D3.4: Foresight study and trend analysis to evaluate future developments in plant phenotyping

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EUROPEAN INFRASTRUCTURE FOR PLANT PHENOTYPING

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Contents

Documents used in the preparation of this deliverable:

- Foresight und Roadmapping: Zukunft strategisch gestalten, https://www.kooperation-international.de/fileadmin/public/downloads/itb/info_18_12_20_SAG.pdf
- EMPHASIS-Prep Deliverable 2.1: Criteria list for infrastructure
- EMPHASIS-Prep Deliverable .2.2: Criteria list for user demand
- EMPHASIS-Prep Deliverable .2.3: Mapping: list of existing/upcoming infrastructures
- EMPHASIS-Prep Deliverable 2.4: gap analysis
- EMPHASIS-Prep Deliverable 2.5: Report on current and future user demands
- EMPHASIS-Prep Deliverable 3.2: Mapping of training activities;
- EMPHASIS-Prep Deliverable 4.1: Map of data practices
- EMPHASIS-Prep Deliverable 4.2: Data management plan
- EMPHASIS-Prep Deliverable 4.3: Link with other information systems
- EMPHASIS-Prep Deliverable 5.1: Scenarios for governance structures
- EMPHASIS-Prep Deliverable 5.2: Rules for the representation of national infrastructures
- EMPHASIS-Prep Deliverable 5.3: Options to form a legal entity
- EMPHASIS-Prep Deliverable 6.1: Report on financial and funding framework

Executive Summary

Plant phenotyping was established as a tool to address the bottleneck in basic plant science to understand the plant –environment interaction and translate this knowledge into application. Plant phenotyping has largely benefited over the alas 10-15 years from technological development in non-invasive sensor technology paired with automation and engineering leading to substantial investment and development of high throughput plant phenotyping installations. The access to the installations is demanded by the user community, which was demonstrated by the infrastructure projects EPPN and EPPN2020 leading to the development of the Research infrastructure EMPHASIS which is supposed to provide a coordinated effort to integrate the plant phenotyping activities in Europe and explore the full potential of plant phenotyping.

Plant phenotyping will most likely further benefit from technological developments and by integrated effort which includes shared use of the facilities deliver towards systemic solution of grand challenges related to sustainable agriculture. Further development will also include the use of plant phenotyping as a tool another disciplines leading to further diversification of solutions needed to address different crops, environmental scenarios, agroecology aspects etc. Commitment of policy makers and funders is essential to develop a long term strategy.

1. Scope of the trend and foresight analysis

The trend/foresight analysis deals with the elaboration of relevant factors that have an influence on future developments in plant phenotyping. The analysis is based on a close interaction with different stakeholders in EU projects such as EPPN and EPPN2020, the COST Action "The quest for tolerant varieties - Phenotyping at plant and cellular level", a range of activities during the Preparatory Phase of EMPHASIS such as a series of regional conferences, dedicated thematic workshops addressing scientific communities, input by the advisory groups (Ministry, Funder, Industry, Support Group), as well as dedicated surveys and interviews and, published reports. On this basis, various possible future scenarios are formulated for a time frame of five to ten years into the future.

In the first step, we will outline the scientific challenges and the development of plant phenotyping as an important tool to advance plant science. In the second step we evaluate the current state of the plant phenotyping community by bibliometric, PESTEL and SWAT analysis and draw final conclusions about potential future developments and requirements to advance plant phenotyping.

2. The scientific challenges and the development of plant phenotyping

2.1 Scientific Challenges

The key scientific challenge in EMPHASIS are easy to describe but difficult to reach: it is the understanding of the interaction between plants and the environment, which includes basic understanding of plant processes and translation of these processes into application i.e. into breeding. Basic plant processes such as photosynthesis and transpiration are the basis of life of our planet, as we know it today. Targeted modification of plants properties such as yield has been initiated over 10000 years ago when people started to use plants for domestic purposes, which fundamentally altered the course of human history[1]. The adaptation of plants to cultivation was vital to the shift from hunter-gatherer to agricultural societies, and it stimulated the development of cities and modern civilization.

[1] Zohary D, Hopf M, Weiss E (2012) Domestication of Plants in the Old World. Oxford University Press, 4th edition

Within the last few decades, genomics has revolutionized our understanding of plants and plant breeding. High-definition genotyping can now be performed with thousands of plants in robotised platforms, which allows for an increasing speed of genotype selection in breeding programs. However, to understand the relation between the plants, their genetic makeup and the environment is essential to establish the relationship between genes and plant trait - the structural and functional properties of plant that determine its growth and productivity in a given environment. Quantitative measurement of such plant traits - plant phenotyping - has become the bottleneck in understanding the relation in particular if the expression is dependent on the environment, particularly in case where complex, quantitative traits are under polygenic control, i.e. depend on hundreds or thousands of genes. Such traits are often highly relevant for key plant processes such as growth, performance and resource use efficiency.

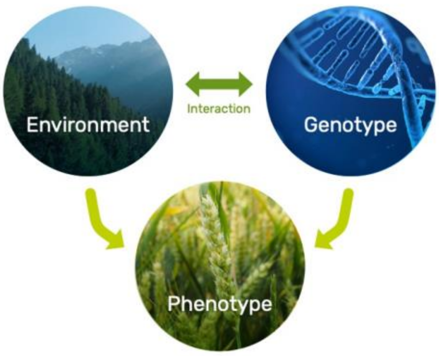

Figure 1: The interaction between the GENOTYPE and the ENVIRONMENT determines the PHENOTYPE.

To quantitatively assess phenotypic traits under the prevailing environment we need a large diversity of very precise methods and technologies that can address a large diversity of plant and the specific traits of interests in model plants, diverse crops and forests. We need to bridge scales from single plants in a greenhouse to vast agricultural areas, address time scales from nanoseconds during light conversion in photosynthetic processes to extended seasonal development, and all that in multiple environmental scenarios. This challenges requires in particular an integration of the community and the establishment of a distributed infrastructure to build installations that are needed and share those, to develop common experimental and data standards and as such advance the plant phenotyping community at large.

2.2 The lead-up to the EMPHASIS infrastructure

The quantitative assessment of plant structure and function has been addressed by plant biologists for decades, yet usually often by using manual or invasive i.e. destructive methods. First approaches to use non-invasive, camera based systems to measure plant traits started in the 1990s by measuring just single organs[2]. The non-invasive approaches were further developed within the next decade leading to 3D shoot imaging approaches[3] functional imaging[4,5], imaging or root and shoot properties[6], transport processes[7]. Application of non-invasive technology for plant phenotyping in high throughput started with the model plant *Arabidopsis*[8] with a sufficient number of genotypes providing the opportunity to associate traits to the genetic make-up of a plant. Further development of new technology and automation has led to the establishment of first companies providing plant phenotyping equipment such as Lemnatec[9] or PSI[10] as well as plant phenotyping projects to address *Arabidopsis* phenotyping in FP6 AGRON-OMICS[11], develop technology for phenotyping of different crops and plant organs in FP7 projects SPICY[12], EURooT[13], DROPS[14]. Those projects indicated an increasing demand for plant phenotyping technology which has led to the FP7 I3 project EPPN[15] (2012-2015 European Plant Phenotyping Network) a starting

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[2] Schmundt D, Stitt M, Jahne B, Schurr, U (1998) Quantitative analysis of the local rates of growth of dicot leaves at a high temporal and spatial resolution, using image sequence analysis. Plant Journal 16, 505-514

[3] Biskup B; Scharr H, Schurr U, Rascher U (2007) A stereo imaging system for measuring structural parameters of plant canopies. Plant, Cell and Environment 30, 1299-1308

[4] Genty B, Meyer S (1995) Quantitative mapping of photosynthesis using chlorophyll fluorescence imaging. . Australian Journal of Plant Physiology 22, 277-284

[5] Chaerle L, Leinonen I, Jones HG, Van Der Straeten D (2007) Monitoring and screening plant populations with combined thermal and chlorophyll fluorescence imaging Journal of Experimental Botany 58, 773-784

[6] Walter A & Schurr U (2005) Dynamics of Leaf and Root Growth: Endogenous Control versus Environmental Impact. Annals of Botany 95, 891–900

[7] Jahnke S et al (2009) Combined MRI-PET dissects dynamic changes in plant structures and functions. The Plant Journal 59, 634-644

[8] Granier C et al (2006)PHENOPSIS, an automated platform for reproducible phenotyping of plant responses to soil water deficit in Arabidopsis thaliana permitted the identification of an accession with low sensitivity to soil water deficit. New Phytologist 169: 623-635

[9] https://www.lemnatec.com/

[10] psi.cz/

[11] https://cordis.europa.eu/project/rcn/85221_en.html

[12] http://www.spicyweb.eu/

[13] http://www.euroot.eu/

[14] https://www6.inra.fr/dropsproject

[15] http://www.plant-phenotyping-network.eu/

community project that provided transnational access to 23 experimental plant phenotyping installations resulting in 66 transnational access experiments. Based on the success of EPPN and the increasing demand for plant phenotyping a H2020 advanced community I3 project EPPN2020[16] was approved (2017-2021) enabling 153 transnational access experiments within 31 key plant phenotyping installations. Furthermore, the COST Action "The quest for tolerant varieties - Phenotyping at plant and cellular level" started in 2011 and created a network and very intense interaction of European scientists with expertise on phenotyping, various omics areas plant physiology important to understand tolerance[17].

In parallel there was a substantial investment in establishing national plant phenotyping infrastructure for instance the German Plant Phenotyping Network (DPPN, 2012-2018: 35 Mil €), The French Plant Phenotyping Network (FPPN, 2013-2020: 30 Mil €), UK with BBSRC and ERC grants (25 Mil €), Belgium (2.5 Mil €) representing many of the installations in EPPN and EPPN2020. The current investment in plant phenotyping infrastructure is estimated to reach over 200 Mil € (own estimates based on the mapping activities Deliverable 2.3).

All these concerted activities have led to a well-established community addressing highly relevant questions, which is indicated by the rising numbers of publication in this field (**Figure 2**). A recent bibliometric study that analysed scientific publication within the field of plant phenotyping for the years 1997 - 2017 indicates that EU co-authors were involved in 41.8% of the analysed papers, followed by USA (15.4%), Australia (6.0%), and India (5.6%) indicating the Europe's leading role of in this field[18]

[16] https://eppn2020.plant-phenotyping.eu/

[17] http://www.cost.eu/COST_Actions/fa/FA1306

[18] Costa et al (2019) Plant Phenotyping Research Trends, a Science Mapping Approach. Front. Plant Sci. 9:1933. doi: 10.3389/fpls.2018.01933

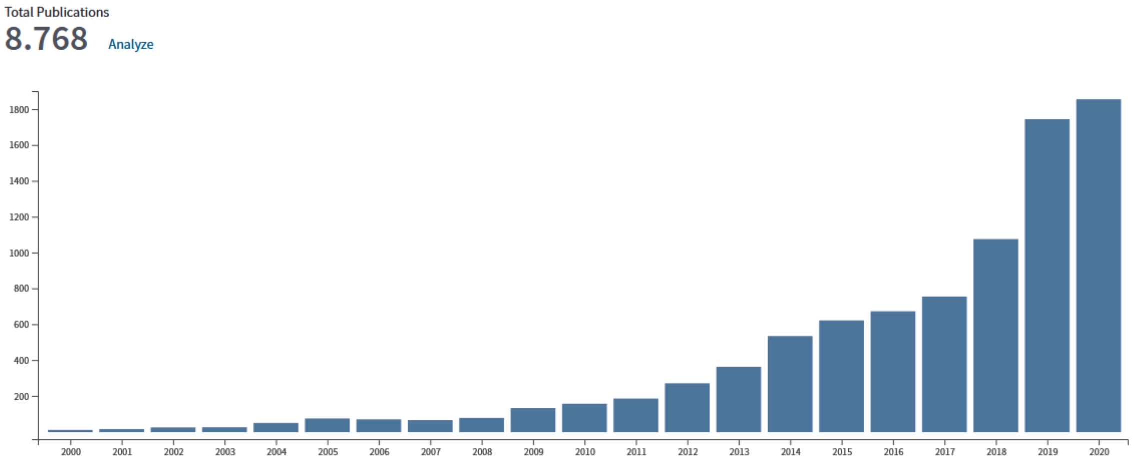

Figure 2: Number of publications from the Web of Science (Clarivate Analytics) that include the tern "plant phenotyping".

Thus, the European community is well established to build a pan-European plant phenotyping infrastructure. EMPHASIS marked then the successful application and entry onto the 2016 ESRFI Roadmap as the only new infrastructure added at that time as part of the Health and Food domain. EMPHASIS has entered the Implementation Phase with 11 countries (last update: June 2021) forming the Interim General Assembly (IGA) to make decisions about future operations.

The key aspect and highest priority for EMPHASIS is the provision of highly demanded services that enable excellent science. Users of phenotyping services will have access to novel methods and technology under controlled and field conditions, which will be complemented by modelling and data and computational services. This will allow the European scientists quantify a diversity of plant traits and enable the analysis of genotype performance in in current and future agro-climatic scenarios. Further development and evaluation of the very dynamic field is important to fully utilize the potential of EMPHASIS to become the nucleus for the quantum leap in understanding plant environment interaction and translation of this knowledge into breeding needed to address future grand challenges.

3. Evaluating the current status of plant phenotyping within the framework of EMPHASIS

3.1 Plant phenotyping contributes to a diversity of research fields

Plant phenotyping has benefited within the last decades from technological developments in non-invasive sensor technologies to increase our understanding of the interaction of plants with the environment. A bibliometric analysis of the scientific publications using the term "plant phenotyping" in the Web of Science (Clarivate Analytics) has resulted in a large number of research areas where plant phenotyping is contributing to. Science technology, plant science, genetics heredity are the top three research areas and a number of disciplines goes beyond plant sciences (**Figure 3**).

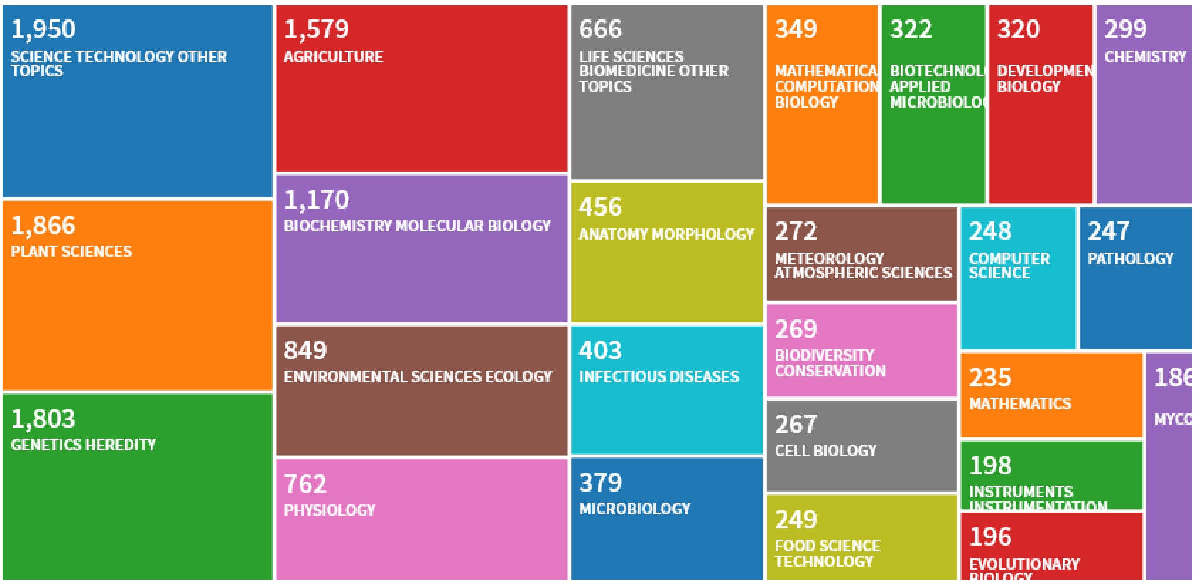

Figure 3: Number of publications from the Web of Science (Clarivate Analytics) that include the term "plant phenotyping" within different research fields within Europe between 2000 – 2020.

With respect to past and current developments plant phenotyping has benefited from technological developments mostly around non-invasive optical sensors used in plant phenotyping facilities. A bibliometric analysis indicates a rather parallel increase of publications related to plant phenotyping and image analysis (**Figure 4**). It is very likely that novel technological, hardware and software solutions will further enhance the development in this field particularly. The bibliometric analysis with combined terms "plant phenotyping" and "robotics" indicates an increase in publications within the last few years (**Figure 4**), which may further increase and be extended when considering the increasing use of machine learning approaches, nano- and quantum technology, gene editing or synthetic biology etc. Thus, further development and application of the technology within the framework of EMPHASIS is expected to further stimulate the development and widen the application of plant phenotyping well beyond plant sciences.

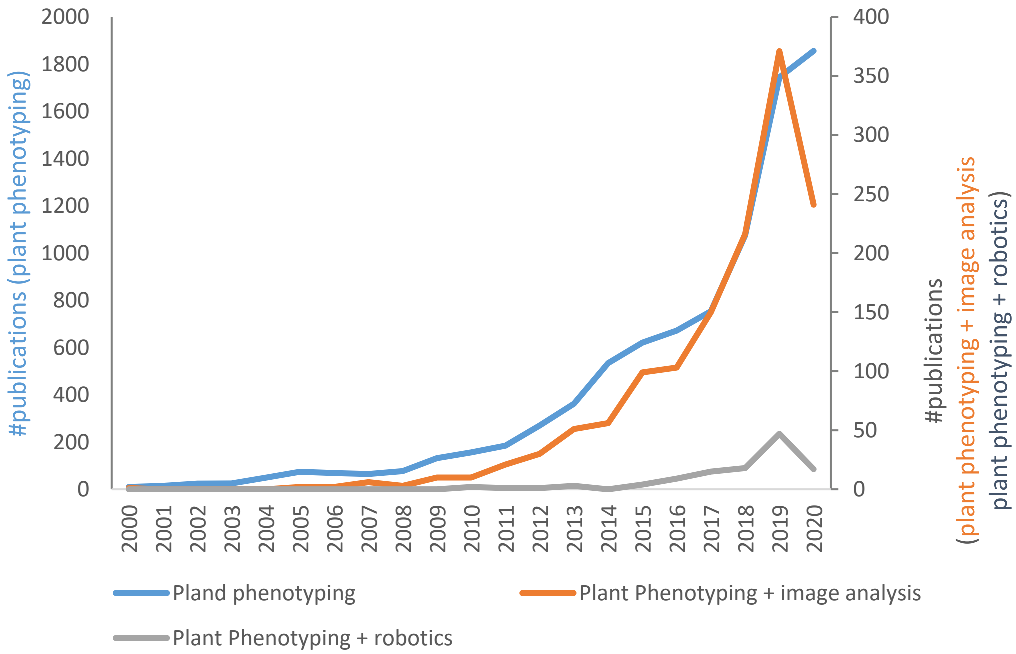

Figure 4: Number of publications from the Web of Science (Clarivate Analytics) related to "plant phenotyping", "plant phenotyping + image analysis" and "plant phenotyping + robotics" between 2000 - 2020.

3.2 PESTLE and SWOT analysis

In order to **analyse the factors that may have an impact on plant phenotyping we performed a PESTEL (Table 1) and SWOT (Table 2) analysis** to assess the current situation for plant phenotyping as a basis to draw conclusions for potential future trends and developments. This analysis will be regularly performed by EMPHASIS to analyse plant phenotyping with focus on the user demand from academia and industry as well as new technological developments and their potential to address new relevant questions to relevant for sustainable and resilient agriculture.

Table 1: Results of an PESTLE analysis on EMPHASIS

Description of the environment	
Political	**Global perspective in a framework of national and European research strategies:** • The European Union has committed itself to foster bioeconomy with a strong plant science / breeding sector as a driving force by developing and implementing several strategies (Greed Deal[19], EU approach to sustainable development[20], The Bioceconomy Strategy[21]; Food 2030[22]; Partnership on agroecology living labs and research infrastructures[23]). Many European countries have developed and implemented national bioeconomy strategies (e.g. Belgium, Finland, France, Germany, Italy, The Netherlands, Norway). • Bioeconomy and sustainable food production represent important elements in the Horizon Europe funding. • Research and innovation particularly in the agricultural sector are considered by many European countries as drivers for economic growth and welfare, resulting in an increase of funding in this sector. • European Commission has identified four major strategic objectives for the new European Research Area[24]: (1) investments and reforms in research towards green and digital transition, (2) strengthen mobility of researchers, (3) boost market uptake, and (4) improve access to excellence. **EMPHASIS specific perspective:** • Research Infrastructures represent an important strategic pillar for the European and national research agendas with plant phenotyping and

19 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
20 https://ec.europa.eu/info/strategy/international-strategies/sustainable-development-goals/eu-holistic-approach-sustainable-development_en
21 https://ec.europa.eu/info/research-and-innovation/research-area/environment/bioeconomy/bioeconomy-strategy_en
22 https://ec.europa.eu/info/research-and-innovation/research-area/environment/bioeconomy/food-systems/food-2030_en
23 https://ec.europa.eu/info/research-and-innovation/research-area/agriculture-forestry-and-rural-areas/partnership-agroecology_en
24 https://ec.europa.eu/info/research-and-innovation/strategy/era_en

	EMPHASIS mentioned in a number of European and national Infrastructure Roadmaps • EMPHASIS is in the Implementation Phase the negotiation within the Interim General Assembly of EMNMPHASIS Implementation Phase and within the national governments of the involved countries may be a lengthy process before starting full operation • EMPHASIS contributes significantly and uniquely to ERA by harmonising activities of plant phenotyping facilities across Europe, supporting interoperability of national funding schemes supporting Green Deal, driving the transformative change needed to ensure food security, and providing access to excellent services around plant phenotyping.
Economic	**Global perspective in a framework of national and European development:** • Plant breeding contributes 14 Billion EUR to the European GDP and plant phenotyping is currently the major bottleneck limiting further advancement in breeding[25]. • Every per cent of crop yield growth in Europe creates additional social welfare of about 500 Million Euros. • Investments that address the phenotyping bottleneck create more competitive agricultural and food market • Increase and stable plant production stabilizes the agricultural market in Europe and beyond • A major bottleneck for innovation in terms of bringing new products and services on the market is a lack of integration of plant phenotyping related stakeholders (academic, industry, politics, legal issues). • Plant phenotyping technology has the potential to be used in many domains beyond breeding and agriculture. **EMPHASIS specific perspective:** • Substantial investment has been done in Europe to establish a plant phenotyping infrastructure

[25] http://www.plantetp.org/system/files/publications/files/hffa_research_paper_plant_breeding_eu.pdf

	• Integration of the national efforts into a European perspective is important to optimize investment in new facilities as well as effectively utilize and harness innovation
Sociological	**Global perspective in a framework of national and European development:** • Migration movements towards Europe from Africa and Middle East to Europe may increase, based on the economic situation, climate change effecting agriculture as a major pillar for many of them. • Plant phenotyping technologies make the agricultural and food sector more attractive, which may reduce rural exodus in particular in Eastern Europe. • Stable food prizes in Europe and beyond • Genetically Modifies Organisms (GMOs) as well as New Genomic Techniques (NGT) are not accepted by the public and plant breeding is often associated with GMOs/NGT **EMPHASIS specific perspective:** • EMHPHASIS may play an important role by engaging global plant breeding organisations and initiatives such as CGIAR and play an important role in knowledge and technology transfer • Communication of the benefits of NGT towards different stakeholders to informed about the need and benefits of these techniques (e.g. to address the goals of the Green Deal or the Sustainable Developmental Goals) are important and can be facilitated by EMPHASIS
Technological	**Global perspective in a framework of national and European development:** • Open data is recognised as the next bottleneck to enable reproducible and as such reusable data and the European Open Science Cloud (EOSC) is integrating data management on the pan-European scale. Data sciences are largely supported financially in many European countries. • New technologies with focus on robotics, machine learning etc. are often developed and implemented on national level. Diversification of technology and methods occurs to address large amount of crops under various environmental scenarios

	• High-throughput sequencing on plant genetics is expected to further deliver massive amount on plant genotypic information, resulting in an increasing demand on high-throughput phenotyping technologies. **EMPHASIS specific perspective:** • Integration of date management from plant sciences is an important goal of EMPHASIS, which will contribute to the EOSC. • Integration of technological developments and implementation of these technologies in plant phenotyping requires a concerted approach of EMPHASIS to avoid fragmentation and doubling of efforts in Europe. Thus, EMPHASIS needs to facilitate the optimization of the investment in new demanded technologies and the utilization of these technologies in plant breeding, precision agriculture etc.
Environmental	**Global perspective in a framework of national and European development:** • Climate change related impact on agriculture and food production is expected to increase for the next decades. • No major land reserves remain in Europe for farming, raising the requirement that about 90 % of future crop production increase has to be based on yield growth instead of farm land extension • Increasing demand for non-food crops competing with food crops puts additional pressure on plant production • CO_2 emissions from agriculture account for 10% of the total carbon emissions[26] • Agriculture has a substantial environmental impact e.g. through the increased use of nutrients in agricultural production[27] • Recent COVID-19 pandemic illustrates the requirement to preventitive address agricultural and ecological challenges related to zoonosis **EMPHASIS specific perspective:** • Plant phenotyping is the bottleneck in breeding of varieties that increase the yield and minimize the impact on the environment

[26] https://ec.europa.eu/eurostat/statistics-explained/pdfscache/16817.pdf
[27] https://ec.europa.eu/eurostat/statistics-explained/pdfscache/38080.pdf

	• Plant phenotyping can be widely used beyond breeding and support the transition towards agro-ecological transition • Plant phenotyping technology can an important element of digital agriculture minimizing the environmental impact of agriculture
Legal	**Global perspective in a framework of national and European development:** • Legal consideration of GMO and NGT affect plant science and breeding • Nagoya protocol has a substantial impact on the utilisation of genetic resources required to breed for resistant varieties **EMPHASIS specific perspective:** • Substantial interest across Europe in plant phenotyping with plant phenotyping as an integral part of European and national Infrastructure Roadmaps • Lengthy negotiation process with many countries to establish the EMHASIS legal entity

Table 2: Results on a SWOT analysis on EMPHASIS.

Strengths	**Opportunities**
• Interdisciplinary interaction within the phenotyping facilities between plant scientists, imaging experts, data managers, engineers etc. • Expertise in the management of phenotyping infrastructure • Alignment with already existing initiatives related to plant phenotyping (EPPN 2020, IPPN, national phenotyping infrastructures) • Key technology developers in plant phenotyping are located in Europe • Europe is leading in plant phenotyping • Well established contacts with policy makers on national and EU level	• Excellent science: closing the phenotyping bottleneck • Nucleus for integration and harmonisation of plant phenotyping (and plant science) beyond Europe • Strong potential for knowledge and technology transfer to stimulate the private sector • Attraction of additional research fields to plant phenotyping (e.g. robotics, data sciences, artificial intelligence) • Sustain European leading position in plant phenotyping

• Well established contacts in the ESFRI community (ENVRIplus, CORBEL, EMMRI RiTrain, EOSC-Life)	
Weaknesses • The brand "EMPHASIS" still has to be further developed and established • Connections to industry stakeholders need to be strengthened • Potential new user communities of plant phenotyping infrastructure still need to be engaged	**Threats** • Lengthy negotiation process until EMPHASIS will be fully operational (within countries and between countries) • A lack of commitment for long-term funding of EMPHASIS on national level

4. Future perspectives

Plant phenotyping is becoming an integral part and important tool in plant sciences and related disciplines as well as and it is important for applications in breeding or precision farming. Phenotyping may be used in a range of disciplines and in several basic scientific questions and analyses by leveraging vision systems, machine learning and robotics to improve efficiencies and accuracy. While a sequencing machine delivers the sequence independently of the crop, there is no one-size-fits-all solution in quantitative phenotyping. Thus, plant phenotyping has to provide multiple solutions to address a large diversity of traits, crops, scientific questions, experimental treatments, environmental scenarios etc. In order to efficiently stimulate the development and utilisation of plant phenotyping integrated approach may be needed with: i) phenotyping and environmental observations of diverse crops, traits of interests, environmental simulations in dedicated facilities available for user access, ii) hardware and software solutions that enable addressing the diversity of required solutions and iii) addressing multi scale systems from single plants to ecosystem level (**Figure 5**).

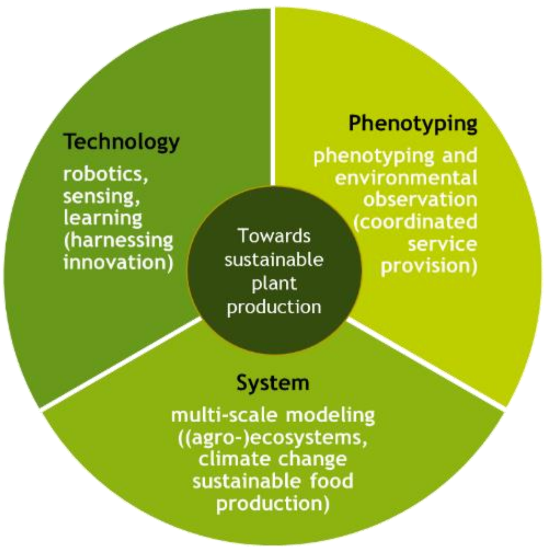

Figure 5: Phenotyping, systems and technology as three integral elements required to advance sustainable plant production.

EMPHASIS will play in this context an essential role to integrate and facilitate the interaction within Europe and beyond. Coordinated effort is essential to address future challenges and effectively explore and utilize the potential of plant phenotyping. The capacity and throughput for plant phenotyping in Europe is growing, but plant phenotyping is still a large bottleneck. Thus, there is a need to further integrate the existing facilities and further development of these facilities by the establishment of good phenotyping practices, FAIR data, knowledge and technology transfer, interaction with users from academia and industry etc. Additionally, new users and scientific challenges have to be addressed by interaction with other disciplines such as agroecology, consideration of circular processes in agriculture, interaction with living labs etc. This will further increase the diversification of plant phenotyping and the potential actions fields and as such increase the relevance of plant phenotyping approaches.

Finally, EMPHASIS needs a long term sustainable commitment of policy makers and funders to be able to develop a long term strategy that can address the dynamic requirements of the community and maintain Europe's leading role in this field.

Annex 1: Check list

Deliverable Check list (to be checked by the "Deliverable leader")

	Check list		Comments
Before	I have checked the due date and have planned completion in due time		*Please inform Management Team of any foreseen delays*
	The title corresponds to the title in the DOW		*If not please inform the Management Team with justification*
	The dissemination level corresponds to that indicated in the DOW		
	The contributors (authors) correspond to those indicated in the DOW		
	The Table of Contents has been validated with the Activity Leader		*Please validate the Table of Content with your Activity Leader before drafting the deliverable*
	I am using the EMPHASIS deliverable template (title page, styles etc.)		*Available in "New EMPHASIS Logo, Templates, CI" on the collaborative workspace*
	The draft is ready		
After	I have written a good summary at the beginning of the Deliverable		*A 1-2 pages max. summary is mandatory (not formal but really informative on the content of the Deliverable)*
	The deliverable has been reviewed by all contributors (authors)		*Make sure all contributors have reviewed and approved the final version of the deliverable. You should leave sufficient time for this validation.*
	I have done a spell check and verified the English		
	I have sent the final version to the WP Leader and to the Project coordinator (cc to the project manager) for approval		*Send the final draft to your WPLeader and the coordinator with cc to the project manager on the 1st day of the due month and leave 2 weeks for feedback. Inform the reviewer of the changes (if any) you have made to address their comments. Once validated by the 2 reviewers and the coordinator, send the final version to the Project Manager who will then submit it to the EC.*