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Foreword

Plant phenotyping: increasing throughput and precision at multiple scales

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Abstract. In this special issue of *Functional Plant Biology*, we present a perspective of the current state of the art in plant phenotyping. The applications of automated and detailed recording of plant characteristics using a range of mostly non-invasive techniques are described. Papers range from tissue scale analysis through to aerial surveying of field trials and include model plant species such as *Arabidopsis* as well as commercial crops such as sugar beet and cereals. The common denominators are high throughput measurements, data rich analyses often utilising image based data capture, requirements for validation when proxy measurement are employed and in many instances a need to fuse datasets. The outputs are detailed descriptions of plant form and function. The papers represent technological advances and important contributions to basic plant biology, and these studies are commonly multidisciplinary, involving engineers, software specialists and plant physiologists. This is a fast moving area producing large datasets and analytical requirements are often common between very diverse platforms.

Introduction

The phenotype is the physical manifestation of genotype and all physical interactions acting on an organism, namely the environmental effect. Phenotyping is the precise measurement of these characteristics with spatial and temporal resolution, and may be at a complex trait level, for example yield, or more likely be at a detailed sub-trait level of factors contributing to yield. Such commonly measured sub-traits might include photosynthetic carbon assimilation efficiency at the biophysical or biochemical, leaf size, shape and orientation for light capture or the dynamics of canopy longevity. Detailed sub-traits may be more and more precise and be the result of just a few genes and such discrete characters have been termed phenes (in analogy to genes); a useful description of the application of this term has been published in relation to root characteristics (York *et al.* 2013).

Plant phenotyping may be defined on many physical scales from the biochemical level, through sub-cellular and cellular studies or whole plant studies with laboratory grown model species through to the scale of plant performance in large monocultures in a crop field.

Whilst there have been rapid advances in high throughput genotyping technology resulting in the ability to genotype or even completely sequence an individual's entire genome rapidly and for low cost, the complexities of describing phenotypes create an inevitable bottleneck, limiting progress in crop breeding (Furbank and Tester 2011). The technologies described here are aimed at either detailed dissection of a phenotype or rapid acquisition of information and thus closing the phene-gene gap, or enabling comparative analyses from large numbers of individuals. Additionally, detailed time courses with a large number of sample points are aided by the same approaches.

Whilst traditionally descriptions of plants and crops have been the realm of plant physiologists or agronomists, the increasing sophistication required for detailed and/or high throughput analysis has resulted in the need to assemble multidisciplinary teams including biologists, physicists, programmers and engineers. The identification of proxy measurements that report on plant growth and health requires both the development of hardware and software solutions. At the same time, appropriate validation and calibration requires specialist plant physiologists, pathologists and botanists. Previous special issues of *Functional Plant Biology* considered the state-of-the-art in plant phenotyping in December 2012 (Volume 39, Issues 10 and 11) and another addressed the specific topic of image analysis (June 2015, Volume 42, Issue 5).

The papers in this special issue have been grouped according to the scale at which they are applied; namely, subcellular analyses of plant-pathogen interactions using hyperspectral cameras, plant scale phenotyping of model plants and crops using multiple types of sensors, field-based phenotyping and finally aerial application of drone technology used to compare ground cover estimates for cotton, sorghum and sugarcane.

The power of hyperspectral sensors to phenotype plant-pathogen interactions and identify resistant germplasm is illustrated in two of the papers included in this issue that focus at the tissue or sub-cellular scale (Leucker *et al.* 2017; Thomas *et al.* 2017). The work by Du *et al.* (2017) on the other hand illustrates the utility of an improved method to study vascular bundles in maize using micro-computer tomography (CT) and their function.

This issue includes multiple manuscripts that present a variety of plant-scale phenotyping approaches aimed at developing tools to identify drought-tolerant crops. In a review by Negin and Moshelion (2017) the authors discuss the importance of proper experimental design including where, when and under which conditions phenotype, which traits to phenotype, what methods are most appropriate to study drought, and also how to translate the large datasets collected into knowledge that can be used by breeders and other scientists. The studies by Acosta-Gamboa *et al.* (2017) working with *Arabidopsis* and Wedeking *et al.* (2017) working with sugar beets demonstrate the power of combining digital phenotyping with other physiological tools and destructive measurements to better understand the plant's responses to water deficit. The studies by Dambreville *et al.* (2017) and Bourgault *et al.* (2017) show that the size of the pots used in current high-throughput phenotyping platforms can have a significant effect in the outcomes of the experiments. In particular, the authors caution in both cases that using small containers can artificially create conditions that could either hide or overly express genotypic variability in some traits in response to drought or elevated CO_2. The work by Gioia *et al.* (2017) describes GrowScreen-PaGe, a novel non-invasive, high throughout phenotyping system based on germination paper that allows quantification of phenotypic diversity and plasticity of root traits under varying nutrient supply. An additional technical advance included here is the work by Barkla and Rhodes (2017) who describe the use of infrared thermography to study crassulacean acid metabolism (CAM) in a system that can be used both in the greenhouse and the field. The plant scale phenotyping section of this special issue is rounded up with the interesting review by Gibbs *et al.* (2017) who discuss the importance of novel automated systems capable of producing 3D models of plants that would significantly aid phenotyping practice and increase accuracy and repeatability of the measurements of interest.

A variety of technical solutions are being implemented, designed for the scale of the question, and recent activity has adapted laboratory solutions for application in the field. These have the capacity for phenotyping plants in the natural environment and in a situation close to commercial crop production, and therefore of direct relevance to breeders and agronomists. An additional complexity in this situation is the vector system for transportation of sensing and measuring equipment. This is ideally automated and designed to have minimal impact on the plants or crops. Two suspended platform solutions (Kirchgessner *et al.* 2017; Virlet *et al.* 2017) and an aerial solution using drones (Duan *et al.* 2017) are described in this volume. Other alternatives include the use of free ranging robots or vehicular based systems (Deery *et al.* 2014).

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