

Letters

One hundred important questions for plant science – reflecting on a decade of plant research

Introduction

In 2011, we published 100 important questions for plant science research pertaining to (A) society, (B) environment and adaptation, (C) species interactions, (D) understanding and utilising plant cells, and (E) diversity (Grierson *et al.*, 2011). The original publication became one of the most read articles in *New Phytologist*, demonstrating wide interest in identifying priorities for plant research. Here, we reflect on developments in plant science since our 2011 paper, with our original questions in mind. Horizon scanning can identify and prioritise gaps in knowledge, but both researchers and funders are interested in how predictable this research can be. Looking back as well as forward can illuminate the trajectory of our field. It also provides context for a new paper identifying the current most important 100 questions in plant science research (Armstrong *et al.*, 2023).

Our questions in 2011 were not designed to enable a quantitative study of research predictability/outcomes and space constraints mean that it is not possible to mention all the excellent work that contributed to advancing plant science in the past decade. Connections between our five categories mean cross-referencing between sections is unavoidable. A full list of questions with their descriptions from Grierson *et al.* (2011) is provided as supplementary data. Questions are referenced (A6) where A is section A and 6 is question 6.

A. Society

The past 10 years brought much greater awareness of the climate change and biodiversity crises and the importance of plants for human survival. Despite this, continued destruction of tropical forests and peat bogs has caused significant losses in biodiversity and climate stability (Holden, 2005; Barlow *et al.*, 2016; Seidl *et al.*, 2017; Kitson & Bell, 2020; Qin *et al.*, 2021), jeopardising global agreement goals (A12, A13, C5, D22, E3). Urgent and radical action is now needed to prevent increasingly catastrophic outcomes (WEF, 2022). In 2016 in Paris, countries agreed to minimise the rise in global average temperature and achieve net zero carbon emissions by 2050 (UNFCCC, 2015) (A6) and in 2021 at COP26 in Glasgow, 45 world leaders committed to accelerate innovation and deployment of clean technologies this decade, with annual progress assessed in Breakthrough Agenda Reports

(IEA, 2022). A noticeable increase in climate activism and rethinking of food systems, including moves to more plant-based diets (Poppy & Baverstock, 2019; Bhunnoo & Poppy, 2020; Raducu *et al.*, 2020), plus international poll results, have indicated strong, global, public support for action to tackle climate change (Flynn *et al.*, 2021; Gaffney *et al.*, 2021) (A1, A3, A14, B6, C5).

Plant science has made important contributions to improving models of climate change and its consequences (Ikeda *et al.*, 2017; Rötter *et al.*, 2018; Merganičová *et al.*, 2019; Kawamiya *et al.*, 2020) (A6, D22). There is evidence that serious consequences of climate change, including drought-related conflict and migration, are happening (Abel *et al.*, 2019). As we and many others acknowledged, there are major risks to food security. Despite significant advances, such as speed breeding protocols (Watson *et al.*, 2018), acceptance of technologies that could accelerate the development of new crops is patchy. Genetically modified (GM) crops (29 cultivating countries, 72 have issued regulatory approvals) occupy *c.* 1.4% of global arable land and a few are grown in many regions (ISAAA, 2019), including the EU and Africa (James, 2015) (A5), but there are signs of change. For example, a survey of how Britons engage with science reported the public 'feel aware of plant science and accept GM organisms, particularly those with health benefits' (Department for Business, Energy, & Industrial Strategy, 2020) (A10, A11, A14, A15). Gene editing regulations around the world range from regulated as a GMO to unregulated (ISAAA, 2021). The UK government has outlined how gene edited crops will make plant breeding faster and more precise (DEFRA, 2021) and the first CRISPR-edited wheat crop was planted in the UK in October 2021 – a European first (Peplow, 2021) (A8, A9a). Despite advances in weed and pest control, reducing fertiliser application and land use, cultural change towards more sustainable models for food production and land use has been patchy and sporadic (A3, A4).

Despite relevance to urgent challenges including climate change prediction, adaptation, mitigation, food security and human health, plant science has received far less funding than fields such as health research (e.g. £50 M for plant science vs £4.8 B for health research in the UK in 2018). Many plant researchers and projects struggle to find funding, leaving plant-related industries without realistic and affordable solutions. Global investment in research for resilient and sustainable agriculture has not grown sufficiently to meet globally agreed climate change goals (IEA, 2022). Also, the preference of publishers, funders and academic employers for high-impact publications and novel discoveries over well-founded incremental knowledge has limited who contributes to research (B7, B8, B9). In response to this, the DORA declaration (Alberts, 2013; DORA, 2013), eminent bodies (e.g. The Royal Society) (Catlow, 2019) and public funders (UKRI, 2019) have recognised other ways to measure merit, impact and fundability.

Plant science provides crucial information that humanity needs to improve our prospects, but an effective response requires political, social and commercial action. As we highlighted 10 years ago, interdisciplinary collaboration is essential (A18), and it is exciting to reflect on an increasingly diverse and integrated research community. Plant scientists have increasingly collaborated with experts in other fields, including commerce, social science, policy and communication and engaged via broadcasters (e.g. the BBC Studios Natural History Unit documentary ‘The Green Planet’) and popular science books (e.g. *In Defence of Plants* by Matt Candeias, 2021, and Wainwright Prize for Conservation Writing winner *Entangled Life* by Merlin Sheldrake, 2021). In frustration at inadequate action on climate change and collapsing biodiversity, some scientists have become political activists (Pancost, 2022; Racimo *et al.*, 2022) (A9a, A9b, A10). We did not imagine 10 years ago that a television programme would influence the political landscape the way *Blue Planet II* did for plastic pollution (May, 2018) (A10, A18). Equally, we did not appreciate how important social media would be for democratising access to scientific information, but also for propagating dangerous misinformation as simple and ‘shareable’ content.

Plant science education has also changed (A9b). Many university degrees now incorporate ‘sustainability’ or ‘entrepreneurship’, including economic, business, ecological and social perspectives (Nordén & Avery, 2021). The diversity of students and the wider plant science community is increasing with steps taken to educate, consult, collaborate with and recognise the contributions of people with an increasingly diverse range of backgrounds.

B. Environment and adaptation

The increasing societal importance and tightly interlinked relationship of the climate and biodiversity crises (B14–20) has been reflected in research, but sustainable solutions have not come quickly enough (IEA, 2022). We underemphasised the importance of collaborations (A18) between countries with different economic profiles to solve climate, biodiversity and food security crises, which disproportionately affect countries in the Global South (Ebi & Del Barrio, 2017; Kunert *et al.*, 2020; Mazhin *et al.*, 2020). However, international programs like CGIAR, Climate Change, Agriculture and Food Security, and the International Institute of Tropical Agriculture (IITA), which aim to support greener agriculture and sustainability at community levels, are growing around the world (B16–B21).

We expected to see more investment in genetic advancements within plant science (B1, B3–B6, B16, B19, E6), for example, improving hybrid wheat, which should have better resilience to climate change, and domesticating new plant species (Davis *et al.*, 2020), but neither has gained much traction. Research centres have continued to apply plant genetics to challenges (Henry, 2020; Mayer *et al.*, 2020) (B10–B15), while vertical and soil-free farming increasingly aim to produce sustainable crops less reliant on environmental stability (Eldridge *et al.*, 2020) (B12). Successful attempts to reclaim deserts by greening (Kaptué *et al.*, 2015; Maclean, 2018) were not mentioned in our paper, although we knew this was an important area to investigate (B21).

C. Species interactions

We identified questions around how plants interact with their living environment and how this relates to nutrition, ecosystem health and diversity. The International Year of Soils in 2015 highlighted the importance of soil preservation and health (C6–C8, C14) and the benefits of plant microbiomes, soil biodiversity (C6–C8) and plant communities (C9) (Berendsen *et al.*, 2012; Thiele-Bruhn *et al.*, 2012; Liu *et al.*, 2016; Rillig *et al.*, 2018; Cheng *et al.*, 2019; Olanrewaju *et al.*, 2019). Work on socially focused weed management and technology-led pest and disease solutions continued (C1–C4, C10–C13, C15) (Bagavathiannan *et al.*, 2019; Graham *et al.*, 2019; J. Zhang *et al.*, 2019). The use of neonicotinoids as a pesticide is an example of the potential benefits of closer interactions between agricultural and ecological sciences, which could reduce commercial risks by identifying potential impacts, for example, on pollinator populations (C1, C4, C5, C10) (Tsvetkov *et al.*, 2017; Woodcock *et al.*, 2017), and drive exploration of better alternatives (C2) (Jactel *et al.*, 2019). While we recognised these tensions (C1, C2, C5), we did not emphasise how climate change might accelerate pest growth and behaviour (Juroszek *et al.*, 2020).

D. Understanding and utilising plant cells

Plant scientists have increasingly worked on global challenges, but the impacts of scientific advancement remain difficult to predict. For example, the discovery of small RNAs in plants (D9) (Molnar *et al.*, 2011) and fundamental mechanisms of chromatin regulation (B2, B8, D7) (Whittaker & Dean, 2017) received the Wolf Prize for agriculture even though they did not have direct agricultural goals. The literature on some topics, such as algal biofuels (D20, D21), has grown less than we anticipated. Model plants continue to support fundamental research; laboratory staples like *Arabidopsis* (Parry *et al.*, 2020) and *Nicotiana* advance our understanding of epigenetic, plant cell and molecular biology (D7, D8, D11, D12), allowing foundational questions to be addressed (D3, D13, D14, D16, D17). The importance of negative results is increasingly recognised (Nature Editorial, 2017) and there have been significant improvements in statistical literacy. Major advances in both efficiency and affordability of gene editing tools, notably CRISPR-Cas9 (A8) (Jinek *et al.*, 2012; Ray & Satya, 2014), are facilitating fundamental research in a range of species, for example, to increase meiotic recombination and hence novelty for plant breeding (Li *et al.*, 2021) (D18, D19). Biosensors and optobiology are among the newest tools for investigating the dynamics of molecular interactions that regulate hormone signalling or cellular kinetics (Papanatsiou *et al.*, 2019; Herud-Sikimić *et al.*, 2021) (D15). Structural biology using CryoEM provides information about plant immune system complexes (Ma *et al.*, 2020; Martin *et al.*, 2020), and whole plant transcriptional landscapes and complex cell fates can be resolved through ultra-high-resolution single-cell RNA sequencing, which was first developed in plants (Denyer *et al.*, 2019; T. Q. Zhang *et al.*, 2019). Collectively, these novel technical and experimental capabilities mean previously unknown mechanisms, networks and pathways are now easier to

capture in multiple model organisms. Reflecting on our questions highlights exciting innovations, from using plant systems to screen for bioreactive molecules with medicinal relevance in humans (D24) to applications in industry (D25) (Drakakaki *et al.*, 2011; Espinosa-Leal *et al.*, 2018; Chandran *et al.*, 2020).

E. Plant diversity

The IPBES Global Assessment (Brondizio *et al.*, 2019) estimated more than a million species are now threatened with extinction, meaning the documentation of plant diversity is more important than ever (E1, E2, E6, E17), especially in the species-rich tropics (Kaptué *et al.*, 2015; Maclean, 2018; Brummitt *et al.*, 2021). The Royal Botanic Gardens, Kew, has been coordinating a periodic assessment of the threats facing plant diversity and sustainable use of plant resources, both domesticated and wild, through its *State of the World's Plants* (Antonelli *et al.*, 2020). While we recognised the increased amount of arable land used for livestock and feed, we understated the direct impact of livestock on the environment and the potential contribution to climate change. The need to preserve native plant genetic diversity (E1–E6, E8, E17, A7) while working with primary food producers of the Global South is even more urgent (A1–A3, A11). New organisations, from local entities like the Crop Science Centre, an alliance between the University of Cambridge and NIAB, to international associations like AIRCA have joined established programmes, such as CIMMYT, CGIAR and the FAO to integrate plant diversity, sustainability, equity and climate adaptability into global agriculture (E3).

Insights have also been gained into the origins of plant diversity, plant histories and phylogenetics (Pellicer *et al.*, 2018; Carta *et al.*, 2020; González *et al.*, 2020; Donoghue *et al.*, 2021) (E9–E17, D4). Scientists advanced genomic knowledge on a larger range of species (Edwards & Batley, 2010; Uauy, 2017; Bayer *et al.*, 2020; Yang & Yan, 2021) and, together with new plant transformation and breeding techniques, increased the range of species available to fundamental and applied research (E7, E8) (Eck, 2018; Watson *et al.*, 2018; Borrill, 2020; Thudi *et al.*, 2021; Varshney *et al.*, 2021), including within-species genome comparisons that revealed novel and exciting mechanisms of plant development, physiology and evolution.

Conclusions

A new iteration of the 100 Questions project has just been completed (Armstrong *et al.*, 2023) that includes some quantitative comparisons with our original questions. Both the BBSRC (Langdale, 2021) and ASPB (Henkhaus, 2020) recently published decadal visions for plant science, confirming the need for strategic investment in plant science. The Breakthrough Agenda Report (IEA, 2022) emphasises the urgent need for investment in research to reduce agricultural greenhouse gas emissions while securing food supplies. We cannot overstate the importance of continued engagement between plant scientists and the range and breadth of plant science topics, from fundamental discoveries to urgent issues affecting daily lives. The COVID-19 pandemic demonstrated that, with the freedom to rapidly deploy funding, diverse

research areas can rapidly deliver powerful solutions to global challenges (e.g. Harper *et al.*, 2021). Plant scientists need to work collaboratively with the broad forces of economics, politics, policy and disciplines so that benefits can be identified and delivered. We celebrate plant research advances over the past decade and look forward to increasing recognition of the importance of plant science and its potential to solve crucial global problems.

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Competing interests

None declared.

Author contributions

CSG initiated and led the project. ERL coordinated the project and wrote initial drafts. All authors contributed the content. EMA and CSG restructured and rewrote the paper in response to editorial and referee comments. EMA, HH, ERL, MWC and CSG added details and examples. ERL, EMA, HH, DG, SK, MWC and CSG edited the final draft, which was approved by all authors. ERL and EMA contributed equally to this work.

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