Viewpoints

One hundred important questions facing plant science: an international perspective

Summary

The 'One Hundred Important Questions Facing Plant Science Research' project aimed to capture a global snapshot of the current issues and future questions facing plant science. This revisiting builds on the original 2011 paper. Over 600 questions were collected from anyone interested in plants, which were reduced to a final list of 100 by four teams of global panellists. There was remarkable consensus on the most important topics between the global subpanels. We present the top 100 most important questions facing plant science in 2022, ranging from how plants can contribute to tackling climate change, to plant-defence priming and epigenome plasticity. We also provide explanations of why each question is important. We demonstrate how focussing on climate change, community and protecting plant life has become increasingly important for plant science over the past 11 years. This revisiting illustrates the collaborative and international need for long-term funding of plant science research, alongside the broad community-driven efforts to actively ameliorate and halt climate change, while adapting to its consequences.

Introduction

Since the original 'One Hundred Important Questions Facing Plant Science Research' paper was published in 2011 (Grierson *et al.*, 2011), plant research continues to be of critical importance to global academic, commercial and policymaking communities. The world's growing population needs plant science to help deliver safe and reliable food, fuel, building materials, textiles and paper; but global inequalities exacerbated by a changing climate mean these basic requirements are frequently not realised equitably. Equally, plants provide a critical avenue for climate change deceleration (Bonan & Doney, 2018). By revisiting the 'One Hundred Important Questions Facing Plant Science Research' project in 2022, we horizon-scan for new areas of pressing research, while including voices from historically excluded communities.

We sought questions about plants, plant science and plant research from diverse sources, ranging from the botanically curious nonexpert to those with years of plant-focussed research expertise. Our panel of experts was chosen to reflect the diverse interests of plant research around the world, with 10 each from both the Global North and South. Our panellists' interests are broad and diverse, ranging from palaeobotany to conservation ecology, agricultural economics and cell biology. A full list of panellist's interests and expertise is available in Supporting Information Notes S1. We ensured that gender balance was met and included voices of those typically excluded from global conversations about plant research to ensure decisions were as inclusive and representative of global communities as possible.

Here, we present the outcome of a global collaboration to identify emerging plant research themes. Since our first 2011 publication, horizon scanning has become a key part of research engagement and policy in many fields (Blumensaat *et al.*, 2019; Goddard *et al.*, 2021; Glaros *et al.*, 2022), and we hope both our methods and outcomes contribute constructively to these important conversations. We provide extensive descriptions for each question in Notes S2, to clarify what each question means, summarise relevant background information and explain why we consider each question important.

We had three goals:

(**1**) Stimulate discussion between often disconnected areas of plant science and related communities, while horizon-scanning key areas for future research;

(**2**) Encourage plant scientists to think beyond the limits of their own research and consider the most important research that could be undertaken;

(**3**) Include historically excluded voices and elicit both region-specific and globally relevant questions.

To achieve these goals, we followed a modified Delphi protocol based on Sutherland *et al.* (2008) to identify the 100 most important questions currently facing the global plant science community. This project began when question collection opened on 18 May 2021 and finished on 30 September 2022.

Materials and Methods

Question collection

Questions were collected virtually from 18 May 2021 to 31 January 2022 at https://tinyurl.com/100PlantScienceQuestions. Question submission was promoted using social media platforms (Facebook, Twitter and Instagram), international and national plant-focussed mailing lists, internal communications across global higher education and research institutions, word-of-mouth, direct contact, newsletters and press releases. Plant-focussed institutions around the world were also contacted, as were farming unions. Emphasis was placed upon contacting plant-focussed research institutions outside the Global North. Data were collected on

Box 1

Category A – Plants and Society: Questions were grouped into this category if they included any of the following criteria: broad topics considering how society interacts with plants, sociology, history, anthropology, economy, psychology, health and well-being, pedagogy, urban environments, academia, Indigenous histories and ethnobotany.
Category B – Plants, Climate Change and Food Production: Questions in this group included any of the following criteria: climate change, food security, food sovereignty, food production, sustainability, crops, productivity and farming. To be included in this category, questions had to make explicit mention of climate change or related terms like 'global warming'.
Category C – Plant–Environment Interactions: Questions were grouped into this category if they included any of the following criteria: broad-scale ecology, biodiversity, microbial interactions, mycorrhizal interactions, pathogens, biotic stress, abiotic stress, soils and carbon storage. Questions that were suited for category B but did not contain the words 'climate change' or related terms like 'global warming' were included in category C.
Category D – Molecular Approaches to Fundamental Plant Biology: Questions were grouped into this category if they included any of the following criteria: cell biology, model organisms, genetics, biochemistry, physiology, evolution, speciation, methodologies, sequencing, photosynthesis, CRISPR and epigenetics.

Some questions were edited for clarity in the final manuscript, without changing the meaning intended by the panel.

question category, submitter's location and profession. The question collection form was available in English, French, Spanish, German, Arabic, Simplified Chinese, Japanese and Brazilian Portuguese. Questions submitted in languages other than English were translated by native speakers.

Question selection and preparation

From the raw 616 questions submitted, questions were sifted and categorised before they were presented to panellists. Questions were manually grouped into four categories, broadly covering: (A) Plants and Society; (B) Plants, Climate Change and Food Production; (C) Plant–Environment Interactions; and (D) Molecular Approaches to Fundamental Plant Biology. Some questions bridged multiple categories. See Box 1 for definitions and keywords for each category.

To improve question selection efficiency by panellists, EMA excluded questions that were not about plants, were not questions, or where the answers are well known, and combined questions with similar themes, topics and wording. Effort was made to ensure key words, concepts and topics were preserved in combined questions, whereas determiners, connectors and prepositions were not preserved. After this exclusion, 208 questions remained for panellists' consideration.

For a full list of all submitted questions, combined question information and frequency of combined questions by category, see Notes S3.

Panellist selection and organisation

Question submitters could express interest in becoming a panellist on the question submission form and were encouraged to apply if they worked in a plant-related career, regardless of location. Prospective panellists were especially encouraged to apply from the Global South and if they had 5+ years experience in a plant-related career. Expressions of interest were followed up with a diversity monitoring form that collected panellist age, location of birth, location of work, gender identity, length of career to date, career sector and additional caring responsibilities. Panellists were encouraged to share a brief overview of their motivations, experience and understanding of the project's aims. In total, 86 people applied to be panellists, with the majority (53%) currently working in Europe, reflecting the initial Europe-centric promotion of this project. This initial European overrepresentation was mediated by adjusting the number of panellists for each region. Additional panellists were contacted to ensure gender balance and industry knowledge in the panellist pool.

Panellists' identifying information was removed and EMA, ERL, HH and CG independently chose prospective panellists based on their supporting statements before amendments for gender balance were made. A total of 20 panellists were selected: six based in Europe (AG, CRW, RA, BL, CM and DF), six based in North and South America (FD, AAC, ML, AB, VP and SS), five based in Asia and Oceania (SSP, XF, DJ, VG and NO), and three based in (or originally from) Africa (IW, BM and YA). Efforts were made to cover a wide breadth of research interests and experiences within panels. Gender parity was achieved between the 20 panellists. Information on panel demographics can be found in Notes S1.

Panellist-led discussions

Four independent regional panels were established: Europe, North and South America, Asia and Oceania, and Africa. This allowed region-specific discussion while reducing time-zone issues. Each regional panel elected a representative to contribute to the final, global panel meetings. Using a modified and nonanonymised Delphi ranking system (Sutherland *et al.*, 2008), each regional panel reduced the 208 questions to a regional ranked list of 100 from March to April 2022 over Zoom. Using an online meeting system ensured those with additional caring or health responsibilities could still attend and allowed global panel assembly.

The final panel consisted of ML, BM, BL, YA, XF, CM and FD and was chaired by EMA. The final global panel met eight times between April and May 2022 over Zoom. Questions were automatically included in the top 100 if all four or three of four regional panels had selected them. Open discussion for the inclusion/exclusion justification of each question was encouraged and panel representatives spoke on behalf of their region, not their own personal views. To choose the exemplary questions, EMA and the final panel determined the categories that received the most question submissions, which categories were the most globally relevant, and worked to identify a timely and relevant presubmitted question that was both innovative and tractable. These questions are presented at the start of the Results section. Full descriptions for questions are provided in Notes S2.

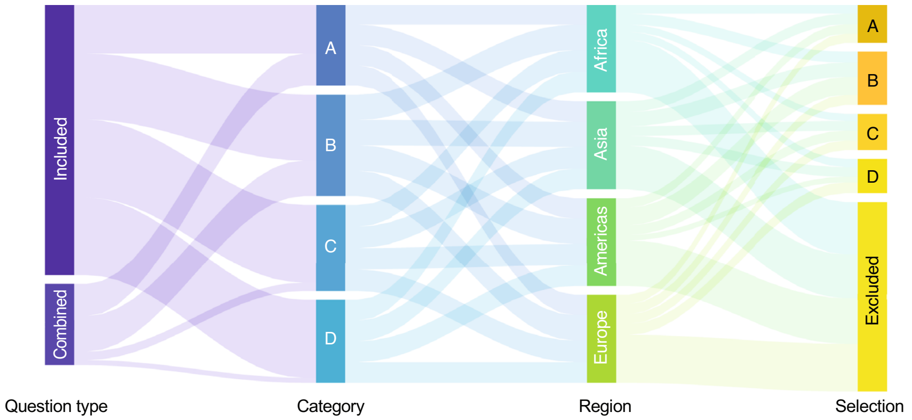

Fig. 1 Visualisation of question combination, question categorisation and regional selection by category. 'Included' is questions with one contributory question, and 'combined' is questions with two or more contributory questions. Each region chose their own independent list of 100 questions. Questions in category A, B, C and D under 'selection' were used to generate the final list of 100 questions after merging and discussion with regional representatives.

Post hoc question analysis

All text analysis was conducted in MATLAB (©2022a). Individual question sets were preprocessed using the inbuilt MATLAB Text Analytics Toolbox to correct spelling errors, improve lemmatization, remove stop words, remove punctuation and remove words < 2 characters and > 15 characters. An additional list of 71 words was not considered to be useful in the context of analysis and was removed. These are listed in Notes S4. Word clouds were generated using a latent Dirichlet allocation (LDA) topic model to find clusters of related words within the set of questions.

Co-occurrence networks were built around the most frequently occurring words found in each individual dataset. Keywords were defined as any word occurring six or more times across all the documents in the question set. Using a cut-off word frequency rather than fixing the number of key words leads to variation in the number of key words between question sets; however, it avoids arbitrary decisions on which words to include if there is a tie in word count. For each keyword, the set of all documents containing that keyword was identified. An edge exists between a keyword and another word if they occur in the same document. For a more detailed description of question analysis and supporting code, please see Notes S5. A representation of question collection, selection, exclusion and inclusion by region is shown in Fig. 1.

Results

To provide further explanation for each question's selection and inclusion, brief explanations of the question's background and context were included. These descriptions were written by different panellists depending on their field of expertise with the aim of making these questions appropriate and engaging to the broadest possible audience. Text justifying inclusion and explaining questions 1–100 can be found in Notes S2.

Eleven areas of critical global importance across diverse plant science research were identified. These 11 areas had the most question submissions during the collection period. Panellists used these categories to collectively identify a representative question for each area from the final question pool. These 11 questions were identified by the panellists as timely and relevant on a global scale, innovative and potentially tractable in a research career.

(**1**) Climate change: how will climate change impact plant abundance, productivity, bioregions and ecosystems?
(**2**) Science in the community: how can we ensure that the varied goals and needs of our diverse societies are understood and fulfilled by plant scientists?
(**3**) Food security: how do we leverage existing genetic diversity to create climate-resilient crops?
(**4**) Biodiversity: how does species diversity develop in novel ecosystems such as restored agricultural land, forests, grasslands and gardens?
(**5**) Sustainability: could plant-defence priming be a platform for a new green revolution?
(**6**) Plant–plant interactions: how are interactions between plant species regulated?
(**7**) Plant disease: how should we prepare for novel pathogens of trees, crops and the natural environment?
(**8**) Plant–microbiome interactions: how does the plant microbiome affect stress tolerance?
(**9**) Plant adaption: what is the plasticity of the epigenome of plants?
(**10**) Plant stress responses: how do plants cope with combined stressors?
(**11**) Ecosystem services: what natural materials could be invested in for a more sustainable future of manufacturing or residential development?

Collectively, our regional representatives agreed it would prove reductive to apply a uniform ranking system to the questions. The remaining 89 questions presented below are grouped by category (A–D) and are presented in no specific order of importance. Box 1 provides category keywords and definitions. If questions were combined or reworded, the original questions and wording can be found in Notes S3. Questions marked with an asterisk indicate panellist suggested questions, representing topics that were not reflected in the original question submissions, but the panellists agreed were important to the wider community.

Category A – Plants and Society

(**12**) How should the scientific community address the negative ecological, climate and educational impacts caused by plant awareness disparity?

(**13**) How should the scientific community better represent the benefits and risks of GMOs and gene-edited plants to the public?
(**14**) How can we make plant science education, practice and research more equitable and inclusive?
(**15**) What new medicinal compounds or volatiles do plants produce that could benefit human health?
(**16**) How can plant scientists develop a global plant biodiversity observation system that provides actionable data about changing states of vegetation?
(**17**) How do we adapt plants for space travel and can scientists create sustainable organic closed systems to support human life in challenging environments?
(**18**) Which plants can materials scientists use for novel materials?
(**19**) How do we ensure enough funding is available to preserve biodiversity in socioeconomically disadvantaged regions?
(**20**) How can scientists work with Indigenous Communities to preserve Indigenous Knowledge on (a) sustainable agriculture, (b) medicinal plants and (c) land stewardship?
(**21**) How do we continue to build resilient urban natural spaces? What positive impact would this have on well-being?
(**22**) How could plant science collaborate with 'city designers', architects and energy engineers to improve air and water quality, and rewild derelict urban land?
(**23**) What nutritional benefits can urban farming bring to urban environments?
(**24**) How can we improve recruitment and retention of a diverse plant science community?
(**25**) How can we harness the power of plant collections (Arboreta, Botanic Gardens and Herbaria) for research, education and public engagement?
(**26**) How do plants benefit human mental health, and how can these benefits be used in practice?
(**27**) What more can we do to raise public awareness of plant extinction?
(**28**) How can plant scientists increase student and society engagement and interest in plant sciences?
(**29**) Can plants be used to create sustainable, 'green' fuel?
(**30**) How can we utilise nonbiological technologies to help produce enough high-quality food?
(**31**) How can we ensure that plant science advances are accurately reflected in new policy? How does this vary globally?
(**32**) How can we balance protection against illegal plant poaching while ensuring Indigenous and Native communities have sustainable access to traditional plants?
(**33**) How can we better incorporate aquatic and riparian plants into environmental policy and research objectives?
(**34**) How do current pollution events affect our food systems and health?
(**35**) How can advances in information systems technology continue to drive a global understanding of plants?*

Category B – Plants, Climate Change and Food Production

(**36**) How will the world produce enough nutritious food with a growing population and a changing climate?
(**37**) How will a changing climate impact plant diseases?
(**38**) How will climate change alter the ability of plants to grow in different longitudes, latitudes and outside their typical environments?
(**39**) How can plant scientists work collaboratively with food producers and policymakers to address food supply chain issues and resource scarcity?
(**40**) How can we optimise fertiliser use in a changing climate?
(**41**) Which plants have the greatest potential to enhance soil carbon storage?
(**42**) How do we manage the impact of monocultures on biodiversity?
(**43**) To what extent is vegetation productivity limited by source constraints (photosynthesis) vs sink constraints (cell division and expansion) and how will these processes be impacted by climate change?
(**44**) Can we significantly reduce the impact of climate change by farming seaweeds more intensively and investing in algal aquaculture? Should we grow more crops under the sea?
(**45**) How can we broaden the range of staple crops?
(**46**) How will climate change alter plant carbon sequestration and what currently unknown feedback loops will emerge?
(**47**) How might plants evolve due to climate change? Are there species that could cope better, or species that we might lose?
(**48**) How can we continue to breed crop plants for productivity, while producing nutritious food using environmentally friendly/sustainable agriculture?
(**49**) Can we use climate change predictions to sustainably redistribute crop-growing regions?
(**50**) Will plant scientists be able to develop and deploy new cultivars fast enough in the face of climate change?
(**51**) Can we improve resource use efficiency in food production in an increasingly variable climate?
(**52**) How can understanding patterns of genetic diversity in crop plants inform food security in a changing climate?
(**43**) How will changing climates impact pollinator–plant interactions?
(**54**) How will plant–plant interactions change under a changing climate?
(**55**) How can we support long-term research on and regular monitoring of plant communities and their microbiota in natural environments?
(**56**) Which wild plants could be used as a new source of crops?
(**57**) How do risks to food security vary throughout the world?
(**58**) Should we use arable land to produce biofuels?
(**59**) How can microbiomes be harnessed to improve plant function for food and biofuel production and climate change mitigation?
(**60**) What long-term impacts will laboratory-grown meat products have on animal feed crops?
(**61**) How will continued green space destruction impact pollinators?
(**62**) How can we integrate biotechnologies into more diverse types of farming?
(**63**) How can we enhance yield and yield stability of our major food crops despite the need to optimise agricultural inputs?
(**64**) In what ways can we upscale agroecological practices?

(**65**) How can we effectively protect and maintain the genetic diversity in crop wild relatives?
(**66**) How can plants help prevent and mitigate flooding?
(**67**) How could resilience and sustainability of (agro)ecosystems be improved using new digital tools?
(**68**) What strategies of habitat restoration and planting will effectively reduce the impact of climate change?
(**69**) How could a shift to plant-based foods impact the environment?
(**70**) How can protein crop production be sustainably upscaled?*
(**71**) Are there quantifiable scientific and nutritional differences between food products grown using organic, biodynamic and conventional agricultural practices?*

Category C – Plant–Environment Interactions

(**72**) Can we engineer, for example algae to clean pollutants, oil spills from water systems?
(**73**) How do plants evolve to face abiotic stress?
(**74**) How can we ensure that plants benefit from the application of mycorrhizal fungi in agricultural contexts?
(**75**) How can we be better prepared to tackle future plant virus disease pandemics?
(**76**) Can we introduce complementary mycorrhizal fungi to pre-existing crops or genetically improve crops to accept mycorrhizal fungi?
(**77**) How can we utilise multitrophic interactions to improve crop breeding?
(**78**) How do plants balance growth and stress responses?
(**79**) How can the horticultural community reduce the threat of invasive ornamental species?
(**80**) Why and how are some plant pathogens able to extend their host range by host jumps?
(**81**) How are broad host range pathogens able to maintain virulence for many host plants?
(**82**) How do we better control plant pests without chemical pesticides?

Category D – Molecular Approaches to Fundamental Plant Biology

(**83**) How do we secure biodiversity by ensuring the necessary ecological knowledge of native plants is stored in seed banks?
(**84**) How do we use gene editing technology (CRISPR) to improve food security?
(**85**) What will be the end point of the improvement of photosynthesis efficiency?
(**86**) Plants are the biggest carbon storers on the planet; what can we learn from plants to engineer carbon storage solutions?
(**87**) How can scientists harness trans-generational transmission of stress-related 'memory' in plants?
(**88**) How do we use emerging whole genome data to study evolutionary processes across entire floras?
(**89**) Does the plant kingdom still have useful bioactive chemicals that are unknown to the wider scientific community? How do we protect these plant communities?
(**90**) What can genomic data still uncover about phylogeny?
(**91**) How does plant plasticity contribute to plant adaption for future climate conditions?
(**92**) How do we work as a global team to slow down pests and pathogens?
(**93**) On what basis can we confidently predict changes in community structure and plant diversity in response to global change?
(**94**) Can we accurately translate smaller-scale (e.g. genetic) knowledge to larger-scale (e.g. ecosystem) understanding?
(**95**) How extensive is horizontal gene transfer across plant species, and is it an important evolutionary stimulus?
(**96**) How can we utilize the knowledge of a limited number of model plant species in > 300 000 plant species including agriculturally and environmentally relevant species?
(**97**) What controls plant genome size and complexity?*
(**98**) How does metabolome variation across plant species help to explain plant coexistence?*
(**99**) How does signalling in plants control nutrient homeostasis, resource allocation and growth?*
(**100**) Can cereals be engineered to produce nitrogen-fixing root nodules?*

In total, 616 questions were submitted during question collection; 4% of questions were submitted from Africa, 13% from Asia, Australia and Oceania, 17% from North and South America, 46% from Europe, and for 17% no location was disclosed. We found that 75% of questions submitted were from those researching or working with plants. Of the final 100 questions, 30 had multiple contributing questions (ranging from 2 to 10 questions). See Notes S3 for contributory question information.

Understanding key themes and topics in the final 100 questions

The question dataset generated in this project allows for word frequency analysis and construction of word co-occurrence networks. Fig. 2 considers word content of the final 100 questions, while Fig. 2(a) highlights 'climate', 'change', 'food' and 'crop' as key words, which each appeared 23, 22, 16 and 13 times, respectively. Equally, these words act as key nodes in Fig. 2(b), alongside 'improve' 'environment' 'community' and 'sustainable'. These words exemplify the key themes and topics found in the 2022 question dataset.

Proof of concept for question exclusion, selection and rewording

To generate the final list of 100 questions, the original 616 questions underwent significant rewording, combination and exclusion. Some 339 questions that were not about plants, were not questions, or where the answers are already known, were excluded. Many questions were combined and reworded at the initial sift stage and by panellists at the final selection and inclusion stage (summarised in Fig. 1). Because of the subjective alteration of submitted data, we were interested to know whether the most

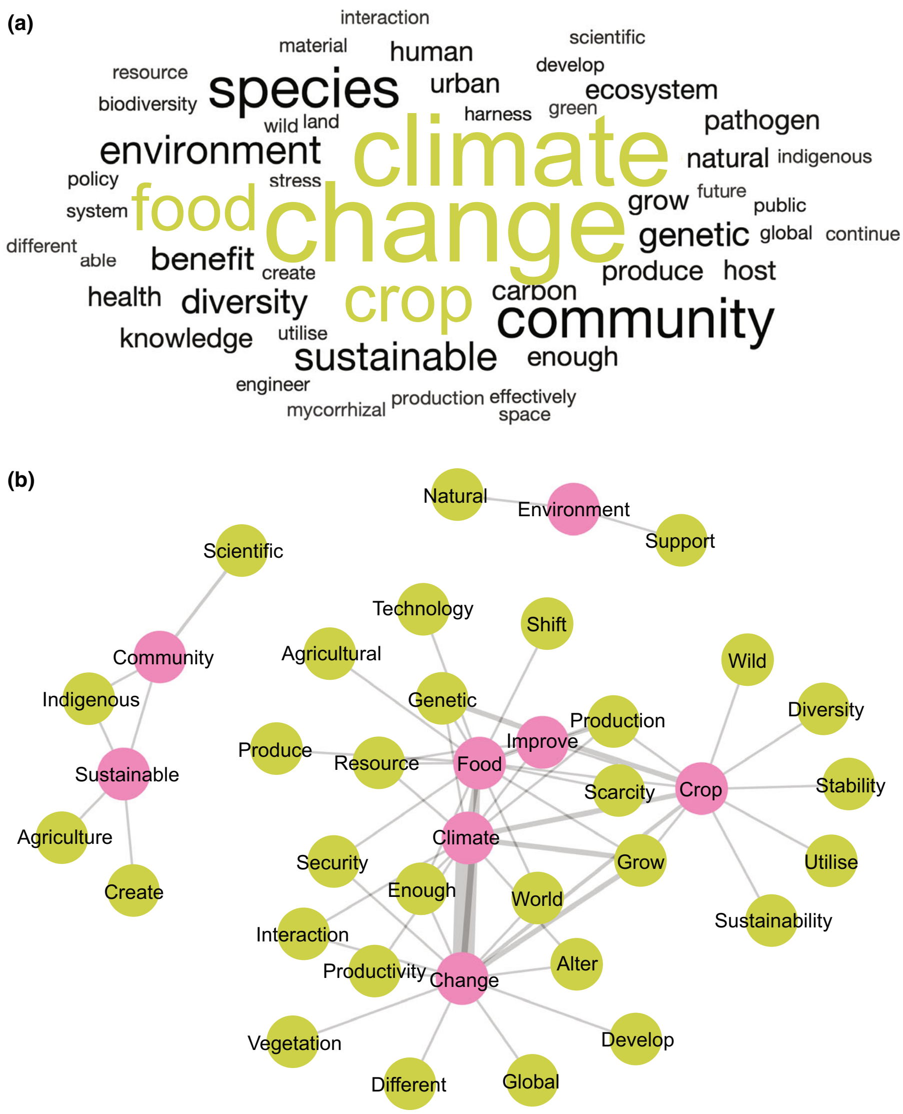

Fig. 2 Question content analysis of the top 100 questions generated in 2022. (a) Word cloud showing the top 30 most commonly occurring words in the 100 questions. Words of the same size have the same frequency, and highlighted words are the most frequently occurring. (b) Word co-occurrence network analysis. Keywords are the most commonly occurring words in the dataset and are shown in pink. Green nodes are associated words. Edge width shows the strength of tie between two nodes given by the number of times two words co-occur in the question set. Nodes are only included if the edge strength is at least two (i.e. the pair of words occur in at least two questions). Key nodes are not shown if they do not co-occur at least twice with another word anywhere in the question set.

frequently occurring words and most common co-occurring themes in submitted questions were accurately reflected in the final question list. If major themes at the 'raw' submission level were not present in the final 100 questions, this would indicate the process failed to accurately reflect the concerns of the wider plant-stakeholder community. The most frequently occurring words (Fig. 3a,b) were very similar in the initial set of 616 submitted questions (climate, change, crop, species and food) and the final list of 100 (climate, change, crop, food, species and community), indicating the panellists were able to preserve key themes despite questions being excluded, combined and reworded.

Comparing question themes and content from 2011 to 2022

We compared the questions generated in 2022 with the published list from 2011 (Grierson *et al.*, 2011). While it would be inappropriate to perform quantitative comparative analyses, word frequency visualisation and word co-occurrence network visualisation enabled a semi-quantitative comparison of themes and word frequency in the question sets. Fig. 4(a) shows the top 30 most frequently occurring words within the top 100 questions for 2011 and the associated word co-occurrence network. The most striking difference between the question sets was the frequency of 'climate' and 'change'. These two words were the joint most commonly occurring words in the 2022 questions, appearing together 11 times, but only appearing twice in the 2011 set, with 'global warming' appearing once (Fig. 4a). Similar patterns are found within the word co-occurrence network (Fig. 4b). 'Climate' and 'change' were key nodes in the 2022 network, but were not featured in the 2011 network. Instead, 'improve,' 'knowledge' and 'control' were key 2011 nodes, indicating an initial focus on more fundamental and foundational aspects of plant science rather than applied plant science.

Both sets of questions frequently mentioned 'crop', 'species', 'ecosystem' and 'environment'. This suggests that the global plant research community continues to acknowledge and prioritise long-standing research themes, while incorporating a more prominent and urgent climate change focus.

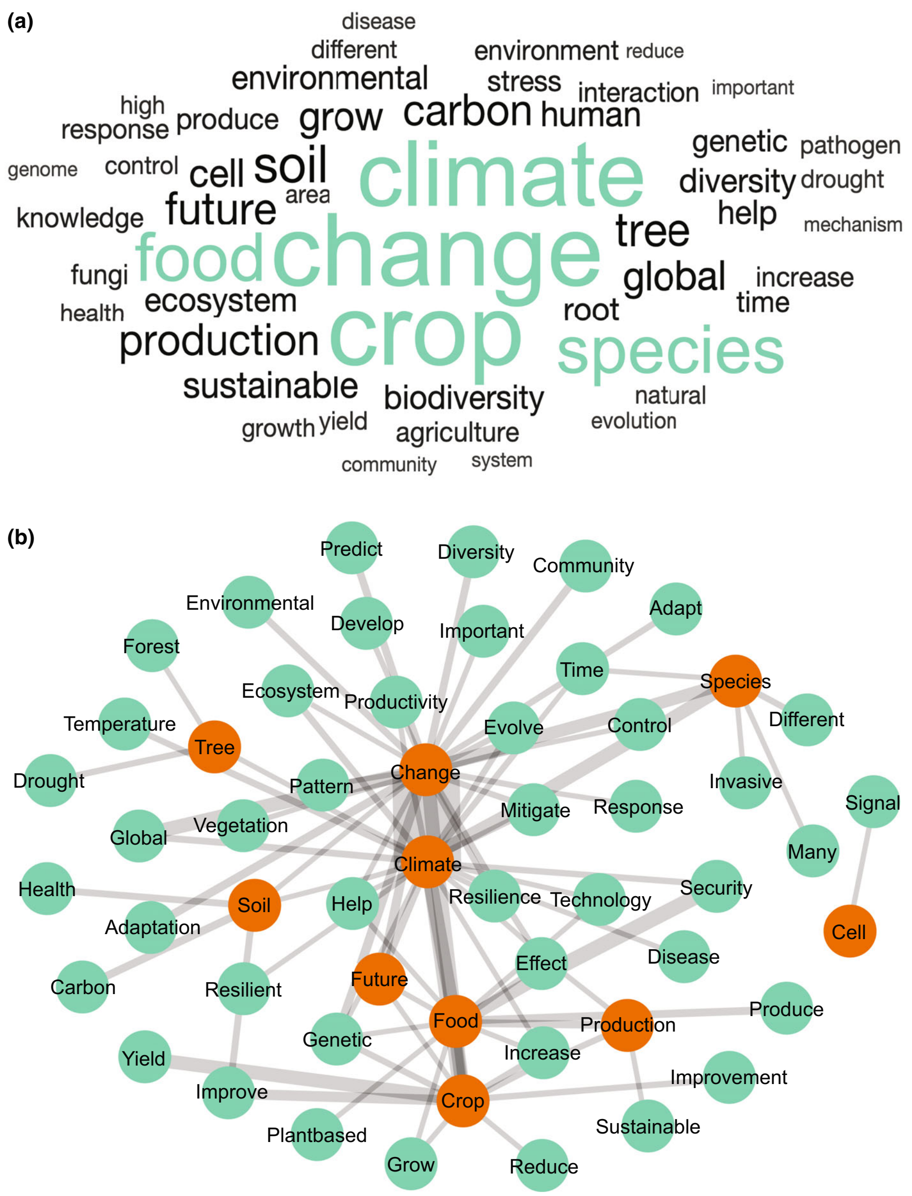

Fig. 3 Question content analysis of all questions ($n = 616$). (a) Word cloud showing the top 30 most commonly occurring words in all submitted questions. Words of the same size have the same frequency, and highlighted words are the most frequently occurring. (b) Word co-occurrence network analysis. Keywords are the most commonly occurring words in the dataset and are shown in orange. Teal nodes are associated words. Edge width shows the strength of tie between two nodes given by the number of times two words co-occur in the question set. Nodes are only included if the edge strength is at least four (i.e. the pair of words occur in at least four questions). Key nodes may not be shown if they do not co-occur at least twice with another word anywhere in the question set.

Comparing regional panel key words

Panellists were split into four broad regions (Europe, North and South America, Asia and Oceania, and Africa) to account for differences in time zones, while reducing time spent meeting colleagues outside traditional working hours. Online meetings facilitated attendance by panellists who may not have been able to attend in-person due to issues such as costs, visa requirements, caring responsibilities or health. This regional split provided an interesting opportunity to investigate potential regional differences in question selection. Each regional panel independently chose 100 questions to form their own lists before these were collectively combined across regions to generate the top 100 global questions.

Word clouds (Fig. 5a–d) and network co-occurrence analyses (Figs S1–S4) for each region were compared. Each independent region's 100 questions selection mirrored the most commonly occurring words in the final list of 100 questions (Fig. 2a): 'climate', 'change', 'crop', 'species' and 'food'. This indicates our panellists collectively prioritised these topics regardless of region. The occurrence of these key words across all regions, and in the top 100, indicates a degree of final question predictability, while demonstrating reliability within our chosen question identification and selection methods.

Despite the same central themes emerging independently in global regions, only 26 questions were selected from the 208 by all regions for inclusion in their final list of 100. Of the 208 questions given to each panel, 46 questions were excluded by all regions, 52 were shared by three regions, 48 were shared by two regions, and 43 questions were selected by one region only. Despite large differences in regional question selection, the shared core terms are a strong indication of shared global consensus on important plant science issues.

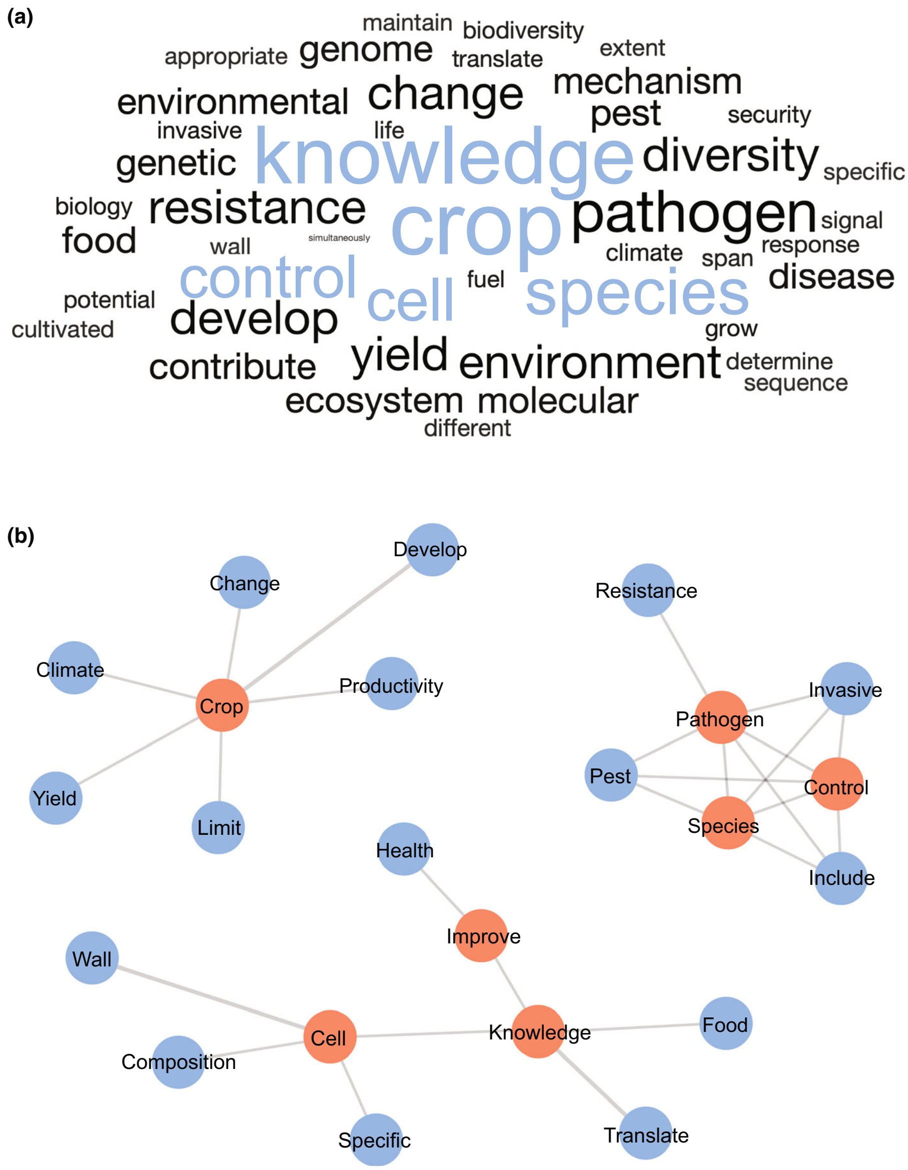

Fig. 4 Question content analysis of the top 100 questions generated in 2011. (a) Word cloud showing the top 30 most commonly occurring words in 2011s 100 questions. Words of the same size have the same frequency, and highlighted words are the most frequently occurring. (b) Word co-occurrence network analysis. Keywords are the most commonly occurring words in the dataset and are shown in orange. Blue nodes are associated words. Edge width shows the strength of tie between two nodes given by the number of times two words co-occur in the question set. Nodes are only included if the edge strength is at least two (i.e. the pair of words occur in at least two questions). Key nodes may not be shown if they do not co-occur at least twice with another word anywhere in the question set.

Concluding remarks

We used an inclusive process that included people of 15 nationalities from five continents, which increased the likelihood that our questions represent global concerns. Despite some regional variations in the choices of specific question wording or the prominence of specific terms, there was remarkable consensus on the most important topics. The clearest outcome of the 100 Plant Science Questions project in 2022 was the prominence of climate change and associated issues. Jurisdictions covering *c.* 1 billion people have declared 'climate emergencies' globally (Aidt, 2022), so the prominence of this topic is not surprising. This was in stark contrast to the 2011 question set, in which climate change as an explicit topic appeared just three times (Grierson *et al.*, 2011). It is worth noting that the topic of 'knowledge' about cells and biological systems was very prominent in the 2011 top questions, whereas in 2022, this term was displaced by 'climate' and 'change'. This clearly indicates how critically important climate crisis research and action are for the plant science community. Out of 616 questions submitted, 21% (130) mentioned the changing climate and many others were highly relevant to climate change adaptation and mitigation. This indicates a collective shift toward focussing plant science research on ameliorating predicted and realised impacts of a changing climate. Understandably, climate change is currently the global focus of both policy and research efforts, and we hope these questions meaningfully encapsulate the breadth and urgency of activity required to develop solutions to the effects of climate change.

It is striking how much critically important knowledge we do not currently possess to successfully mitigate and adapt to climate change, including, for example: which crop species and varieties will grow reliably in each region (Qs 1, 3, 9, 10); how much carbon plants can capture and store, which species are best for this, and where they can grow reliably (Qs 41, 46, 86); and how this will be

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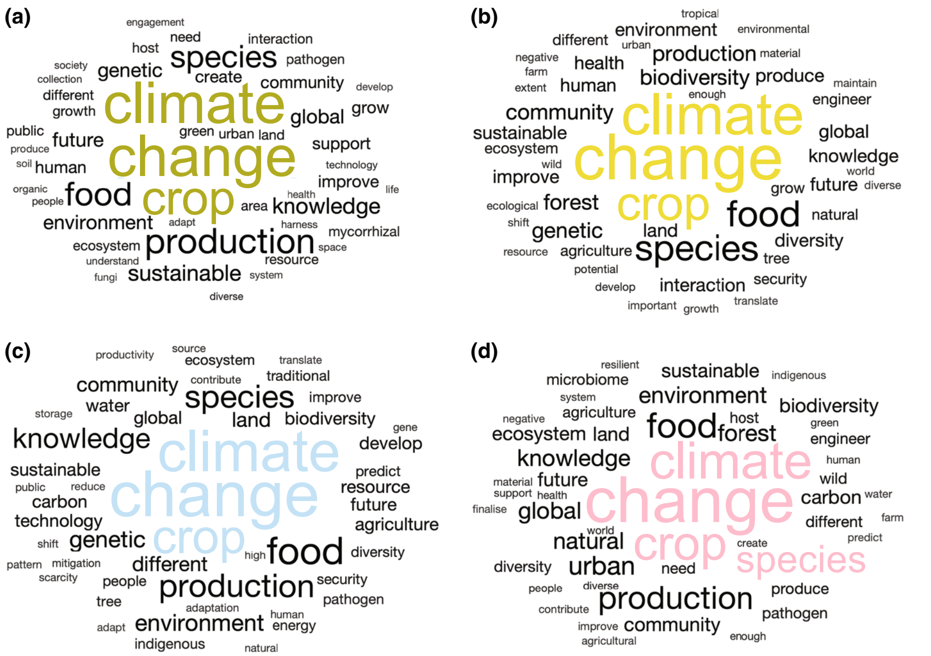

Fig. 5 Question content analysis of the top 100 questions selected by each regional panel. Word clouds show the top 30 most commonly occurring words, words of the same size have the same frequency, and highlighted words are the most frequently occurring. (a) Africa. (b) Asia. (c) North & South America. (d) Europe.

affected by the climate-induced migration of pests and diseases (Qs 7, 37, 75). A major barrier to answering such questions is uncertainty about the future climate. One partial exception is horticulture, which can proceed if the climate is stable enough for buildings to remain standing with sufficient energy, fertiliser and fresh water, but we do not know how to grow staple crops well indoors and even if we did, the indoor space required would be vast and expensive (van Delden *et al.*, 2021). Plant scientists can contribute significantly to predicting and stabilising the climate, for example, through work on vegetation, forests or agriculture (Bonan & Doney, 2018; Di Marco *et al.*, 2019; Harrison *et al.*, 2020). However, delivering a stable climate also depends on urgent global, corporate, political and social action and accurate climate science (Ginanjar & Mubarrok, 2020; Pörtner *et al.*, 2022). The more varied, unfamiliar and uncertain the climate scenarios are that plant scientists must work with, the greater, more difficult and more expensive the work will be to achieve satisfactory solutions. Given that climate change is already causing widespread problems, including crop failures, wildfires and freshwater shortages (Vermeulen *et al.*, 2012; Tol, 2018; Fawzy *et al.*, 2020), the urgent need for action and research cannot be overstated.

Many of our questions are best addressed by interdisciplinary teams. For example, questions such as Q2, Q14, Q19, Q20, Q24, Q27, Q28, Q31, Q32 and Q33 would benefit from social science input. In many cases, cooperation and collaboration will be required beyond academia to include policymakers (e.g. Q31, Q32 and Q33), nongovernmental organisations (e.g. Q2, Q12, Q14, Q16, Q19–21, Q23 and Q27), media (e.g. Q2, Q12–14, Q24 and Q27) and commerce (e.g. Q3, Q5, Q7, Q8, Q10, Q11, Q14–18, Q22–24, Q26, Q29, Q30, Q35, Q39, Q40 and Q42).

Most public engagement with life sciences takes a 'top-down' engagement approach. Typically, 'top-down' engagement shares research outcomes with nonspecialist audiences but provides little opportunity for this audience to shape future research. By using a 'bottom-up' approach, this project's structure provided a rare opportunity for lay people to contribute to the research agenda. Like public-patient involvement championed in the medical sector, engaging lay people at the horizon-scanning and scoping level of research offered an opportunity for some of those who will be impacted most by research outcomes to be heard. By embedding public questions, ideas and concepts of plant science at the horizon-scanning level, we enabled a culture of equity where nonspecialists' ideas had equal importance as those from experts. In total, 25% of questions submitted were from nonexperts, with 25% of our final 100 questions reflecting nonexpert contributions. Combining a citizen-science approach with opinions from experts means these questions ultimately reflect important, imaginative and robust ideas about plant science and its future.

Our panellists remarked that some of the submitted questions already had answers that were not widely known. This raises questions about how we can improve 'top-down' public engagement with plant science knowledge and how we can better train plant researchers to communicate their innovative and relevant findings beyond the plant science community.

The original 2011 horizon scan looked for questions that could realistically be addressed in a scientific career, so it is not surprising that many of those questions overlap with those presented here (e.g. Q1, Q10, Q25, Q31, Q82 and Q85; Grierson *et al.*, 2011). This underlines how important these research questions are and illustrates the time required to address some very important topics. Progress will require the establishment of new technologies and methods. Such work has uncertain outcomes and high risk, which affect research careers and funding agencies that are assessed on the efficiency and productivity of their awards. Many research funding models support short projects (3–5 years) when the risks are lowest and the outputs most newsworthy. To address urgent challenges, we need funding regimes that support high-risk, high-reward research and provide continuity so that projects can proceed quickly, without the regular pauses caused by stop-start funding (Langdale, 2021).

In the original 2011 paper, it was noted that 'we need to attract the brightest and best to careers in plant research'. Eleven years later, this important question remains a high priority. The plant science community is relatively small and poorly funded, which is not a new challenge (Arntzen, 1989; Martin, 2011). For example, there has been a stagnation in UK funding for both fundamental and applied plant sciences (Langdale, 2021), with the field receiving *c.* £50 M per year since 2008. The Gatsby Foundation was responsible for 23% of funding in 2019–2020, but private philanthropy from foundations like this is not indefinitely sustainable (Langdale, 2021). To put this in context, UK funding for human health research was £4.8 billion in the calendar year 2018 (HRCS Online, 2018). There is still relatively little long-term career support for early-career plant scientists, making plant research a precarious career choice in many parts of the world.

In summary, we believe this project showcases the importance of integrating insights from nonexperts into horizon-scanning and public-facing research activities. We acknowledge these questions are multifaceted and will require truly interdisciplinary approaches to address. Equally, we provide a responsive online framework that allows global scientific voices to be heard more equitably than in the past. This project clearly illustrates the collective global need for long-term funding of plant science research and very broad, collaborative efforts to actively decelerate, halt and adapt to the consequences of climate change, while underlining the importance of international cooperation and conversation.

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Competing interests

None declared.

Author contributions

EMA, HH, ERL and CSG designed the research. EMA performed the research. EMA performed data analyses with guidance from CRW. Data interpretation and writing of the manuscript was performed by EMA, HH, ERL and CSG, with significant input from panellists SSP, NO, IW, VP, AB, DJ, AAC, YA, CRW, XF, ML, BL, SS, AG, DF, DM, CM and FD. All panellists, HH and EMA wrote question descriptions. For more detail about panellist contributions, see Notes S6.

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Data availability

The data that support the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional Supporting Information may be found online in the Supporting Information section at the end of the article.

Fig. S1 Word co-occurrence network analysis from top 100 questions selected by Africa's regional panel.

Fig. S2 Word co-occurrence network analysis from top 100 questions selected by Asia's regional panel.

Fig. S3 Word co-occurrence network analysis from top 100 questions selected by North and South America's regional panel.

Fig. S4 Word co-occurrence network analysis from top 100 questions selected by Europe's regional panel.

Notes S1 Anonymised overview of selected panellist demographics (age range, birth location, work location, gender, self-ID disability, sexual orientation, additional caring responsibilities and career length) and panellist research interests.

Notes S2 Summative descriptions and justifications of questions 1–100.

Notes S3 Questions submitted during the 100 Plant Science Questions project, 2021–2022.

Notes S4 MATLAB 'stop' words.

Notes S5 MATLAB GitHub code links and instructions for use.

Notes S6 Full list of author contributions, in authors' own words.

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