Introduction to emerging technologies in plant science

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In recent years, an array of new technologies is propelling plant science in exciting directions and facilitating the integration of data across multiple scales. These tools come at a critical time. With an expanding global population and the need to provide food in sustainable ways, we as a civilization will be asking more of plants and plant biologists than ever before. This special issue on emerging technologies in plant science brings together a set of reviews that spotlight a range of approaches that are changing how we ask questions and allow scientific inquiry from macromolecular to ecosystem scales.

Scientific discovery and new applications of research exist in the swift current of evolving technologies. Across all areas of science, the set of tools currently available for exploring nature from atomic structure to ecosystems is incomparable to any point in history. This is fortunate, as over the next decades agricultural productivity must increase to keep pace with growing populations, while adapting to changing climate, developing equitable and sustainable food security, and minimizing environmental impacts [1–3]. The tools currently available to plant scientists, along with the enrichment of data at multiple scales from the macromolecular to environmental systems, are shaping future questions for understanding plants and their processes.

Classic techniques that allow examination of genomes, transcript, proteins, and cells are leading to methods that offer new opportunities for data generation and analyses at multiple levels of detail and scales, as well as the capacity to integrate such information. Gurazada et al. [4] summarize how transcriptomics can provide spatially referenced single-cell gene expression data for unraveling developmental programs in plants. Mass spectrometry, already a cornerstone for metabolite and protein analyses, is constantly adapting to leverage advances in plant genomics and computation for large, complex samples. Alvarez and Naldrett [5] and Smythers and Hicks [6] provide two snapshots of using mass spectrometry for untargeted metabolomics and mapping proteomic systems in response to stresses, respectively. Both reviews look ahead to connecting data on metabolites and proteins, as well as achieving cellular resolution to complement emerging transcriptome strategies. Schaffer et al. [7] introduce readers to three technologies that are revolutionizing structural biology for understanding macromolecular function.

With more and better data comes the opportunity to analyze and model systems using a variety of computational approaches. Matthews and Marshall-Colon [8] review how computational models that span multiple biological scales are being developed with the goal of understanding and predicting physiological processes and how to engineer those systems for plant improvement. The impact of machine learning on data extraction from plant phenomics studies is discussed by Buckner et al. [9]. New imaging applications are allowing the visualization of the ‘hidden-half’ of plants in ways that are as powerful as non-invasive medical imaging tools. Dowd et al. [10] examine a combination of imaging systems that provide three-dimensional views of root systems and their environment with minimal impact on their natural growth.

Remote sensing technologies employed from the plant to field are rapidly entering use and can inform computational modeling. Sibers et al. [11] review how measuring photosynthesis by methods from hyperspectral imaging of leaves to solar-induced fluorescence observed by satellites can be
applied for modeling global ecosystem productivity. The revolution in monitoring systems is also leading to tools for surveillance of plant pests and pathogens, as described by Silva et al. [12]. Similarly, the combination of robotics, imaging and machine learning analysis tools is enabling high-throughput phenotyping of plants across a spectrum of ecologically relevant environments, as reviewed by van de Zeddé et al. [13]. McNicol et al. [14] provide an update on stable isotope ecology — a traditional tool for examining plant–environment interactions — and how new advances in modeling and meta-analyses allow for insights into regional and global nutrient cycles.

The last three reviews in the series cover emerging areas for improving agriculture. Breakfield et al. [15] give an industry view of the search for and use of plant growth-promoting microbes as an application for enhancing productivity in the field while reducing synthetic fertilizers. Efforts to meet the challenge of feeding a growing population also sparks efforts to bring new crops to farmers through technology-enabled rapid domestication, as reported by Marks et al. [16], who use pennycress, a new oilseed cash cover crop as an example. Schlautman et al. [17] focus on perennial groundcovers that can increase both the production and regenerative potential of agricultural systems if key multiscale interactions can be better understood.

Overall, this collection of reviews aims to cover emerging technologies that are enabling plant scientists to look into the cell, into the plant, and into the environment in new and exciting ways. Although the reviews here only provide a glimpse of some (not all) of the palette currently available to plant science, this is a truly exciting time to be a plant biologist — whether one is interested in the intricacies of molecular and cellular function in the plant cell to feeding the world, or both — building a comprehensive understanding of these fascinating organisms is the foundation of those goals.

**Competing Interests**

The authors declare that there are no competing interests associated with the manuscript.

**References**