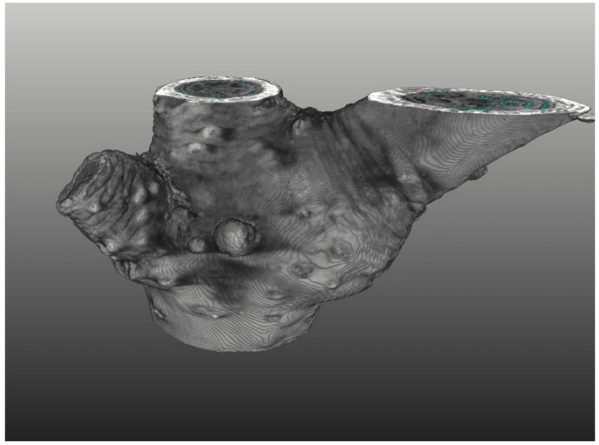
- **Shoot traits**
  - projected shoot area (computed from 6 cameras and 3 different angles)
  - estimation of plant height
  - chromatic traits
- **Dynamic shoot traits**



- **Root traits**
  - total root length
  - spatial distribution of roots
    - root length density
    - rooting depth / width
    - area covered by roots
- **Dynamic root traits**

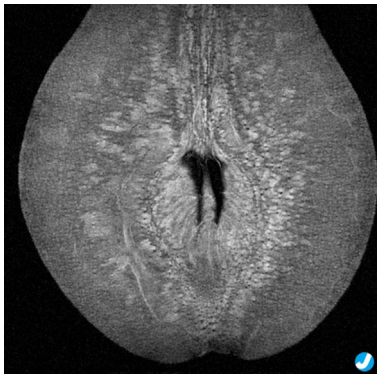
NON-INVASIVE IMAGING OF STRUCTURE AND FUNCTION

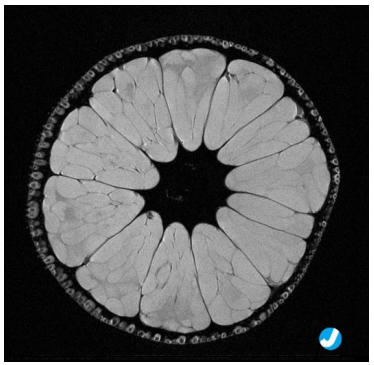
Computer Tomography of wood



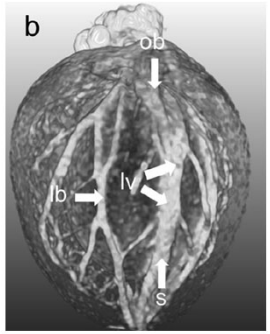
Multiple xylem vessels marked manually, segment vessel system by region growing algorithm

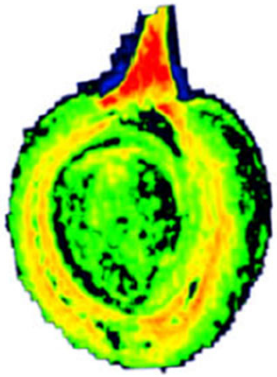
Structural MRI of fruits





Functional MRI of fruits (water uptake)





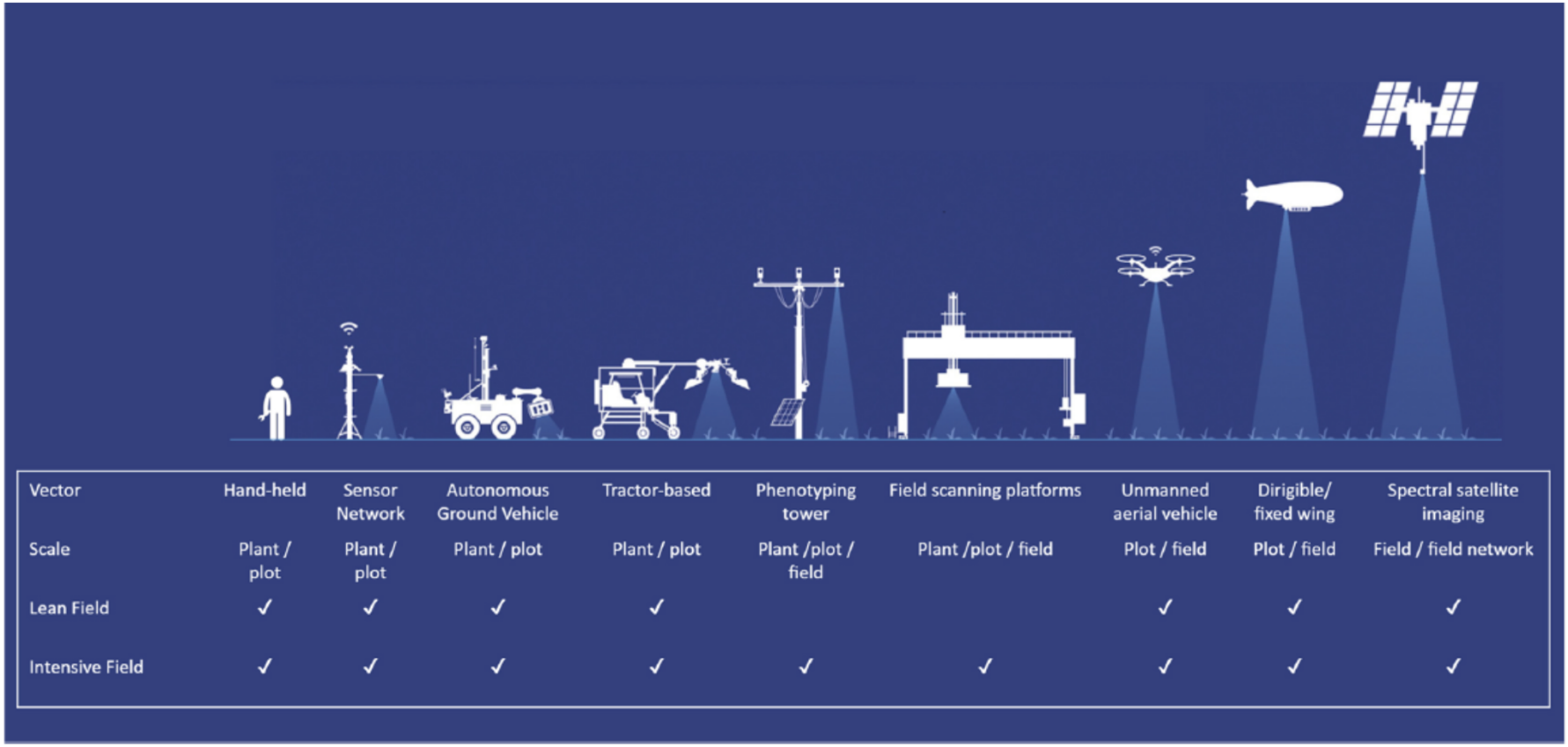
Portable MRI Formation of embolisms in fruit trees in the field

Hochberg et al. 2016

Phenotyping in the field

HOW TO ACHIEVE HIGH THROUGHPUT IN THE FIELD? USE OF THE OPTIMAL POSITIONING SYSTEMS

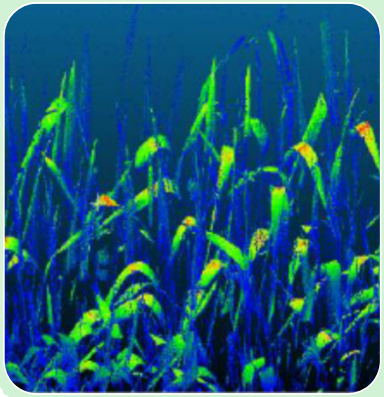
Field dynamics



Vector	Hand-held	Sensor Network	Autonomous Ground Vehicle	Tractor-based	Phenotyping tower	Field scanning platforms	Unmanned aerial vehicle	Dirigible/ fixed wing	Spectral satellite imaging
Scale	Plant / plot	Plant / plot	Plant / plot	Plant / plot	Plant /plot / field	Plant /plot / field	Plot / field	Plot / field	Field / field network
Lean Field	✓	✓	✓	✓			✓	✓	✓
Intensive Field	✓	✓	✓	✓	✓	✓	✓	✓	✓

Morisse et al. 2022 Field Crops Research

FIELD PHENOTYPING CONCEPT





Traits	Sensors	Positioning systems	Experiments	Environmental sensors
Roots Structure Water Photosynthesis	Stereoimaging PlantEye LIFT Sun-Induced-Fluorescence	Field4cycle Fieldcop Fieldsnake Fieldweasel Fieldbees	BreedFACE Phenorob Photovoltaics Cassava IITA	PPFD Air temperature Soil temperature CO_2 …

Cendrero-Mateo et al. 2016 in Chabbi et al. "Terrestrial Ecosystem Research Infrastructures: Challenges, New developments and Perspectives"
Morisse et al. 2022 Field Crops Research

POSITIONING SYSTEMS TO ASSIST QUANTIFYING SHOOT TRAITS

fieldbee (s)

fieldwing

fieldsnake

field4cycle (s)

fieldcop

fieldweasel

In functional throughput

At relevant time points

WHAT IS MEASURED?

Photosynthesis is quantified by fluorescence measured from the leaf to the sky

SIF by Fluowat

cm^2

LIFT in miniplots

cm^2-dm^2

LIFT & FLOX in sugarbeet plots

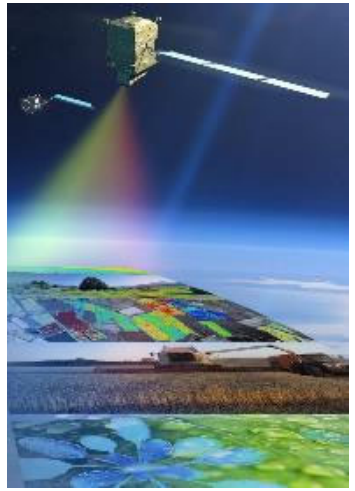
cm^2-m^2

SIF in field plots

cm^2-m^2

SIF by Hyplant in large field

$1m^2$

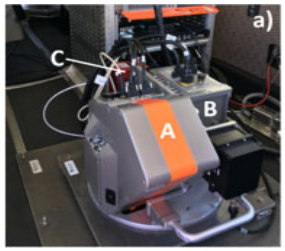


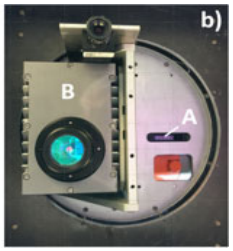
SIF by FLEX

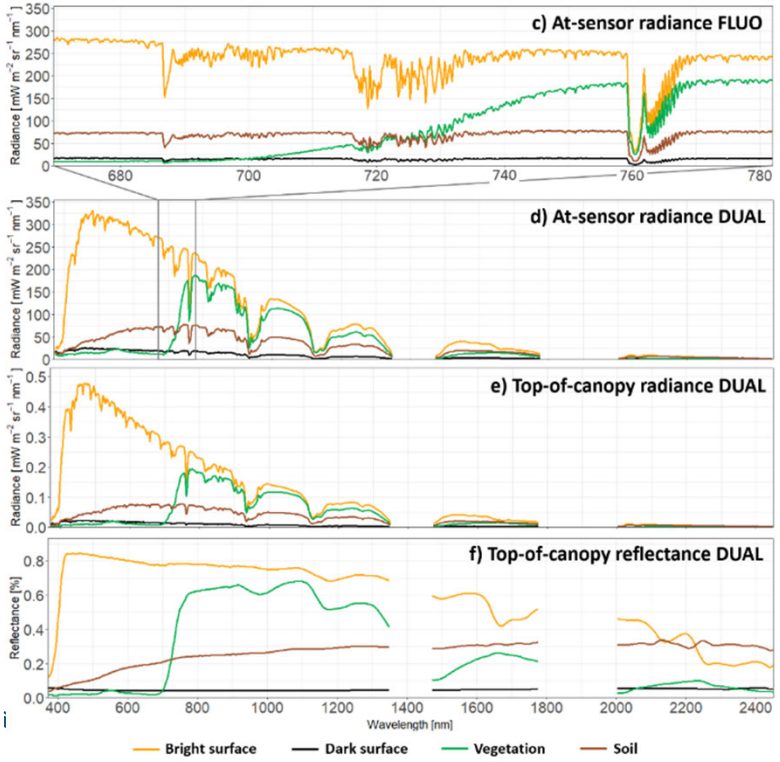
$300m^2$

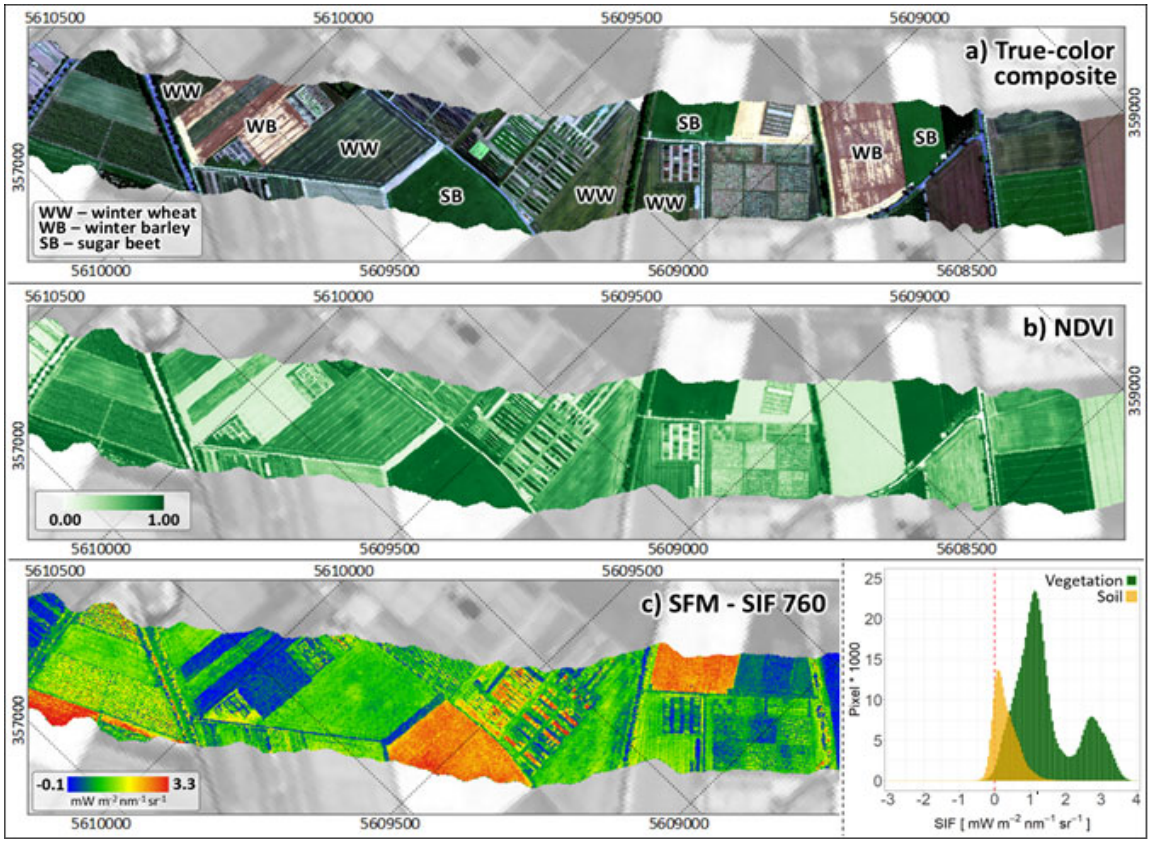
Fluorescence
- Active using a controlled light source such as in the Light Induced Transient (LIFT) device
- Passive solar induced fluorescence (SIF) measured by e.g. FLOX, Hyplant or Flex

MEASURING PHOTOSYNTHESIS (SIF) FROM THE AIRCRAFT (HYPLANT)









Siegmann et al. (2019)

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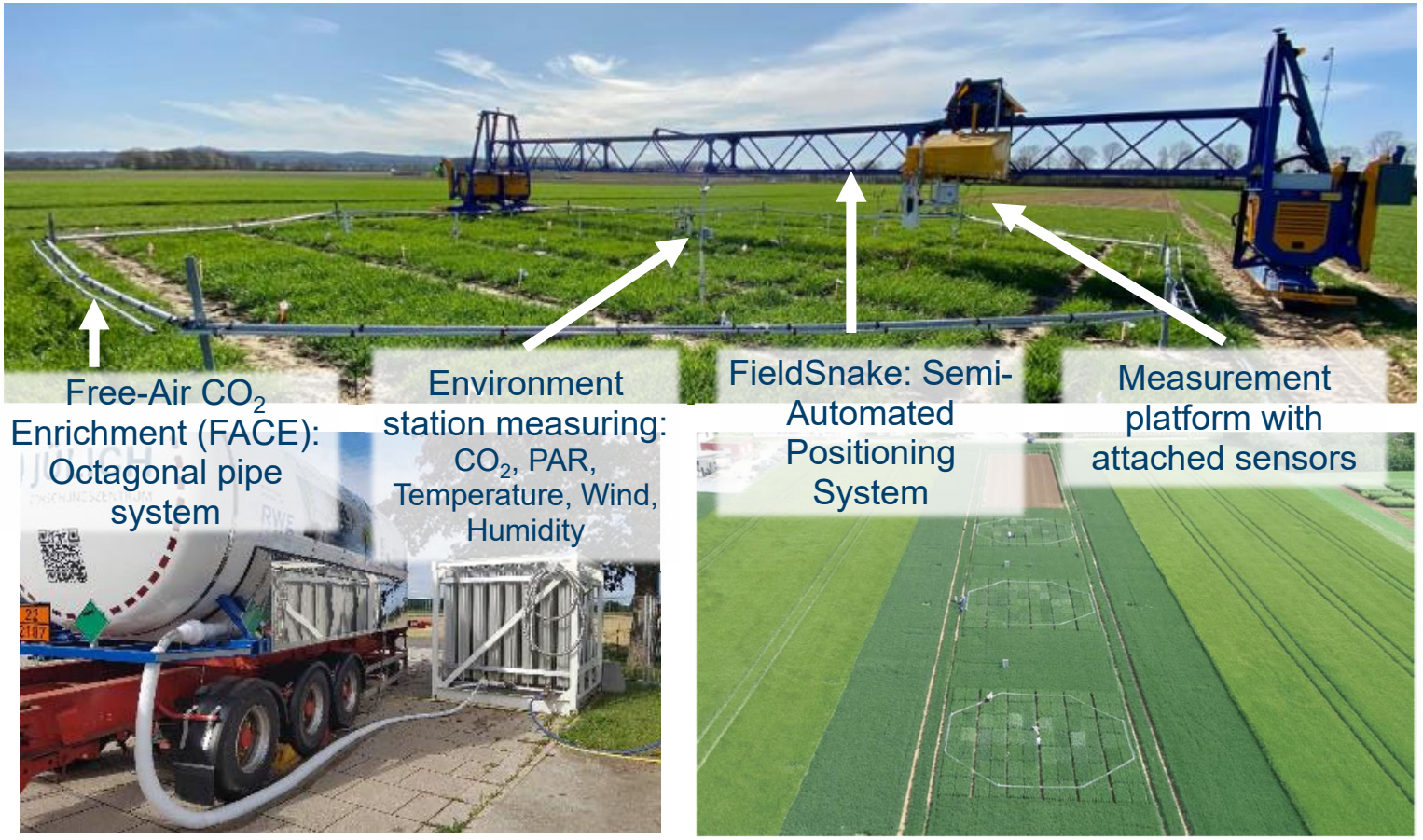
CROP PERFORMANCE UNDER FUTURE CO_2, BREEDFACE FIELD PHENOTYPING UNDER ELEVATED CO_2



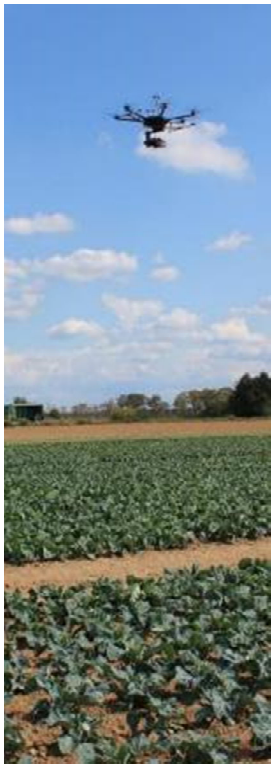
- Elevated CO_2 600ppm
- Major (german) crops e.g. winter wheat, potato, soybean

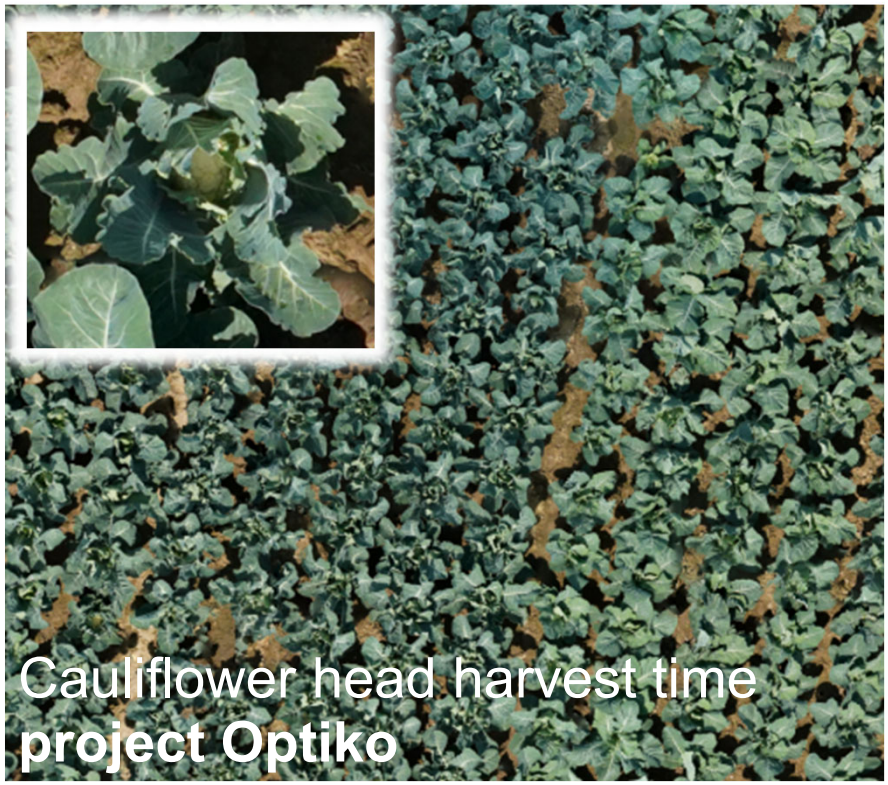
Deutsches Pflanzen Phänotypisierungs-Netzwerk e.V.
DPPN
JÜLICH Forschungszentrum

STRUCTURE AND REFLECTANCE SHOOT TRAITS

from RGB or Multipspectral cameras for horticulture applications

using machine learning techniques





Cauliflower head harvest time
project Optiko

Pod traits in bush bean ***Project Shape and Color***

Leaf diseases in carrots

Federal Ministry for Economic Affairs and Energy

Ministerium für Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen

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AGRI-PV: A NEW PRODUCTION SYSTEM WITH MANY OPTIONS

High-intensity research facility

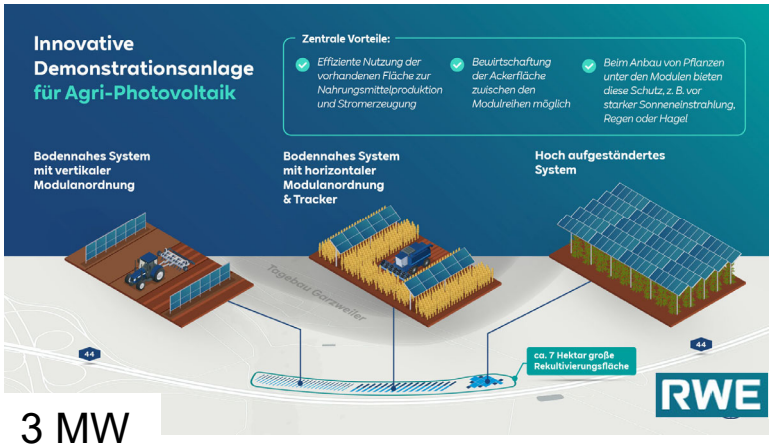
incl. new PV material development

AgriFEE - Agro-Food-Energy Park (Old Morschenich)

https://www.biooekonomierevier.de/Innovationslabor_APV_2_0

Practice and demo facilities

- In NRW
- Network Germany
- Global (different climate zones)

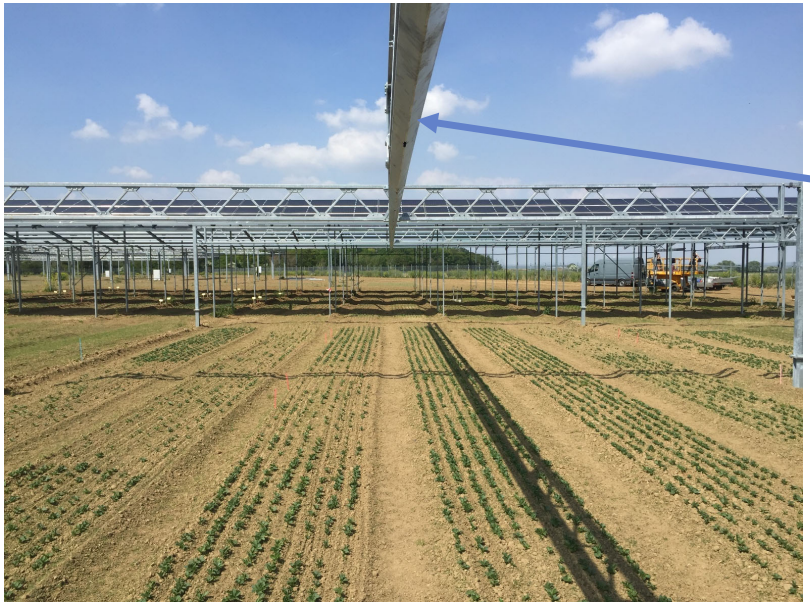


3 MW

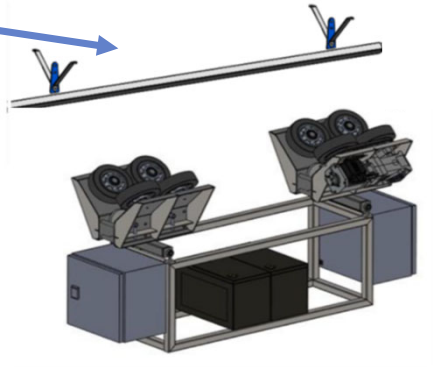
New opportunity for energy transition and agriculture (fz-juelich.de)

Cooperation networks AgriPV in Germany and Europe are under construction

PHENOTYPING IN AGRI-PV SYSTEMS



Integrated
Rail system



Original
image

Biomass -
Image

Camera car

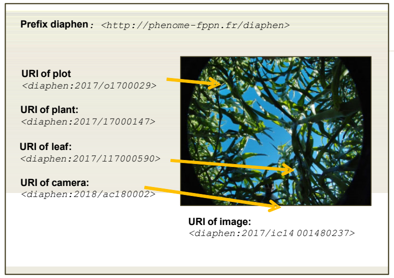
Phenotyping data systems

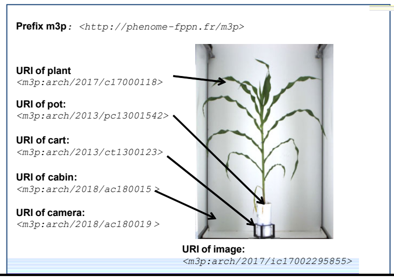
Requirements for information system

Current status → **Requirements**
Information system

All objects have unambiguous identifyers (cameras, plants, pots, sensors) URIs

Findable Reusable



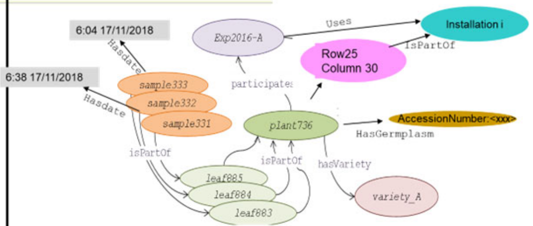


Controlled vocabulary (ontologies) for
- Objects
- Events
- Traits

Reusable

Standardize or track/ map names with 'quadruple': entity/definition/ method/unit

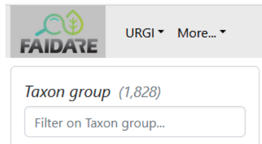
- semantic web allows automatic metadata collection



Accessible via web

Findable Accessible

Webservices



Galaxy Europe

Interoperable

Long term storage Policy
Which information kept?
With tools e.g. EGI

Findable Acccessible

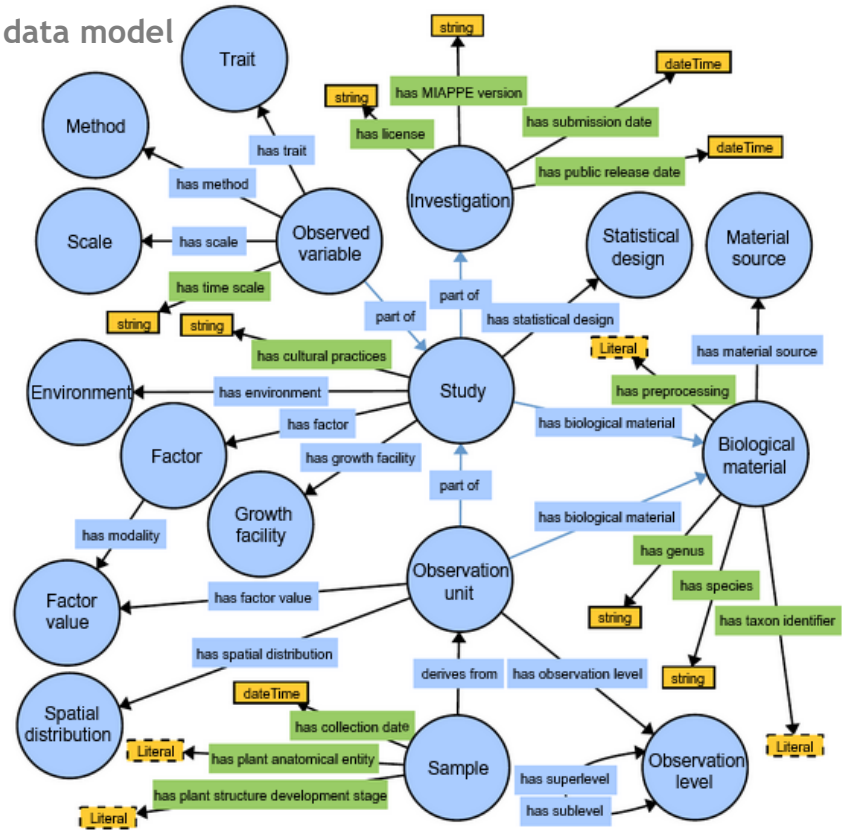
Standards: Minimum Information About Plant Phenotyping Experiment

miappe

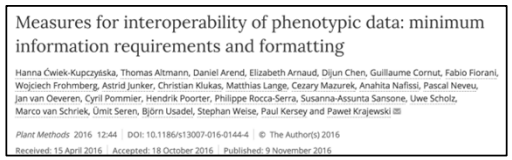
Checklist to standardize the description of experiments

BrAPI

MIAPPE data model



- Standard
  - Data exchange and traceability
  - Repositories
- Input and output for analysis pipelines developed for phenotyping data
- Implementations
  - Repositories/Databases
  - Files
  - Web Service



Measures for interoperability of phenotypic data: minimum information requirements and formatting

Hanna Ćwiek-Kupczyńska, Thomas Altmann, Daniel Arend, Elizabeth Arnaud, Dijun Chen, Guillaume Cornut, Fabio Fiorani, Wojciech Frohmberg, Astrid Junker, Christian Klukas, Matthias Lange, Cezary Mazurek, Anahita Nafissi, Pascal Neveu, Jan van Oeveren, Cyril Pommier, Hendrik Poorter, Philippe Rocca-Serra, Susanna-Assunta Sansone, Uwe Scholz, Marco van Schriek, Ümit Seren, Björn Usadel, Stephan Weise, Paul Kersey and Paweł Krajewski

Towards recommendations for metadata and data handling in plant phenotyping

MIAPPE Operation

- Contribution
  - **European Infrastructures : Elixir (Bioinformatics), Emphasis/EPPN/EPPN2020 (Phenotyping)**
  - **National Institutes: France, Germany, Poland, UK, Portugal, Slovenia, Nederland, Belgium, Italy**
- Steering committee
  - **Elixir: European Bioinformatic infrastructure**
  - **Emphasis: European plant phenotyping infrastructure**
  - **Bioversity International - CGIAR**
- Current Versions
  - **Version 1 (2016)**
  - **Version 1.1 (2019)**
  - **Adaptations to new implementations**

Methods

Enabling reusability of plant phenomic datasets with MIAPPE 1.1

Phenotyping networks

EUROPEAN PLANT PHENOTYPING NETWORK PROJECTS

2012-2015

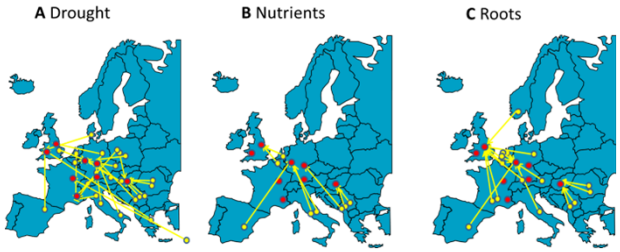
Access to 21 installations

in Europe

5.5 M€, 14 partners

Transnational access: ~2 M€

- 66 accesses > 50 publications
- >200 users directly involved in the experiments



2017-2022

Access to 31 installations

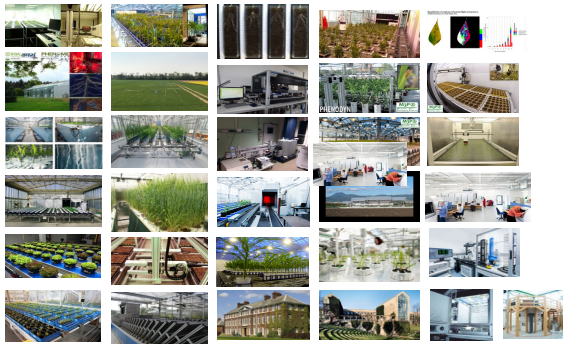
in Europe

10 M€, 21 partners

Transnational access: ~5 M€

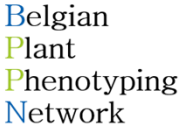
- Capacity for ~150 accesses

  expected >100 publications



Plant phenotyping initiatives to address the demand

PPN-Ireland



EUROPEAN
NATIONAL
INFRASTRUCTURE

More projects in development

EUROPEAN
REGIONAL
PROJECTS /
NETWORKS

AgroServ

EMPHASIS

ESFRI

Long-term and stable organization

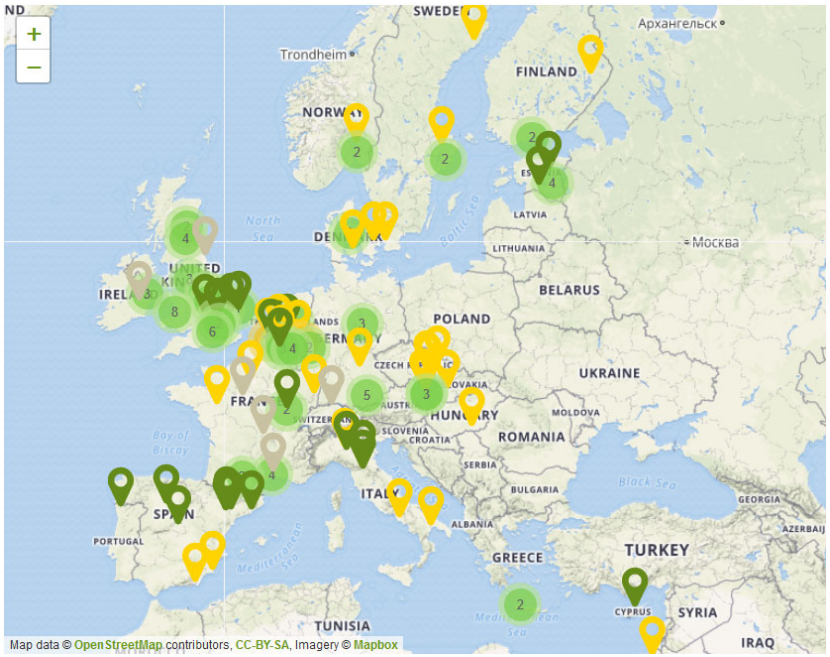
- integrating and operating a pan-European infrastructure

Objectives

DEVELOPING INFRASTRUCTURE AND PROVIDING ACCESS

Infrastructure categories in EMPHASIS

PLANT PHENOTYPING REQUIRES INTEGRATED CONCEPTS TO FULLY EXPLORE ITS POTENTIAL



Source: EMPHASIS homepage (https://emphasis.plant-phenotyping.eu/emphasis_infrastructure_map)

CONTROLLED CONDITIONS

- ✓ Greenhouses and growth chambers
- ✓ Monitoring of environmental conditions
- ✓ Throughput typically between 100-1000s plants

LEAN FIELD

- ✓ Field trials with environmental monitoring
- ✓ Phenotyping equipment for basic traits
- ✓ ground based or airborne sensing systems

INTENSIVE FIELD

- ✓ Detailed environmental monitoring
- ✓ High quality phenotyping measurements
- ✓ Semi-controlled intensive field sites

MODELLING

- ✓ Virtual platforms
- ✓ Different types of models: Crop Models, FSPM
- ✓ integrated or interfacing with installations

DATA & COMPUTATIONAL SERVICES

- ✓ FAIR Information systems plant phenotyping data
- ✓ Access to data
- ✓ integrated information systems

The road to Operation

Preparatory Phase (2017-2020)

- Funded via a H2020 grant (€4m)
- Work undertaken as per the EC proposal
- Evaluate the phenotyping landscape in Europe
- Development of business plan with user strategy, governance, …

Implementation Phase (2019-2024)

- Aligned to the long-term operations
- Governed via interim agreement to enable implementation
- Formal decision making for EMPHASIS future of operations
- Official representation of ministries/funders
- Set up of EMPHASIS pan-European Services
- Widen membership to new countries
- Set up of National Nodes

Operational Phase (2025/6 onwards)

- Long-term legal framework is in place
- Fully function governance bodies (decision-making, advisory etc.)
- Annual membership contributions to support operation
- Full access for EMPHASIS members to facilities and services

EMPHASIS towards sustainable service provision

PILOT SERVICES


Field pilot


Harmonisation pilot


Innovation pilot

TNA

Phenomics Webinar


Training pilot


Data pilot


Modelling pilot


Infrastructure map


Data sharing tools

INFRASTRUCTURE PROJECTS

AgroServ: (2022-2027)
Provide services to advance agroecology

AI4Life: (2022-2025)
Provide services to advance AI based image analysis

EOSC-Life (2019-2023)
create an collaborative space for digital biology

RI-VIS (2019-2022)
partnership to broader scientific communities

EMPHASIS
EMPHASIS-PREP (2017-2021)
Develop a business plan for EMPHASIS

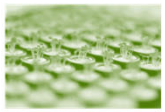
EPPN 2020
2017-2021
provide access to phenotyping facilities

Ritrain
managerial capacity building

BlueCloud ENVRI CORBEL
use synergies with biomedical and environmental research infrastructures

IPPN
Link to phenotyping centres beyond Europe


User Access: facilitate user access to installations and facilitate under controlled and field conditions


Advancing phenotyping practices: develop and implement methods, tools for phenotyping workflow


Industry engagement: facilitate knowledge and technology transfer


Data management and modelling: establish FAIR data principles and a European information system


Communication: engage all relevant stakeholders in a research infrastructure environment


Training and education: develop and implement training activities

PLANT PHENOTYPING CROSSING BORDERS AND OPENING WINDOWS FOR SCIENCE, CROP PRODUCTION AND BREEDING

14 SEPTEMBER 2023 I ULI SCHURR (U.SCHURR@FZ-JUELICH.DE),
FABIO FIORANI, MARK MÜLLER-LINOW, ONNO MULLER, UWE RASCHER AND MANY OTHERS