New Phytologist

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 regreening (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.

Acknowledgements

EMA and HH were supported by the Bristol Centre for Agricultural Innovation. ERL was supported by the School of Biological Sciences at the University of Bristol.

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.

ORCID

Emily May Armstrong https://orcid.org/0000-0002-8342-1489
Mark W. Chase https://orcid.org/0000-0002-9927-4938
Claire S. Grierson https://orcid.org/0000-0002-4000-0975
Don Grierson https://orcid.org/0000-0002-2238-8072
Helen Harper https://orcid.org/0000-0002-6683-6148
Graham Jellis https://orcid.org/0000-0003-0416-2720
Jonathan D. G. Jones https://orcid.org/0000-0002-4953-261X
Sandra Knapp https://orcid.org/0000-0001-7698-3945
Emily R. Larson https://orcid.org/0000-0002-5498-8152
Giles Oldroyd https://orcid.org/0000-0002-5245-6355

Emily R. Larson[1†], Emily May Armstrong[1†], Helen Harper[1], Sandra Knapp[2], Keith J. Edwards[1], Don Grierson[3], Guy Poppy[4], Mark W. Chase[5,6], Jonathan D. G. Jones[7], Ruth Bastow[8], Graham Jellis[9], Steve Barnes[10], Paul Temple[11], Matthew Clarke[12], Giles Oldroyd[13] and Claire S. Grierson[1]*

[1]School of Biological Sciences, Bristol University, 24 Tyndall Avenue, Bristol, BS8 1TQ, UK;
[2]Natural History Museum, Cromwell Road, London, SW7 5BD, UK;
[3]School of Biosciences, University of Nottingham, Sutton Bonington Campus, nr Loughborough, LE12 5RD, UK;

[4]Biological Sciences, University of Southampton, University Road, Southampton, SO17 1BJ, UK;
[5]Department of Environment and Agriculture, Curtin University, Perth, WA 6845, Australia;
[6]Royal Botanic Gardens Kew, Richmond, London, TW9 3AE, UK;
[7]The Sainsbury Laboratory, Norwich Research Park, Norwich, NR4 7UH, UK;
[8]Crop Health and Protection Ltd, York Biotech Campus, Sand Hutton, York, YO41 1LZ, UK;
[9]Agrifood Charities Partnership, The Bullock Building, University Way, Cranfield, Bedford, MK43 OGH, UK;
[10]Independent Researcher;
[11]Wold Farm, Driffield, East Yorkshire, YO25 3BB, UK;
[12]Bayer – Crop Science, Monsanto UK Ltd, 230 Science Park, Cambridge, CB4 0WB, UK;
[13]Crop Science Centre, Lawrence Weaver Road, Cambridge, CB3 0LE, UK
(*Author for correspondence: email lacsg@bristol.ac.uk)
[†]These authors contributed equally to this work.

References

Abel GJ, Brottrager M, Cuaresma JC, Muttarak R. 2019. Climate, conflict and forced migration. *Global Environmental Change* **54**: 239–249.

Alberts B. 2013. Impact factor distortions. *Science* **340**: 787.

Antonelli A, Fry C, Smith RJ, Simmonds MSJ, Kersey PJ, Pritchard HW, Abbo MS, Acedo C, Adams J, Ainsworth AM *et al.* 2020. *State of the World's plants and fungi 2020.* London, UK: Royal Botanic Gardens.

Armstrong EM, Larson ER, Webb CR, Harper H, Dohleman F, Araya Y, Meade C, Feng X, Mukoye B, Levin MJ *et al.* 2023. One hundred important questions facing plant science: an international perspective. *New Phytologist* **238**: 470–481.

Bagavathiannan MV, Graham S, Ma Z, Barney JN, Coutts SR, Caicedo AL, De Clerck-Floate R, West NM, Blank L, Metcalf AL *et al.* 2019. Considering weed management as a social dilemma bridges individual and collective interests. *Nature Plants* **5**: 343–351.

Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, Nally RM, Thomson JR, de Barros Ferraz SF, Louzada J, Oliveira VHF *et al.* 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* **535**: 144–147.

Bayer PE, Golicz AA, Scheben A, Batley J, Edwards D. 2020. Plant pan-genomes are the new reference. *Nature Plants* **6**: 914–920.

Berendsen RL, Pieterse CMJ, Bakker PAHM. 2012. The rhizosphere microbiome and plant health. *Trends in Plant Science* **17**: 478–486.

Bhunnoo R, Poppy GM. 2020. A national approach for transformation of the UK food system. *Nature Food* **1**: 6–8.

Borrill P. 2020. Blurring the boundaries between cereal crops and model plants. *New Phytologist* **228**: 1721–1727.

Brondizio ES, Settele J, Díaz S, Ngo HT, eds. 2019. *Global assessment report on biodiversity and ecosystem services.* Bonn, Germany: IPBES Secretariat.

Brummitt N, Araújo AC, Harris T. 2021. Areas of plant diversity–what do we know? *Plants, People, Planet* **3**: 33–44.

Carta A, Bedini G, Peruzzi L. 2020. A deep dive into the ancestral chromosome number and genome size of flowering plants. *New Phytologist* **228**: 1097–1106.

Catlow R. 2019. *Tools to support and steward research culture.* Royal Society. [WWW document] URL https://royalsociety.org/topics-policy/projects/research-culture/tools-for-support/ [accessed 27 October 2022].

Chandran H, Meena M, Barupal T, Sharma K. 2020. Plant tissue culture as a perpetual source for production of industrially important bioactive compounds. *Biotechnology Reports* **26**: e00450.

Cheng YT, Zhang L, He SY. 2019. Plant-microbe interactions facing environmental challenge. *Cell Host & Microbe* **26**: 183–192.

Davis AP, Gargiulo R, Fay MF, Sarmu D, Haggar J. 2020. Lost and found: *Coffea Stenophylla* and *C. Affinis*, the forgotten coffee crop species of West Africa. *Frontiers in Plant Science* **11**. doi: 10.3389/fpls.2020.00616.

DEFRA. 2021. *Genetic technologies regulation: government response.* [WWW document] URL https://www.gov.uk/government/consultations/genetic-technologies-regulation/outcome/genetic-technologies-regulation-government-response [accessed 27 October 2022].

Denyer T, Ma X, Klesen S, Scacchi E, Nieselt K, Timmermans MCP. 2019. Spatiotemporal developmental trajectories in the Arabidopsis root revealed using high-throughput single-cell RNA sequencing. *Developmental Cell* **48**: 840–852.

Department for Business, Energy & Industrial Strategy. 2020. *Public attitudes to science 2019.* [WWW document] URL https://www.gov.uk/government/publications/public-attitudes-to-science-2019 [accessed 27 October 2022].

Donoghue PCJ, Jill Harrison C, Paps J, Schneider H. 2021. The evolutionary emergence of land plants. *Current Biology* **31**: R1281–R1298.

DORA. 2013. *San Francisco declaration on research assessment.* DORA (blog). [WWW document] URL https://sfdora.org/read/ [accessed 27 October 2022].

Drakakaki GA, Robert S, Szatmari A-M, Brown MQ, Nagawa S, Van Damme D, Leonard M, Yang Z, Girke T, Schmid SL *et al.* 2011. Clusters of bioactive compounds target dynamic endomembrane networks *in vivo. Proceedings of the National Academy of Sciences, USA* **108**: 17850–17855.

Ebi KL, Del Barrio MO. 2017. Lessons learned on health adaptation to climate variability and change: experiences across low- and middle-income countries. *Environmental Health Perspectives* **125**: 65001.

Eck JV. 2018. Genome editing and plant transformation of solanaceous food crops. *Current Opinion in Biotechnology* **49**: 35–41.

Edwards D, Batley J. 2010. Plant genome sequencing: applications for crop improvement. *Plant Biotechnology Journal* **8**: 2–9.

Eldridge BM, Manzoni LR, Graham CA, Rodgers B, Farmer JR, Dodd AN. 2020. Getting to the roots of aeroponic indoor farming. *New Phytologist* **228**: 1183–1192.

Espinosa-Leal CA, Puente-Garza CA, García-Lara S. 2018. *In vitro* plant tissue culture: means for production of biological active compounds. *Planta* **248**: 1–18.

Flynn C, Yamasumi E, Fisher S, Snow D, Grant Z, Kirby M, Browning P, Rommerskitchen M, Russel I. 2021. *The peoples' climate vote.* United Nations Development Programme. UNDP, University of Oxford Department of Sociology. [WWW document] URL https://www.undp.org/publications/peoples-climate-vote [accessed 27 October 2022].

Gaffney O, Tcholak-Antitch Z, Boehm S, Barthel S, Hahn T, Jacobson L, Levin K, Liverman D, Stoknes PE, Thompson S *et al.* 2021. *The global commons survey.* Global Commons Alliance. [WWW document] URL https://globalcommonsalliance.org/wp-content/uploads/2021/08/Global-Commons-G20-Survey-full-report.pdf [accessed 27 October 2022].

González AV, Gómez-Silva V, Ramírez MJ, Fontúrbel FE. 2020. Meta-analysis of the differential effects of habitat fragmentation and degradation on plant genetic diversity. *Conservation Biology: The Journal of the Society for Conservation Biology* **34**: 711–720.

Graham S, Metcalf AL, Gill N, Niemiec R, Moreno C, Bach T, Ikutegbe V, Hallstrom L, Ma Z, Lubeck A. 2019. Opportunities for better use of collective action theory in research and governance for invasive species management. *Conservation Biology* **33**: 275–287.

Grierson CS, Barnes SR, Chase MW, Clarke M, Grierson D, Edwards KJ, Jellis GJ, Jones JD, Knapp S, Oldroyd G *et al.* 2011. One hundred important questions facing plant science research. *New Phytologist* **192**: 6–12.

Harper H, Burridge A, Winfield M, Finn A, Davidson A, Matthews D, Hutchings S, Vipond B, Jain N, The COVID-19 Genomics UK (COG-UK) Consortium *et al.* 2021. Detecting SARS-CoV-2 variants with SNP genotyping. *PLoS ONE* **16**: e0243185.

Henkhaus N. 2020. *Plant science research network releases decadal vision 2020–2030.* Plant Science Today. [WWW document] URL https://blog.aspb.org/plant-science-research-network-releases-decadal-vision-2020-2030/ [accessed 27 October 2022].

Henry RJ. 2020. Innovations in plant genetics adapting agriculture to climate change. *Current Opinion in Plant Biology* **56**: 168–173.

Herud-Sikimić O, Stiel AC, Kolb M, Shanmugaratnam S, Berendzen KW, Feldhaus C, Höcker B, Jürgens G. 2021. A biosensor for the direct visualization of auxin. *Nature* **592**: 1–5.

Holden J. 2005. Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions. Series A, Mathematical, Physical and Engineering Sciences* **363**: 2891–2913.

IEA. 2022. *Breakthrough agenda report 2022 – analysis.* International Energy Agency. [WWW document] URL https://www.iea.org/reports/breakthrough-agenda-report-2022 [accessed 27 October 2022].

Ikeda DH, Max TL, Allan GJ, Lau MK, Shuster SM, Whitham TG. 2017. Genetically informed ecological niche models improve climate change predictions. *Global Change Biology* **23**: 164–176.

ISAAA. 2019. *Global status of commercialized biotech/GM crops: 2019 - ISAAA brief 55.* ISAAA.Org. [WWW document] URL https://www.isaaa.org/resources/publications/briefs/55/default.asp [accessed 27 October 2022].

ISAAA. 2021. *Breaking barriers with breeding: a primer on new breeding innovations for food security.* Ithaca, NY, USA: ISAAA. [WWW document] URL https://www.isaaa.org/resources/publications/briefs/56/download/isaaa-brief-56-2021.pdf [accessed 27 October 2022].

Jactel H, Verheggen F, Thiéry D, Escobar-Gutiérrez AJ, Gachet E, Desneux N. 2019. Alternatives to neonicotinoids. *Environment International* **129**: 423–429.

James C. 2015. *20th Anniversary (1996 to 2015) of the global commercialization of biotech crops and biotech crop highlights in 2015.* ISAAA Brief No. 51. Ithaca, NY, USA: ISAAA.

Jinek M, Chylinski K, Fonfara I, Hauer M, Doudna JA, Charpentier E. 2012. A programmable dual-RNA-Guided DNA endonuclease in adaptive bacterial immunity. *Science* **337**: 816–821.

Juroszek P, Racca P, Link S, Farhumand J, Kleinhenz B. 2020. Overview on the review articles published during the past 30 years relating to the potential climate change effects on plant pathogens and crop disease risks. *Plant Pathology* **69**: 179–193.

Kaptué AT, Prihodko L, Hanan NP. 2015. On regreening and degradation in sahelian watersheds. *Proceedings of the National Academy of Sciences, USA* **112**: 12133–12138.

Kawamiya M, Hajima T, Tachiiri K, Watanabe S, Yokohata T. 2020. Two decades of earth system modeling with an emphasis on model for interdisciplinary research on climate (MIROC). *Progress in Earth and Planetary Science* **7**: 64.

Kitson E, Bell NGA. 2020. The response of microbial communities to peatland drainage and rewetting: a review. *Frontiers in Microbiology* **11**: 582812.

Kunert KJ, Botha A-M, Oberholster PJ, Yocgo R, Chimwamurombe P, Vorster J, Foyer CH. 2020. Factors facilitating sustainable scientific partnerships between developed and developing countries. *Outlook on Agriculture* **49**: 204–214.

Langdale J. 2021. *UK plant science research strategy: a green roadmap for the next ten years.* BBSRC. [WWW document] URL https://www.ukri.org/wp-content/uploads/2021/03/BBSRC-120321-PlantScienceStrategy.pdf [accessed 27 October 2022].

Li F, Jin C, Zhang L, Wang J. 2021. Hyper-recombinant plants: an emerging field for plant breeding. *Critical Reviews in Plant Sciences* **40**: 446–458.

Liu H, Meng J, Bo W, Cheng D, Li Y, Guo L, Li C, Zheng Y, Liu M, Ning T *et al.* 2016. Biodiversity management of organic farming enhances agricultural sustainability. *Scientific Reports* **6**: 23816.

Ma S, Lapin D, Liu L, Sun Y, Song W, Zhang X, Logemann E, Yu D, Wang J, Jirschitzka J *et al.* 2020. Direct pathogen-induced assembly of an nlr immune receptor complex to form a holoenzyme. *Science* **370**: eabe3069.

Maclean R. 2018. *The great African regreening: millions of 'magical' new trees bring renewal.* The Guardian, sec. World News. [WWW document] URL http://www.theguardian.com/world/2018/aug/16/regreening-niger-how-magical-gaos-transformed-land [accessed 27 October 2022].

Martin R, Qi T, Zhang H, Liu F, King M, Toth C, Nogales E, Staskawicz BJ. 2020. Structure of the activated ROQ1 resistosome directly recognizing the pathogen effector XopQ. *Science* **370**: eabd9993.

May T. 2018. *Prime Minister's speech on the environment: 11 January 2018.* Gov.UK. [WWW document] URL https://www.gov.uk/government/speeches/prime-ministers-speech-on-the-environment-11-january-2017 [accessed 27 October 2022].

Mayer M, Hölker AC, González-Segovia E, Bauer E, Presterl T, Ouzunova M, Melchinger AE, Schön C-C. 2020. Discovery of beneficial haplotypes for complex traits in maize landraces. *Nature Communications* **11**: 4954.

Mazhin SA, Khankeh H, Farrokhi M, Aminizadeh M, Poursadeqiyan M. 2020. Migration health crisis associated with climate change: a systematic review. *Journal of Education and Health Promotion* **9**: 97.

Merganičová K, Merganič J, Lehtonen A, Vacchiano G, Sever MZO, Augustynczik ALD, Grote R, Kyselová I, Mäkelä A, Yousefpour R *et al.* 2019. Forest carbon allocation modelling under climate change. *Tree Physiology* **39**: 1937–1960.

Molnar A, Melnyk C, Baulcombe DC. 2011. Silencing signals in plants: a long journey for small RNAs. *Genome Biology* **12**: 215.

Nature Editorial. 2017. Rewarding negative results keeps science on track. *Nature* **551**: 414.

Nordén B, Avery H. 2021. Global learning for sustainable development: a historical review. *Sustainability* **13**: 3451.

Olanrewaju OS, Ayangbenro AS, Glick BR, Babalola OO. 2019. Plant health: feedback effect of root exudates-rhizobiome interactions. *Applied Microbiology and Biotechnology* **103**: 1155–1166.

Pancost RD. 2022. *Climate scientist activisam.* The Uncertain World (Blog). [WWW document] URL https://richpancost.blogs.bristol.ac.uk/2022/08/29/climate-scientist-activism/ [accessed 27 October 2022].

Papanatsiou M, Petersen J, Henderson L, Wang Y, Christie JM, Blatt MR. 2019. Optogenetic manipulation of stomatal kinetics improves carbon assimilation, water use, and growth. *Science* **363**: 1456–1459.

Parry G, Provart NJ, Brady SM, Uzilday B. 2020. Current status of the multinational Arabidopsis community. *Plant Direct* **4**: e00248.

Pellicer J, Hidalgo O, Dodsworth S, Leitch IJ. 2018. Genome size diversity and its impact on the evolution of land plants. *Genes* **9**: E88.

Peplow M. 2021. UK trials first CRISPR-edited wheat in Europe. *Nature Biotechnology* **39**: 1174.

Poppy GM, Baverstock J. 2019. Rethinking the food system for human health in the Anthropocene. *Current Biology* **29**: R972–R977.

Qin Y, Xiao X, Wigneron J-P, Ciais P, Brandt M, Fan L, Li X, Crowell S, Wu X, Doughty R *et al.* 2021. Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nature Climate Change* **11**: 442–448.

Racimo F, Valentini E, De León GR, Santos TL, Norberg A, Atmore LM, Murray M, Hakala S, Olsen FA, Gardner CJ *et al.* 2022. The role of life scientists in the biospheric emergency: a case for acknowledging failure and changing tactics. *Zenodo.* doi: 10.5281/zenodo.7047049.

Raducu R, Soare C, Chichirez C-M, Purcarea MR. 2020. Climate change and social campaigns. *Journal of Medicine and Life* **13**: 454–457.

Ray S, Satya P. 2014. Next generation sequencing technologies for next generation plant breeding. *Frontiers in Plant Science* **5**: 367.

Rillig MC, Lehmann A, Lehmann J, Camenzind T, Rauh C. 2018. Soil biodiversity effects from field to fork. *Trends in Plant Science* **23**: 17–24.

Rötter RP, Hoffmann MP, Koch M, Müller C. 2018. Progress in modelling agricultural impacts of and adaptations to climate change. *Current Opinion in Plant Biology* **45**: 255–261.

Seidl R, Thom D, Kautz M, Martin-Benito D, Peltoniemi M, Vacchiano G, Wild J, Ascoli D, Petr M, Honkaniemi J *et al.* 2017. Forest disturbances under climate change. *Nature Climate Change* **7**: 395–402.

Thiele-Bruhn S, Bloem J, de Vries FT, Kalbitz K, Wagg C. 2012. Linking soil biodiversity and agricultural soil management. *Current Opinion in Environmental Sustainability, Terrestrial Systems* **4**: 523–528.

Thudi M, Palakurthi R, Schnable JC, Chitikineni A, Dreisigacker S, Mace E, Srivastava RK, Satyavathi CT, Odeny D, Tiwari VK *et al.* 2021. Genomic resources in plant breeding for sustainable agriculture. *Journal of Plant Physiology* **257**: 153351.

Tsvetkov N, Samson-Robert O, Sood K, Patel HS, Malena DA, Gajiwala PH, Maciukiewicz P, Fournier V, Zayed A. 2017. Chronic exposure to neonicotinoids reduces honey bee health near corn crops. *Science* **356**: 1395–1397.

Uauy C. 2017. Wheat genomics comes of age. *Current Opinion in Plant Biology* **36**: 142–148.

UKRI. 2019. *Introducing a better way for you to evidence your contributions.* [WWW document] URL https://www.ukri.org/apply-for-funding/how-were-improving-your-funding-experience/introducing-a-better-way-for-you-to-evidence-your-contributions/ [accessed 27 October 2022].

UNFCCC. 2015. *Paris agreement: decision 1/CP.17 - UNFCCC document FCCC/CP/2015/L.9/Rev.1.* [WWW document] URL http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf [accessed 27 October 2022].

Varshney RK, Bohra A, Roorkiwal M, Barmukh R, Cowling WA, Chitikineni A, Lam H-M, Hickey LT, Croser JS, Bayer PE *et al.* 2021. Fast-forward breeding for a food-secure world. *Trends in Genetics* **37**: 1124–1136.

Watson A, Ghosh S, Williams MJ, Cuddy WS, Simmonds J, María-Dolores Rey M, Hatta AM, Hinchliffe A, Steed A, Reynolds D *et al.* 2018. Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants* **4**: 23–29.

WEF. 2022. *Global risks report 2022.* World Economic Forum. [WWW document] URL https://www.weforum.org/reports/global-risks-report-2022/in-full/ [accessed 27 October 2022].

Whittaker C, Dean C. 2017. The FLC locus: a platform for discoveries in epigenetics and adaptation. *Annual Review of Cell and Developmental Biology* **33**: 555–575.

Woodcock BA, Bullock JM, Shore RF, Heard MS, Pereira MG, Redhead J, Ridding L, Dean H, Sleep D, Henrys P *et al.* 2017. Country-specific effects of neonicotinoid pesticides on honey bees and wild bees. *Science* **356**: 1393–1395.

Yang N, Yan J. 2021. New genomic approaches for enhancing maize genetic improvement. *Current Opinion in Plant Biology* **60**: 101977.

Zhang J, Huang Y, Ruiliang P, Gonzalez-Moreno P, Yuan L, Kaihua W, Huang W. 2019. Monitoring plant diseases and pests through remote sensing technology: a review. *Computers and Electronics in Agriculture* **165**: 104943.

Zhang T-Q, Zhou-Geng X, Shang G-D, Wang J-W. 2019. A single-cell RNA sequencing profiles the developmental landscape of Arabidopsis root. *Molecular Plant* **12**: 648–660.

Key words: adaptation, environment, plant diversity, plant science questions, societal importance, species interactions.

Received, 27 October 2022; accepted, 14 November 2022.