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# A European perspective on opportunities and demands for field-based crop phenotyping

Merlijn Morisse [a], Darren M. Wells [b], Emilie J. Millet [c,l,1], Morten Lillemo [d], Sven Fahrner [e], Francesco Cellini [f], Peter Lootens [f], Onno Muller [g], Juan M. Herrera [h], Alison R. Bentley [i,*], Michela Janni [j,k,**]

[a] VIB-UGent Center for Plant Systems Biology, Technologiepark-Zwijnaarde 71, 9052 Ghent, Belgium
[b] School of Biosciences, University of Nottingham, Sutton Bonington Campus, Sutton Bonington LE12 5RD, UK
[c] Biometris, Wageningen University and Research, Wageningen, The Netherlands
[d] Faculty of Biosciences, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Aas, Norway
[e] Institute of Plant Sciences (IBG-2), Forschungszentrum Jülich, Jülich, Germany
[f] Agenzia Lucana di Sviluppo e di Innovazione in Agricoltura (ALSIA), Centro Ricerche Metapontum Agrobios, S.S. Jonica 106 Km 448,2, 75012 Metaponto di Bernalda, MT, Italy
[g] Plant Sciences Unit, Research Institute for Agriculture, Fisheries and Food (ILVO), 9090 Melle, Belgium
[h] Agroscope, Nyon, Switzerland
[i] International Wheat and Maize Improvement Center (CIMMYT), El Batan, Mexico
[j] Institute of Bioscience and Bioresources, Via G. Amendola 165/A, 70126 Bari, Italy
[k] Institute of Institute of Materials for Electronics and Magnetism, Parco Area delle Scienze 37/A, 43124 Parma, Italy
[l] LEPSE, INRAE, Université Montpellier, SupAgro, Montpellier, France

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ABSTRACT

The challenges of securing future food security will require deployment of innovative technologies to accelerate crop production. Plant phenotyping methods have advanced significantly, spanning low-cost hand-held devices to large-scale satellite imaging. Field-based phenotyping aims to capture plant response to the environment, generating data that can be used to inform breeding and selection requirements. This in turn requires access to multiple representative locations and capacities for collecting useful information. In this paper we identify the current challenges in access to field phenotyping in multiple locations in Europe based on stakeholder feedback. We present a map of current infrastructure and propose opportunities for greater integration of existing facilities for meeting different user requirements. We also review the currently available technology and data requirements for effective multi-location field phenotyping and provide recommendations for ensuring future access and co-ordination. Taken together we provide an overview of the current status of European field phenotyping capabilities and provides a roadmap for their future use to support crop improvement. This provides a wider framework for the analysis and planning of field phenotyping activities for crop improvement worldwide.

## 1. Introduction

Adaptation of agricultural systems to support productivity increases whilst minimising adverse climate change effects are key elements underpinning food security. This will in part require the development and deployment of innovative tools and resources to improve crop production, with one of the most promising being plant phenotyping. This is a core element of plant breeding, allowing the identification of superior genotypes in order to achieve selection gain (Würschum, 2019). It enables the linking of phenotype to genotype (and increasingly genome), across environments and time, and is thus central to accurate selection of high performing germplasm in breeding programs. Therefore, the use of high-throughput field phenotyping (HTFP) methods and tools are of increasing relevance in crop research and breeding.

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* Corresponding author.

** Corresponding author at: Institute of Bioscience and Bioresources, Via G. Amendola 165/A, 70126 Bari, Italy.

*E-mail addresses:* a.bentley@cgiar.org (A.R. Bentley), michela.janni@ibbr.cnr.it (M. Janni).

[1] Current address: LEPSE, INRAE, Université Montpellier, SupAgro, , Montpellier, France.

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In more detail, plant phenotyping refers to a quantitative description of anatomical, physiological and biochemical properties (Dhondt et al., 2013) as well as interactions with the environments (Watt et al., 2020). This also encompasses the capturing of unknown features for example high throughput near-infrared spectroscopy for use in phenomic selection (Rincent et al., 2018). Over the last decade, non-destructive sensor-based phenotyping has broadened its applications from the characterization of single-plant traits in controlled conditions towards applications of robust techniques in field plots and canopies (Walter et al., 2015). Until now, the most widely adopted methods for large-scale field phenotyping rely on aerial sensing technologies that measure crop characteristics throughout the season using spectral reflectance (Reynolds et al., 2020; Jin et al., 2021). Field phenotyping targets multiple user categories and scales. For example, plant breeders generally require access to medium to large field sites for selection whilst crop researchers and technology-developers are more oriented towards small to medium numbers of field plots for collection of data and the testing or validation of methods. This creates varying demand for phenotyping infrastructure. Multi-site field phenotyping supports crop research and plant breeding and typically requires easy access to field sites covering major pedoclimatological regions. This allows for the testing of crops and assessment of traits of interest across different environmental conditions (Atkinson et al., 2018), which is crucial in order to understand how plant genotypes respond to environmental changes through complex genotype x environment (GxE) interactions. In addition to physical trials, the coordination and quality control of data production, extraction and management systems will greatly impact the quality of outcomes from multi-site phenotyping (Billiau et al., 2012).

Field phenotyping is considered one of the biggest challenges within the area of crop phenotyping. An online survey of 320 respondents in 2018 revealed that 86% of phenotyping users had demand for intensive (52%) and lean field (34%) phenotyping facilities (https://emphasis.plant-phenotyping.eu/lw_resource/datapool/systemfiles/elements/files/58cd4632–35BCE-11e9–952e-dead53a91d3/current/document/Infographic_report_on_the_2018_survey_FINAL.pdf; Fig. 1A). In addition, a recent online survey was performed in the framework of the EMPHASIS project in 2020 (Global Plant Phenotyping Survey 2020/21 n = 396 respondents; full details from (Fahrner et al., 2021) available at doi:10.5281/zenodo.4723409. This emphasised the need for multi-site or multi-location field trials as a crucial resource or enabler for crop science and breeding to tackle future production challenges (79% of respondents, n = 267). This included work on yield related traits as well as on plant growth, development, and physiological traits (Fig. 1B). Stützel et al. (2016) highlighted the gap in capital and infrastructure resources available in many individual universities and research institutes to enable maintenance of multiple field trial sites covering a range of natural conditions. This restricts current use of state-of-the-art monitoring and experimental variation with diverse environmental factors including temperature, $CO_2$, and water. A key point reflected in survey responses is that at present, the exploitation of multisite phenotyping experiments relies primarily on access to existing research networks (33%, n = 186), personal contacts (32%, n = 181), then through establishment of research consortia (16%, n = 91) and host institutions (17%, n = 98; Fig. 1C). The 2020/21 survey highlights the needs for an organized network of field trials at European level, with a mechanism in place to facilitate access to field phenotyping equipment and the identification of accessible field sites.

On a global scale, plant phenotyping in Europe has been on the

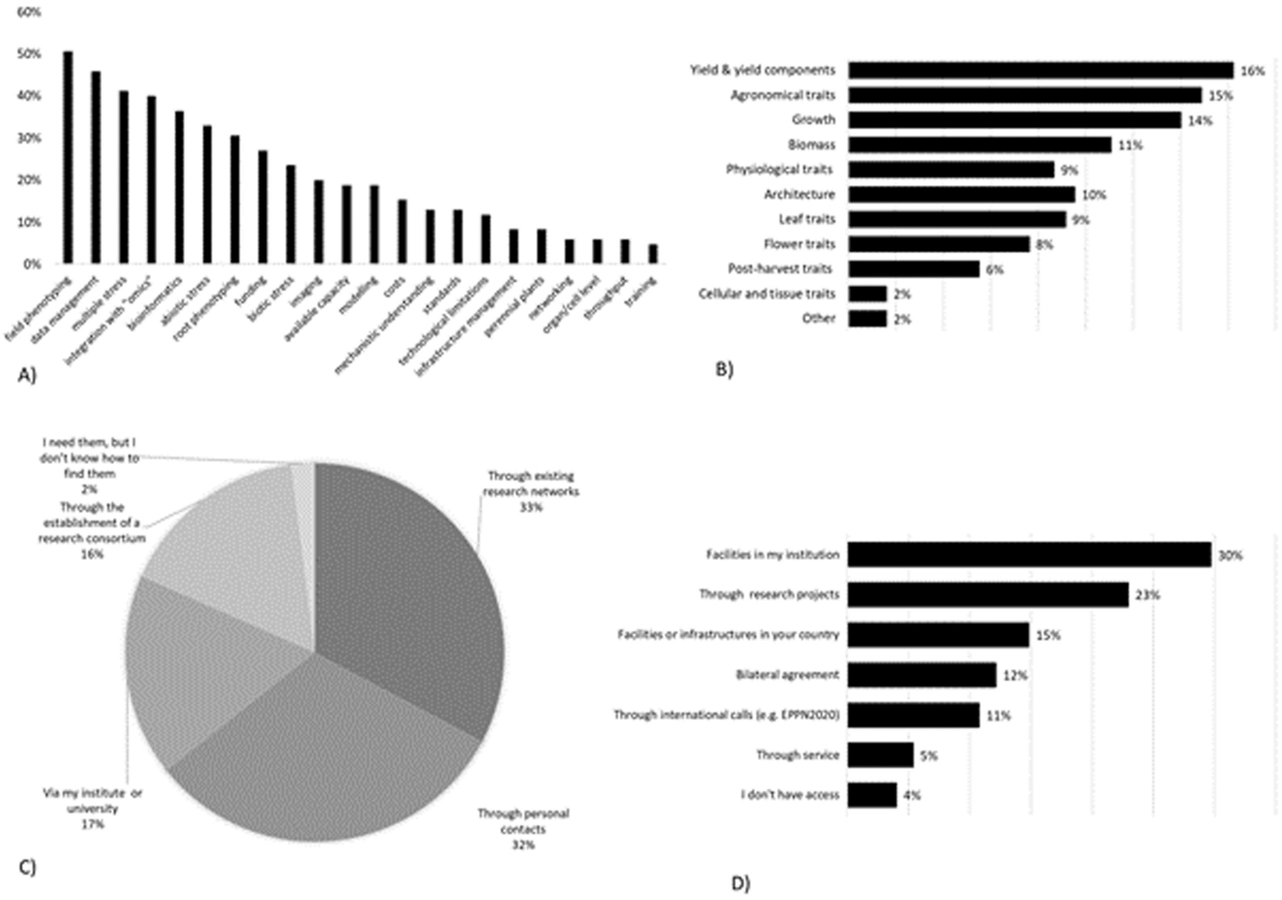


**Fig. 1.** Field phenotyping user demand and orientation recorded through EMPHASIS and IPPN surveys launched in 2017, A panel, and 2021, B-C panels. Multiple answers allowed. A) The largest challenge in plant phenotyping in the future, B) Plant traits covered with field phenotyping, C) Approaches for the identification of field sites, D Mode of access to field phenotyping experiments.

forefront for many years, as illustrated by the findings that the majority of co-authorships of scientific publications on plant phenotyping between 1997 and 2017 stem from European countries (Costa et al., 2019). This observation is in line with a sustainable development of plant phenotyping infrastructure initiatives in Europe, helping to provide and disseminate the necessary multidisciplinary competence and knowledge. In recent years these included the COST Action FA 1306, the Horizon 2020 Integrating Activities EPPN and EPPN$^{2020}$, and ESFRI research infrastructure EMPHASIS. These developments have also resulted from the fact that Europe has developed sound pan-continental funding schemes and structures that can effectively support cross-national research activities (specifically the European Framework Programmes, currently Horizon Europa, and the European Strategy Forum for Research Infrastructures ESFRI). From a geographical perspective, field phenotyping in Europe offers the unique potential to cover a wide range of climatic conditions relevant for crop production on large scales.

Whilst field phenotyping is a global effort, this publication focuses on European field phenotyping due to its comparatively prominent position. Therein, we highlight the strong demand for an effective, coordinated Europe-wide field phenotyping network facilitating transnational access to field infrastructures. Such a network requires sustained long-term administrative and financial support in order to provide the crop research community with the necessary administrative and financial security to ensure that consistent data return from long-term experiments can be supported. This network structure would allow coordinated and complementary development of individual sites, ensuring necessary specialization and optimal resource allocation throughout Europe. In parallel, it is envisaged that such a pan-European approach could facilitate standardized plant phenotyping experiments and data interoperability. Moreover, boosting visibility and collaboration across field phenotyping facilities will deliver added benefits for the user community. Finally, the recommendations for greater co-ordination are complemented by next steps to ensure maximum value is returned to the user community. These findings and recommendations are based on the current status of field phenotyping in Europe but can be extended to other regions to which many of the recommendations are broadly applicable.

In this opinion paper, we present the current developments in field phenotyping in Europe, show examples of successful trans-national collaborations, highlight current challenges and present recommendations for future investments.

## 2. Surveys to establish plant phenotyping user demand

Two surveys were carried out in the framework of the EMPHASIS project in 2018 and 2020 (the latter in collaboration with IPPN 2020). The aim was to assess the phenotyping user demand and the user orientation toward the EMPHASIS prep services (https://emphasis.plant-phenotyping.eu/EMPHASIS_pilots).

The 2018 survey was performed by using an online platform and was shared mainly through EMPHASIS social media, newsletter and project partners and research institutions. The survey target was the plant phenotyping community (breeders, modellers, scientists, students, technical staff, technology developers) from the private and public sector, but also to new communities interested in plant phenotyping. Full survey results are available via the EMPHASIS website (https://emphasis.plant-phenotyping.eu/lw_resource/datapool/systemfiles/elements/files/58cd4632–35 BCE-11e9–952e-dead53a91d31/current/document/Infographic_report_on_the_2018_survey_FINAL.pdf).

In 2020 a second broader survey of the international community was untaken using the SoSci Survey platform (www.soscisurvey.de) in collaboration with IPPN 2020. The target was to understand community demands, build a strong co-ordinated community and to engage new partners (e.g. private companies'). This survey reached 640 respondents in total, including 368 respondents from the European community. Dedicated questions regarding field phenotyping and modes of access were included. The full survey results are available via https://zenodo.org/record/4723409#. YWV2MZpBw2y (Fahrner et al., 2021).

## 3. Current status of European field phenotyping capabilities

In order to develop an access-structure of field sites in Europe covering different climatic regions, the first step is understanding the existing availability and accessibility of plant phenotyping infrastructures. This includes the field site characteristics and environmental conditions, along with available expertise and resources. This knowledge can also support adoption of common standards and facilitate the access to collaborative partners for multi-site field experiments.

Alongside the significant increase in plant phenotyping technology for use in controlled conditions (Watt et al. 2020), field phenotyping stations have been set up around the world that combine different measurement approaches and sensor positioning systems (Fig. 2) (e.g., Araus et al., 2014; Kirchgessner et al., 2017; Shakoor et al., 2017). Field phenotyping installations can be broadly grouped into two categories: intensive field experimental sites, characterised by highly equipped platforms with near-continuous monitoring of both plant phenotype and environmental conditions; and lean field trials with minimal plant phenotyping equipment performed in agriculturally-relevant conditions and often based on a network of individual sites (Pieruschka and Schurr, 2019).

Highly equipped installations are usually based in a single location and set up to allow the detailed study *in agri* of hundreds of plant microplots through frequent measures of multiple plant traits. The main assignment of intensive field sites is the quantification of the plant phenotype in high temporal resolution of plant traits. Dynamic measurements of canopy architecture and function are obtained via proximal or remote sensing systems, either by fixed systems or carried on gantries, phenomobiles or aerial platforms (aircraft, dirigibles and drones) (see for example Lyra et al. (2020) or Roth et al. (2020)). Sensors operate across the electromagnetic spectrum from visible light cameras (for 2D and stereo imaging), multi- and hyperspectral cameras, thermal imagers, LIDAR (for shape quantification) and synthetic aperture and ground penetrating radar (Atkinson et al., 2018). There is a trade-off between detailed quantification of plant traits, often with specific sensors at different stages during the plant growth cycle, and throughput of analyzing many genotypes. Simulation studies have shown that increasing the number of samples and environments using high-throughput approaches can lead to better results than higher-accuracy phenotyping of fewer samples (Lane and Murray, 2020). In the intensive field site the emphasis is on deciphering complex plant traits through the study of genotypic variation and precise response to environmental conditions (Kronenberg et al., 2020).

Some highly equipped field platforms also allow a degree of environmental control and manipulation, for example using rain-out shelters (e.g De Swaef et al., 2021) and irrigation to control rainfall and soil water content, respectively, or Free Air $CO_2$ Enrichment (FACE) to manipulate $CO_2$ levels to simulate future climatic conditions (Kimball, 2016). Soil conditions (temperature, nutrient treatment, management schemes) can also be monitored and manipulated.

Lean field experiments using minimal plant phenotyping equipment take place in trial fields managed following standard agricultural practices and are often part of networks of sites operated over multiple years. The same range of sensors utilised in intensive platforms can be deployed via mobile carrier systems though usually at a lower temporal frequency (days/weeks). Throughput is site-dependent but typically in the hundreds to thousands of microplot range. For many users, cost-effective phenotyping solutions are crucial to allow incorporation of a sufficient number of trials within the available research budget. Depending on the context and objectives, "cost-effective" phenotyping may involve either low investment ("affordable phenotyping"), or initial high investments in sensors, vehicles and pipelines that result in higher

**Fig. 2.** Map of field phenotyping sites in Europe, mapped by the EU-funded project EMPHASIS-PREP.

quality and lower operational costs (Reynolds et al., 2019). Lean phenotyping, using affordable technologies like for example phenocarts or field phenotyping robots for proximal sensing and light-weight multispectral UAVs for remote sensing will likely be attractive for users in academia and industry with limited research budgets. Recent years have seen big advancements in the field of low-cost field phenotyping ranging from home-built phenocarts to user-friendly multispectral UAVs (e.g. DJI Phantom 4 Multispectral, https://www.dji.com/no/p4-multispectral) for use in agriculture. Recent review papers provide an overview of available low-cost phenotyping technologies for field-based crop phenotyping (Chawade et al., 2019) and breeder-friendly phenotyping solutions (Reynolds et al., 2020). In future it may be possible to develop imputation methods to bring together data from lean and extensive fields. This offers the potential for wider coverage in field phenotyping, but likely requires significant development of data processing and analyses.

For both types of installation, environmental monitoring of site conditions is essential. For intensive installations, environmental variables (e.g. air and soil temperature, humidity, rainfall, solar radiation, soil water content) are measured at a similar frequency to the phenotypic traits (typically hourly). In lean field sites with minimal equipment, measurement is usually done via a local weather station with less frequent and broader scale (e.g. site-level) quantification of field environmental conditions. As phenotyping technologies are rapidly advancing, it is crucial for users to be able to identify the right technology for the different phenotyping purposes. A good example of ongoing efforts in this respect is the Public Private Partnership in Plant Phenotyping Project (6P), funded by the Nordic Council of Ministers. In this project, running since 2015, Nordic based plant breeding companies and academic partners are joining forces to test and evaluate low-cost phenotyping technologies for plant breeding purposes and develop phenotyping methodologies, focusing mainly on UAVs. It also operates the Nordic Plant Phenotyping Network (NPPN), which organizes workshops, field days and training schools to facilitate the exchange of information between research institutions, plant breeding companies and industry technology providers and support the dynamic development of affordable field phenotyping methodologies (https://nordicphenotyping.org/).

The EU funded research infrastructure project EMPHASIS-PREP has extensively mapped more than 200 plant phenotyping research installations across Europe, including indoor installations (in greenhouses and growth rooms, where environmental conditions can be partially or thoroughly controlled and automated system are available to evaluate the crop performance), field installations, data management systems and crops models (e.g. https://www.quantitative-plant.org/). To date, 81 existing field trial sites, capturing both intensive and lean fields, have been mapped across Europe. This includes both lean (55) and intensive field sites (26) covering capabilities present in most European countries.

The mapped installations have been included in a phenotyping installations map (Fig. 2) and basic information (e.g. location) is publicly available (https://emphasis.plant-phenotyping.eu/emphasis_infrastructure_map). However, there remains a high demand from the field-based crop science community to map more details on available field phenotyping stations across Europe. This mapping needs to contain relevant details, e.g. environmental conditions, pedoclimatic conditions, field size, agricultural management (e.g. conventional or organic management), and presence of phenotyping infrastructure/equipment. This would aid the determination of the fit of a particular field site for a proposed single- or multi-site project. These details should also be made available to the community with mapping resources and scale of capacities (as in Fig. 3) regularly updated to capture available facilities and sites.

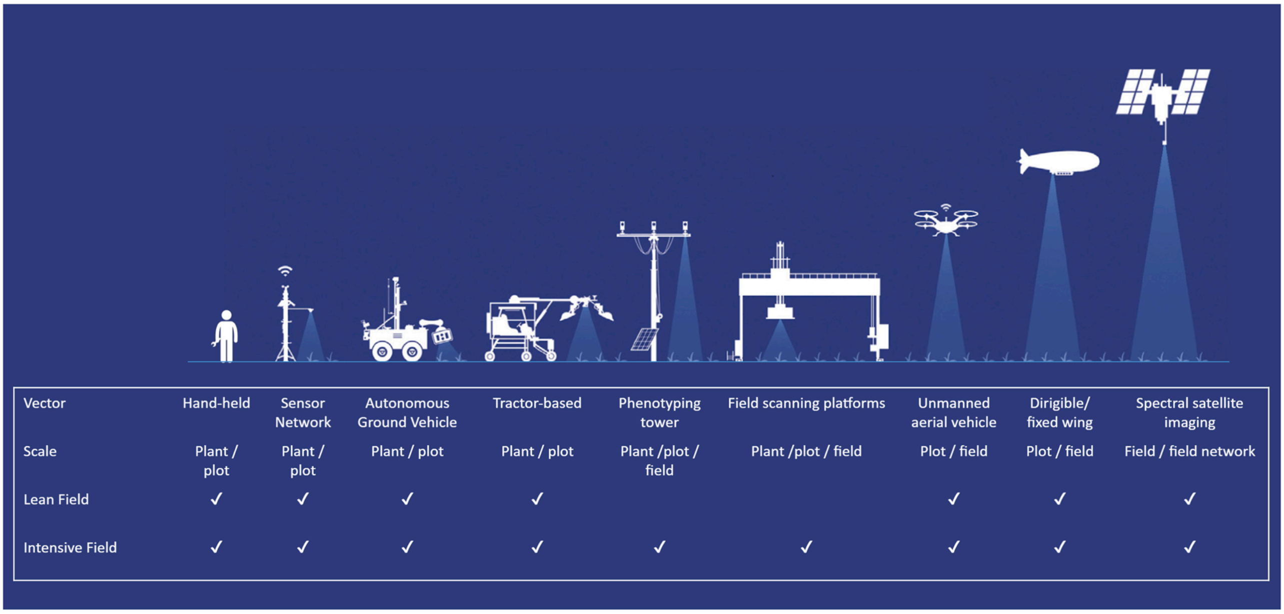
Of the sites mapped to date, roughly half (42 of 81) have shared information about capacity and size of fields and available phenotyping systems. Climatic properties (such as soil characteristics, temperature, humidity) are available for 24 sites. Strikingly, only 24% of the mapped sites have structured access modes.

## 4. Demands and opportunities from multi-location field phenotyping

The aim of multi-location field trials is to capture sufficient information to enable accurate identification of G×E interactions (Cooper and DeLacy, 1994). This determines which phenotypes result from the interplay between the genotype and the trial environment, with environment being determined both by location, e.g. within Europe, but also including the different growing seasons and thus different years. As such a good multilocation trial is executed in different regions (soil types, climatic conditions) and over several years (ideally 3–5). In an agricultural production context, management (M) plays an important role by influencing the phenotype, resulting in the additional need to investigate the G×E × M interaction (Hammer et al., 2014). Various classical statistical strategies are already used to analyze multi-environment experiments (van Eeuwijk et al., 2016) and are also extended to the use of the new phenotyping technologies (van Eeuwijk et al., 2019). For these strategies to be efficient, a wide set of environmental conditions and production systems is needed, for example to assess all parameters of a growth model in an identifiable way (De Swaef et al., 2019).

The development of a sensor network and environmental grid makes it possible to include more precise environmental characterization in G×E analyses (Resende et al., 2021). De Swaef et al. (2019) stated that identifiability analysis also provides a sound approach for optimizing the design of multi-location trials ensuring proper exploitation of phenotypic data and cost-effective multi-location experimental designs.

Recent projects successfully performed multi-location field trials across Europe, and these provide insight into both demands and future opportunities. Here we present two recent project examples along with opportunities to link multi-site phenotyping with statutory testing networks, and the key learnings from each project. The EU-FP7 DROught-tolerant yielding plantS (DROPS) project, which ran from 2010–2015) focused on maize, wheat and sorghum grown in multi-climatic regions in Europe and characterized drought tolerant traits, including seed abortion, maintenance of vegetative growth, root-system architecture and transpiration efficiency (https://cordis.europa.eu/project/id/244374). The maize panel consisted of 246 maize hybrids grown in 29 field experiments (defined as combinations of site × year × watering regime) spread along a climatic transect from west to east in Europe, plus one experiment in Chile (Millet et al., 2016). DROPS partners (nine public and six private partners) conducted experiments using a standardized approach that focused on environmental conditions and collection of associated meta-data. Common experimental design and protocols were used, with a balance between local practices (e.g. plot sizes) and common management (e.g. sowing date, irrigation) employed to explore a range of environmental scenarios (e.g. well-watered over the whole crop cycle or targeted drought around flowering time). A common set of data and meta-data for both plant and environmental measurements was agreed upon by all partners (following common data standards) and a data exchange format created, allowing all partners to



| 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 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Fig. 3.** Overview of field phenotyping platforms. Phenotyping approaches operate at a range of physical scales.
Figure adapted from (Shakoor et al., 2017).

store and exchange their data in a traceable way with controlled conventions.

The current European Consortium for Open Field Experimentation (ECOFE) brings together field phenotyping sites covering climate zones from Scandinavia to the Mediterranean, and including Ireland to the eastern border of the EU (www.ecofe.eu; Stützel et al., (2016)) with 12 partners conducting multi-location wheat trials. An identical common experimental design is deployed in all locations (replicates, nitrogen fertiliser treatments). A core set of cultivars is assessed (with each location providing the best cultivar for their location) with the same starting seed lot used for each cultivar and for all trial years. Low-cost predefined measurement protocols were used in all locations with common data sheets used to gather data and execute management operations (fertilizer applications, crop protection, sowing, harvesting). Specific post-harvest analyses were executed, based on samples from all locations, but analyzed in one central laboratory. Partners also used common protocols for the use of high-throughput field phenotyping using UAVs, i.e. execute weekly UAV flights with RGB, modified RGB and/or multispectral sensors (MS) to assess canopy height and vegetation indices over time with high spatial resolution (for RGB approx. 1 cm up to 2 mm and for MS approx. 2 cm), allowing knowledge sharing between teams and the evaluation of sensors and the assessed replicability of vegetation indices across a wide range of environmental conditions while keeping constant genotypes and N inputs.

Perhaps the most widespread and established multi-location trials are those to determine the Value of Cultivation and Use (VCU) of field crops. VCU trials are conducted every year in most European countries for the most cultivated crops. Connected through similar protocols and tools these already established trials across countries can be considered a natural target for collaborative field based phenotyping. Indeed, two recent EU Horizon 2020 projects address at least partially this goal; INNOVAR (https://www.h2020innovar.eu/) and INVITE (https://www.h2020-invite.eu/). InnoVar aims to augment and improve the efficacy and accuracy of European crop variety testing and decision-making, using an integrated approach incorporating genomics, phenomics and machine learning. The goal of INVITE is to foster the introduction of new varieties better adapted to varying biotic and abiotic conditions and to more sustainable crop management practices. In the latter, besides RGB and MS sensors, hyperspectral and thermal sensors are used to better detect e.g drought tolerance and the approaches most suitable for VCU trials. An extensive list of major projects performing multi-location field trials across the world is reported in Supplementary Table S1.

One of the major factors in the success of these multi-site experiments is intensive discussions and meetings between partners to (i) reach agreement on shared protocols, the minimum information and the data format for sharing, and (ii) select the locations, including their characterization and the homogenization of the quality of the field material (e.g. buying new sensors, having single seed stocks). Ensuring consistency often requires test trials, i.e. trials at the selected location/s using a subset of the proposed panel of genotypes. During the experiment, a close monitoring of the environmental conditions and the plants is required to ensure quality and traceability of data. For example, in the DROPS project partners were asked to send partial climatic data about a third of the way through the experiment in order to allow for an early quality check and to adjust in-season management if necessary. The exchanges also continue beyond the experimental timeframe, particularly during data collection and processing, both of which rely heavily on field management expertise. A major benefit of the harmonized data collection from such well-managed multi-sites is the reduction in experimental error from the use of different phenotyping protocols, which can provide new insight into GxE interactions and increased statistical power for variety testing (Millet et al., 2016).

As the case studies of DROPS and ECOFE show, logistics and administrative details in multi-site field experiments are an essential component but are often resource intensive. For example, multiplying and distributing seeds (to ensure a common seed lot is used) to different trial locations across multiple countries requires significant technical and administrative effort. Recognition of the logistics challenges inherent in the running and co-ordination of multi-site field phenotyping activities is an important factor in ensuring successful outcomes.

## 5. Access and data assembly demands and opportunities

Organizing a single point of access for users and stakeholders interested in accessing multi-site field networks for research and breeding is of primary importance for making field phenotyping more accessible. Ideally, a structural mechanism (such as could be provided by the European Strategy Forum on Research Infrastructures) could provide a “one-stop-shop” service for access to phenotyping infrastructures of all categories, including field trials. This could support potential users in identifying and accessing optimal site or collections of sites to achieve their experimental objectives. At present, public availability of information about existing collaborative experimental field networks is limited. Typically, these types of networks are established on an ad hoc basis through third-party funded projects and cannot be maintained beyond the project lifetime. A key recommendation is that a sustained structural and long-lasting collaborative field infrastructure network is needed in order to provide greater collective benefit to the crop science and breeding community.

Datasets collected at plant phenotyping installations have an associated cost and are labour intensive and difficult to reproduce (given the seasonal variation inherent in field trialling). Hence, it is essential that datasets can be used not only by the primary user but also re-used and re-analysed by the wider scientific community. At present, numerous datasets are lost due to a lack of proper data management. As open and accessible data is currently required by most journals, public research and funding institutions based on FAIR principles (Findable, Accessible, Interoperable and Reusable; Wilkinson et al. 2016), appropriate data management is not only the basis for sound scientific research but also a prerequisite for future data use.

Deploying an information system in each European local infrastructure is a necessary step in order to reach the goal of FAIR datasets from field trials. Exchanging spreadsheets, as is current practise, is not compatible with the ’findable’ and ’accessible’ principles, and is plagued with problems such as software obsolescence and non-accessible metadata (i.e. the information one needs to reanalyse an experiment). For example, the ontology driven ‘Phenotyping Hybrid Information System (PHIS)’ (Neveu et al., 2018) enables sharing and integration of data from multiple sources and scales along with associated metadata. It could be possible to link this to the Genoplante Information System (GnpIS) for genetic and genomic data (member of ELIXIR) (Steinbach et al., 2013) via the Breeding API (BrAPI, https://brapi.org), allowing further interrogation of datasets e.g. for genome-wide association studies.

Starting in 2020, a pilot service conceptualised by the research infrastructure EMPHASIS data pilot is working towards making datasets collected at European installations, including field phenotyping sites, available to a large community of plant scientists, following the FAIR principles. The rationale is that a user can re-analyze published datasets and/or perform meta-analyses by compiling multiple datasets.This data pilot works in close collaboration with the genomics infrastructures ELIXIR (https://www.elixir-europe.org/excelerate/plants), via the Minimum Information About a Plant Phenotyping Experiment (MIAPPE working group; Papoutsoglou et al., 2020, http://www.miappe.org/) and AGMIP (modelling, https://agmip.org/), so the datasets can be used for different purposes by different scientific communities.

The overall recommendation for ensuring best practice is that each group should install their local information system, e.g. PIPPA (https://pippa.psb.ugent.be) or PHIS (Neveu et al., 2019). This would firstly ensure that local data management is set up. Then using ontologies and controlled vocabularies, following the MIAPPE guidelines will make the dataset interoperable, within and between groups, and enable their publication in dataverse such as Cyverse, used by the maize genomes to fields (G2F) project (https://www.genomes2fields.org/resources/).

## 6. Incorporating technology and innovation: the case of satellites

Plant phenotyping technologies progress at a very fast pace, following the rapid developments of science and technology branches such as electronics, sensors, informatics, computing, robotics. Active monitoring and exploitation of research and development results are necessary if infrastructure is to remain up-to-date and at the very forefront of plant phenotyping for the future. Both constant (re-)development and investment capacity are needed to ensure that facilities employ the best available technologies and methods, and continue to provide high performance and quality of service. Harmonization of technology used at field network nodes will be needed to facilitate data exchange and interpretation. This needs to be balanced against the needs for each partner location to explore new technologies and find what gives the best data for different purposes. Interaction between infrastructure operators/users and technology developers and suppliers will foster exchange of information and access to new relevant technologies. Structured forums, such as workshops and technical meetings between technology developers and users are needed in order to exchange updated information and implement testing and developments of innovative technologies in operational open field infrastructures. Coordination of these activities is essential to ensure the long-term sustainability of open field infrastructures to support and drive innovation in technologies, tools and methods for use by the wider industrial and academic communities.

A striking example is represented by the rapid evolution of satellite remote sensing, among which the advent of micro and nano satellites promises to dramatically change field phenotyping. In this respect, access to satellite data and capacity of satellite data management and analyses should be carefully monitored and considered in open field infrastructure. Remote sensing relying on satellites has the capacity to provide repetitive information on crop status throughout the season at different scales, making this information cost-effective and in some cases freely available. These applications range from yield forecasting, field preparation, crop health monitoring, irrigation, and site-specific management (Karthikeyan et al., 2020). The significant improvements in satellite observations, in terms of spatial (0.3–0.7 m ground sampling distance; Zhang et al. 2020), spectral, and temporal resolution has promoted their use for new applications, including plant breeding (Weiss et al., 2020; Chawade et al. 2019). Satellite sensors cover optical, thermal, microwave, and fluorescence frequencies allowing the estimation of vegetation indices that deliver information about biotic and abiotic stresses.

Data from medium resolution satellites Sentinel 2 and Landsat 8 are freely available, whilst data from the high-resolution satellite are only available commercially. Although still limited by the actual cost of high-resolution commercial satellite images, applications of satellite imaging for plant breeding are relevant for evaluation of moderate to large sized trial plots. For smaller plots, remote sensing with UAVs and proximal phenotyping are viable alternatives. However, imagery costs are expected to reduce significantly in the future, whilst resolution and frequency of recording is expected to increase. This is likely to make high-resolution imaging more accessible for application in crop science and plant breeding. A recent report by (Behrens and Lal, 2019) reported that image costs have already decreased by 1–2 orders of magnitude relative to 2017, with image resolutions reaching 1 m or below.

Nanosatellites and other satellites launched after 2000, such as GeoEye-1 (2008), Pleiades-1A (2011), Worldview-3 (2014), SkySat-2 (2014), and Superview-1 (2018), collect multispectral images at a high spatial resolution of <2 m m with a daily or sub-daily revisit period (see also Zhang et al., 2021). Pleiades-1A and Worldview-3 have been used for many precision agriculture applications requiring high spatial resolution imagery, including disease and crop water stress detection (Navrozidisa et al., 2018; Salgadoe et al., 2018). Further crop traits using satellite imagery such as vegetation indices, lodging, plant height, phenology, leaf area (Zhang et al., 2021) are quantified at resolutions moving towards use for field phenotyping in larger breeding plots. On the practical side, a recent paper (Jain et al., 2019) showed how microsatellite data management can have a big impact on agriculture sustainability in developing countries. Data were used to detect the impact of sustainable intensification interventions at large scales and to target the fields that would benefit the most, doubling yield gains.

It is worth noting, however, that many satellite imaging solutions are affected by cloud cover. Especially in northern Europe, the number of cloud-free days can be few during the growing season, limiting data gathering at all critical plant developmental stages. Despite flying under the clouds UAV imaging is also limited by the cloud cover especially for reflectance-based crop traits and therefore does not always provide a reliable alternative. Rather joint acquisition of satellite and UAV data in intensive breeding programs will complement each other e.g. Sankaran et al. (2019). Furthermore, new technologies for satellites may increase the opportunities to use satellites. For example, Synthetic Aperture Radar (SAR), available in some satellites recently launched, is an effective technique for monitoring crops, even in northern europe, where the data quality does not depend on weather conditions because it relies on geometrical structures and dielectric properties of the targets.

## 7. European field trials of the future: key recommendations

### 7.1. Minimal data requirement lists are required to ensure quality

Quality assurance (QA) is essential for ensuring high quality data that is reproducible and interoperable. A future quality assurance service for field phenotyping would enable excellence in science for field-based plant phenotyping research in Europe. Accordingly, multi-climate field experiments will help to address relevant crop science challenges. In addition to the many stakeholders' benefits of QA, a number of studies have identified significant financial benefits for organizations that establish QA by for example obtaining certification from the International Organization for Standardization (ISO) 9001 (https://www.iso.org/; Sharma, 2005; Chatzoglou et al., 2015).

Data quality can also be established by describing and defining minimal requirements of field phenotyping experiments together with guidelines for good practices. For example, for field experimental setups, statistical design, best practices in management and data production. (Poorter and Sack, 2012) defined a checklist for plant experiments and the MIAPPE principles also contain guidelines and lists of minimal information. A strategy for data integration and standardization was also developed in the EPPN$^{2020}$ project, including topics such as camera calibration, data interoperability and data analysis. For each topic, two levels were defined: level 1 was the necessary conditions for a platform to host transnational access and level 2 is the objective to reach for the future pan-European research infrastructure EMPHASIS (i.e. an advanced phenotyping community). Those standards were defined for controlled conditions but are directly adaptable for field experiments. For example, the experimental designs level 1 consisted of describing the layout of the platform in a statistically intelligible way together with expected gradients of environmental variability. This is also a required information for field experiments. Level 2 requires a use of appropriate software to provide checks and visualization of the designs. Such software will also provide a map file, often as a csv file, directly usable in the information system, ensuring data traceability and interoperability. A major recommendation is that future co-ordinated European field phenotyping should require structured explanations on how to manage physical experiments (e.g. experimental design, seed, inputs), equipment operations and minimum standards for data and QA in data processing.

### 7.2. Common access to administrative support and advisory services increases efficiency

The case projects described above (ECOFE and DROPS) highlight the importance of administrative and logistical support when implementing successful field phenotyping conducted by a network of partners. Broadly this includes reaching consensus on protocols, standardizing processes and experimental components and data exchange. Typically, these are underestimated tasks and financial security for long-term activities is not commonly in place. Therefore, a recommendation is made for administrative and advisory support for the organisational and logistical aspects of the multi-sited field experiments.

### 7.3. Enabling transboundary access, policies and funding

Access to controlled condition plant phenotyping installations has been successfully established in Europe through the European Plant Phenotyping Network (EPPN) and EPPN$^{2020}$ projects. EPPN offered transnational access to 23 different plant phenotyping facilities between January 2012 and December 2015. EPPN$^{2020}$ (2017–2021), provided transnational access to 31 plant phenotyping installations. Despite the fact that EPPN$^{2020}$ also organized open access for some highly equipped field sites in Europe, both projects excluded access to networks of lean field sites or field equipment.

While controlled condition platforms are used to measure traits on single plants that can be used as proxies or predictors of final agronomic targets such as yield, multi-site field phenotyping experiments are key to scaling up phenotyping for use in applied crop science and plant breeding as it allows testing genotypes of important crops in different climatic conditions in agriculturally relevant settings. Breeding programs within industry rely on multi-site field trials to determine if new candidate varieties will be more productive than the current ones in the targeted environments and/or regions.

European multi-site field experiments, in academia, are currently mostly organised through bilateral collaborations, predominantly in EU funded projects. Access models to field sites and field equipment are currently ad hoc agreements between institutes and universities, or via private collaborations. Although bilateral collaborations will continue to exist, more streamlined access to infrastructure would make it more straightforward for a wide range of researchers to access field phenotyping. The establishment of transboundary access to field sites and equipment is therefore recommended and could be co-ordinated within large ongoing initiatives (e.g. EMPHASIS, which has the ambition to be the long-term successor of the EPPN$^{2020}$). This will co-ordinate and support broad and open access to plant phenotyping facilities, both in controlled and field conditions. However, this is only feasible with long-term funding, which would provide the field phenomics community the necessary administrative and financial security to provide long-term services.

## 8. Conclusion

The academic field phenotyping sector in Europe needs collaborative multi-region projects to tackle G×E interactions related to the changing climate and improve statistical significance for variety screening, as exemplified by the DROPS and ECOFE projects. A clear inventory of available field capacity, along with phenotyping equipment is needed to ensure easy selection of collaborative partners and open access to fields. A predefined “minimal requirement list” should ensure qualitative phenotyping fields and user-friendly access models for smooth development of new experiments. Facilitation of administration should be done by a coordinated team, to make fields available for access and make it easier for [=researchers to set up multi-sited experiments. Furthermore, facilitation of multi-sited field trials will need support to identify funding, develop procedures and calls for open access and enable training for specific available equipment or software use and the specific requirements for fields.

Such a co-ordinated field phenotyping capability will create benefit in Europe with wider applicability in other regions and geographies as it will (i) allow crop testing in different climates in real agronomic conditions with state-of-the-art field phenotyping equipment (ii) improve statistical significance for variety screening by multi-sites/climates experiments (e.g. yield increase) (iii) provide the tools for multi-site experiments to establish a unique way of finding suitable crop varieties for adaptation and mitigation to a changing climate (iv) create high quality field data acquisition (v) facilitate international collaborations, and (vi) ensure a global leading role in crop research.

The overview and recommendations presented are intended to help European field plant phenotyping to move forward and help in generating an even stronger contribution to the global challenges related to biomass production and food security in the context of climate change. Developing European field phenotyping, though, will require close exchange and cooperation with phenotyping beyond Europe where to some extent similar challenges as presented here for Europe exist. A sound basis for such an effort already exists in terms of close links of phenotyping communities around the world, organised among others in the framework of the International Plant Phenotyping Network IPPN. European field phenotyping can thus help to move forward field phenotyping on a global level.

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## CRediT authorship contribution statement

**Merlijn Morisse:** Conceptualization, Data curation, Project administration, Writing – original draft. **Darren M. Wells:** Conceptualization, Investigation Writing – original draft, **Emilie J. Millet:** Conceptualization, Investigation, Writing – original draft. **Morten Lillemo:** Conceptualization, Investigation, Writing – original draft. **Sven Fahrner:** Methodology, Writing - review & editing. **Francesco Cellini:** Methodology, Investigation, Writing – review & editing. **Peter Lootens:** Methodology, Investigation, Writing – review & editing. **Onno Muller:** Methodology, Investigation, Writing – original draft. **Juan M. Herrera:** Methodology, Investigation, Writing – review & editing. **Alison R. Bentley:** Conceptualization, Investigation, Writing – original draft. **Michela Janni:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2021.108371.

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