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PERSPECTIVE

What do changing weather and climate shocks and stresses mean for the UK food system?

Pete Falloon[1,*], Daniel P Bebber[2], Carole Dalin[3], John Ingram[4], Dann Mitchell[5,7], Tom N Hartley[6], Penny J Johnes[5,7], Tim Newbold[8], Andrew J Challinor[9,10], Jessica Finch[11], Marcelo V Galdos[9], Celia Petty[12,13], Ros Cornforth[12], Riaz Bhunnoo[14], Edward Pope[1], Andrew Enow[15], Aiduan Borrion[16], Amy Waterson[1], Katrina MacNeill[1] and Alice Houldcroft[17]

1 Met Office Hadley Centre, Met Office, Exeter, United Kingdom
2 Department of Biosciences, University of Exeter, Geoffrey Pope Building, Stocker Road, Exeter EX4 4QD, United Kingdom
3 Institute for Sustainable Resources, Bartlett School of Environment, Energy and Resources, University College London, London, United Kingdom
4 Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom
5 Cabot Institute for the Environment, University Road, University of Bristol, Bristol BS8 1SS, United Kingdom
6 Strategic Surveillance, Food Standards Agency, Foss House, 1-2 Peasholme Green, York YO1 7PR, United Kingdom
7 School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, United Kingdom
8 Centre for Biodiversity and Environment Research, Department of Genetics, Evolution and Environment, University College London, London, United Kingdom
9 Institute of Climate and Atmospheric Science (ICAS), School of Earth and Environment, University of Leeds, Leeds, United Kingdom
10 CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), c/o CIAT, Cali, Colombia
11 Department for Environment, Food and Rural Affairs, Seacole Building, 2 Marsham Street, London SW1P 4DF, United Kingdom
12 Walker Institute, University of Reading, Reading RG6 6EU, United Kingdom
13 Evidence for Development, University of Reading, Reading RG6 6EU, United Kingdom
14 Global Food Security Programme, UK Research and Innovation, Swindon, United Kingdom
15 Biotechnology and Biological Sciences Research Council, UK Research and Innovation, Swindon, United Kingdom
16 Department of Civil, Environmental and Geomatic Engineering, University College London, Chadwick Building, Gower Street, London WC1E 6BT, United Kingdom
17 Communications Team, Met Office, Exeter, United Kingdom
* Author to whom any correspondence should be addressed.

E-mail: pete.falloon@metoffice.gov.uk

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Supplementary material for this article is available online

In light of the publication of Henry Dimbleby's National Food Strategy (www.nationalfoodstrategy.org/) and the COP26 climate meeting in Glasgow, it is timely to consider the impacts of weather and climate extremes on the UK food system.

Climate change-driven changes in extreme weather events are one of the highest-risk future shocks to the UK food system [1], underlining the importance of preparedness across the food chain [2]. Here, we identify major knowledge gaps in the primary impacts of extreme weather and climate change across the UK's food system, its functioning and their interactions to provide information to support adaptation and resilience planning. Research tends to focus on individual food system activities rather than taking a systematic approach [3, 4]. However, strong evidence exists about the impacts of long-term climate trends and extremes [5] on primary food production [6]. The major knowledge gaps therefore concern post-primary production dimensions [4], notably food system activities between the 'farm-gate' and consumption—which are the core focus of this paper (supplementary material S1 available online at stacks.iop.org/ERL/17/051001/mmedia). These constitute major economic and social dimensions but are often the 'missing middle' in food system discussions. We use the UK food system as an illustrative case study, and consider both global and domestic risks and implications. We present methods, tools and frameworks for systemic analysis of climate impacts on food systems, consider the funding landscape, and highlight priorities for future research.

1. Impacts of changing weather and climate shocks on the UK food system

1.1. Risks to domestic and overseas primary production

Future changes in weather and climate extremes [5] (supplementary material S2.1) could have wide-ranging impacts on the UK food system (figure 1 [7–15], supplementary tables S1(a) and (b)), including well-established impacts on domestic and overseas primary production (supplementary material S2), i.e. agriculture, horticulture and fisheries [14].

1.2. Risks to other food system activities

Climate risks extend beyond primary production to other food systems activities that are critical for food security, including the processing, storage, transportation, and consumption of food [16]. While there is much less information available on the impact of weather and climate change shocks on post-primary production aspects (figure 1, supplementary tables S1(a) and (b)), there is sufficient evidence to raise concerns [16]. Consistent themes include:

- Increased variability in supply quantity and quality which can affect processing where it depends on a reliable input supply and quality standards that determine end use;
- Heat and cold health impacts on workforces across the food chain;
- Disruption to transport and infrastructure;
- High temperature and humidity impacts on storage and transport practices to avoid spoilage and issues from toxins—highly perishable foods (such as fruit, vegetables, meat, dairy and fish) are particularly vulnerable to climate hazards during storage and transport [4];
- Changes in consumer demand (for example during high temperatures, the demand for barbecue food, salads and fresh fruit increases but supply will also may be impacted through heat stress).

Increases in ambient temperature will strongly affect food dependent on the cold-chain, as it can increase food spoilage and food poisoning risks [13]—this will increase energy use leading to a positive feedback whereby changing climate increases energy consumption and hence greenhouse gas emissions, leading to further climate change. Impacts of extreme weather on food safety are currently highly uncertain: there are many pathways through which climate change may affect food safety but few have been rigorously examined. Examples include higher temperature and humidity increasing risks from algal blooms, plant and animal-based pathogens and toxigenic fungi, increased food contamination and water-borne diseases via heavy rainfall and flooding, and indirect impacts from infrastructure damage [4]. The high food standards controlled within the UK provide some food safety resilience to extreme weather impacts through regulatory limits for pathogens and chemicals, combined with detection, monitoring, surveillance and horizon scanning, but it is unknown whether these will be sufficient in the context of a changing climate and increasing unpredictability [17]. Storm surges and flooding can disrupt port facilities and other transport infrastructure (rail and roads), causing delays, depreciation of goods and additional costs [15] if cargo is re-routed.

Even when considering only one type of meteorological extreme, impacts could potentially propagate through the food chain with complex, cumulative effects (supplementary figure S2). Given the relative lack of evidence on likely impacts on individual food chain activities beyond primary production, the cumulative impacts of weather and climate extremes across the whole food chain remain an uncertain, significant knowledge gap.

2. Tools, frameworks and case studies

The potential for extreme weather and climate change to impact every aspect of the UK food system (figure 1, supplementary tables S1(a) and (b)) highlights the need for systems approaches to adaptation and mitigation [18]. These include models and risk assessment frameworks that incorporate all stages of the supply chain and are capable of robustly assessing food system shocks, their interactions with shocks caused by other drivers (e.g. economic, political and pandemics [19]) and system-wide risk transmissions, interactions and cascades [20]. Potential candidates are discussed in supplementary material S3.1.

Achieving increased resilience of the UK food system requires significant improvements and standardisation in the collection, quality, synthesis and application of data and information to support decision-making. This will need to be both through capitalising on ongoing improvements in weather and climate information across temporal and spatial scales (figure 2) and in utilising a broad range of food chain data, particularly for post-primary production activities. Key emerging avenues are highlighted in figure 2, and expanded in supplementary material S3.2.

3. Research funding landscape—current and future

The broad, system-wide impacts of extreme weather and climate change on the food chain highlight the need for the research funding landscape to reflect that perspective. A key priority will be to support a stronger evidence base on the impacts of weather and climate shocks on post-primary production aspects of the UK food chain, given the knowledge gaps noted here. The UK's cross-government Global Food Security Programme (GFS: www.foodsecurity.ac.uk) is leading two major strategic research programmes funded by UK Research and Innovation (UKRI) in partnership with government departments that have

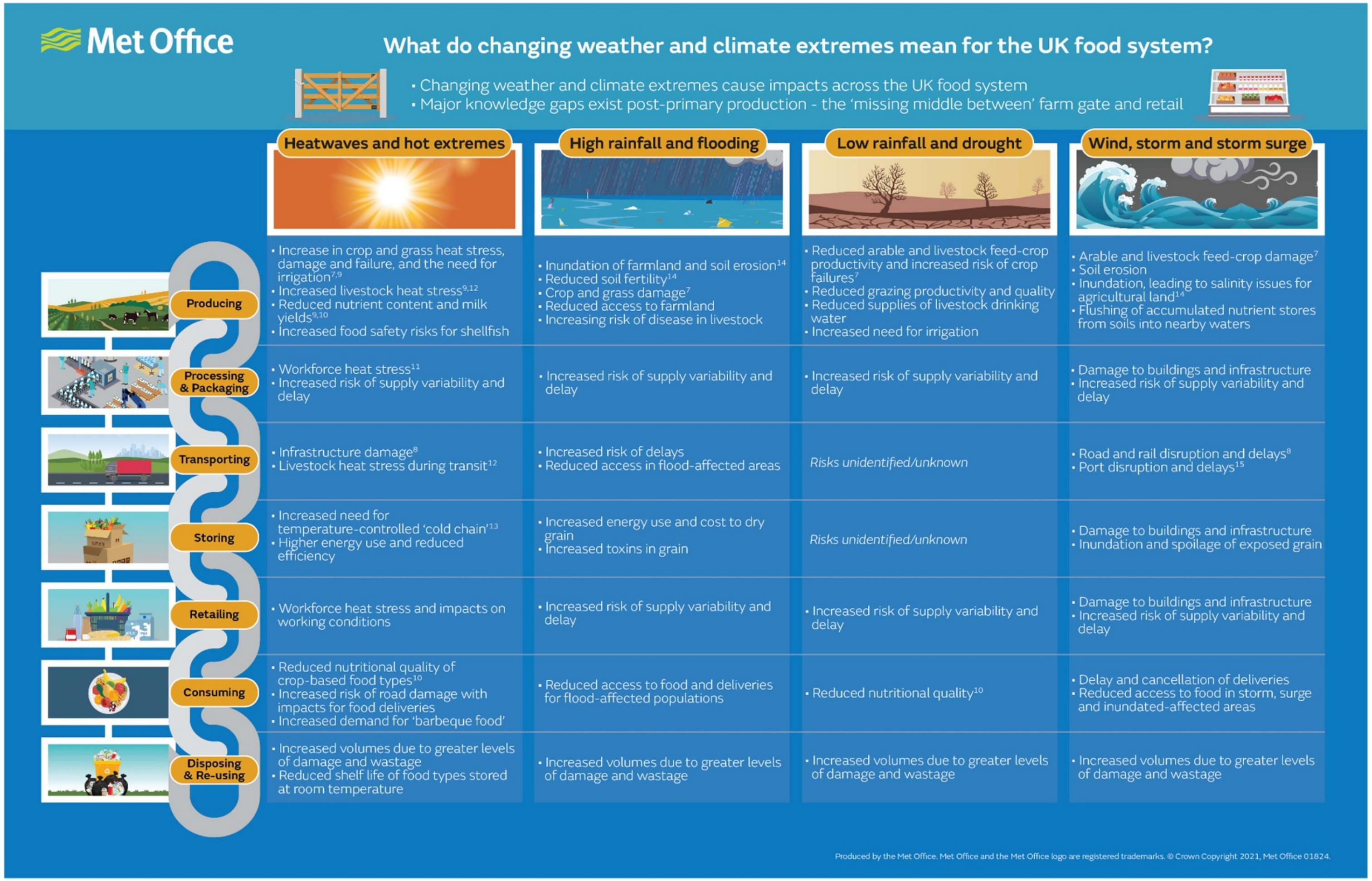

Figure 1. Key risks to UK food system activities from climate change and weather extremes [7–15]. Bullet points without references indicate that these risks lack strong scientific evidence and need further attention, and were identified through expert discussions within the author group. Risks unidentified/unknown indicate that evidence was unavailable and that expert discussions did not identify specific risks. © Crown Copyright 2021, Met Office.

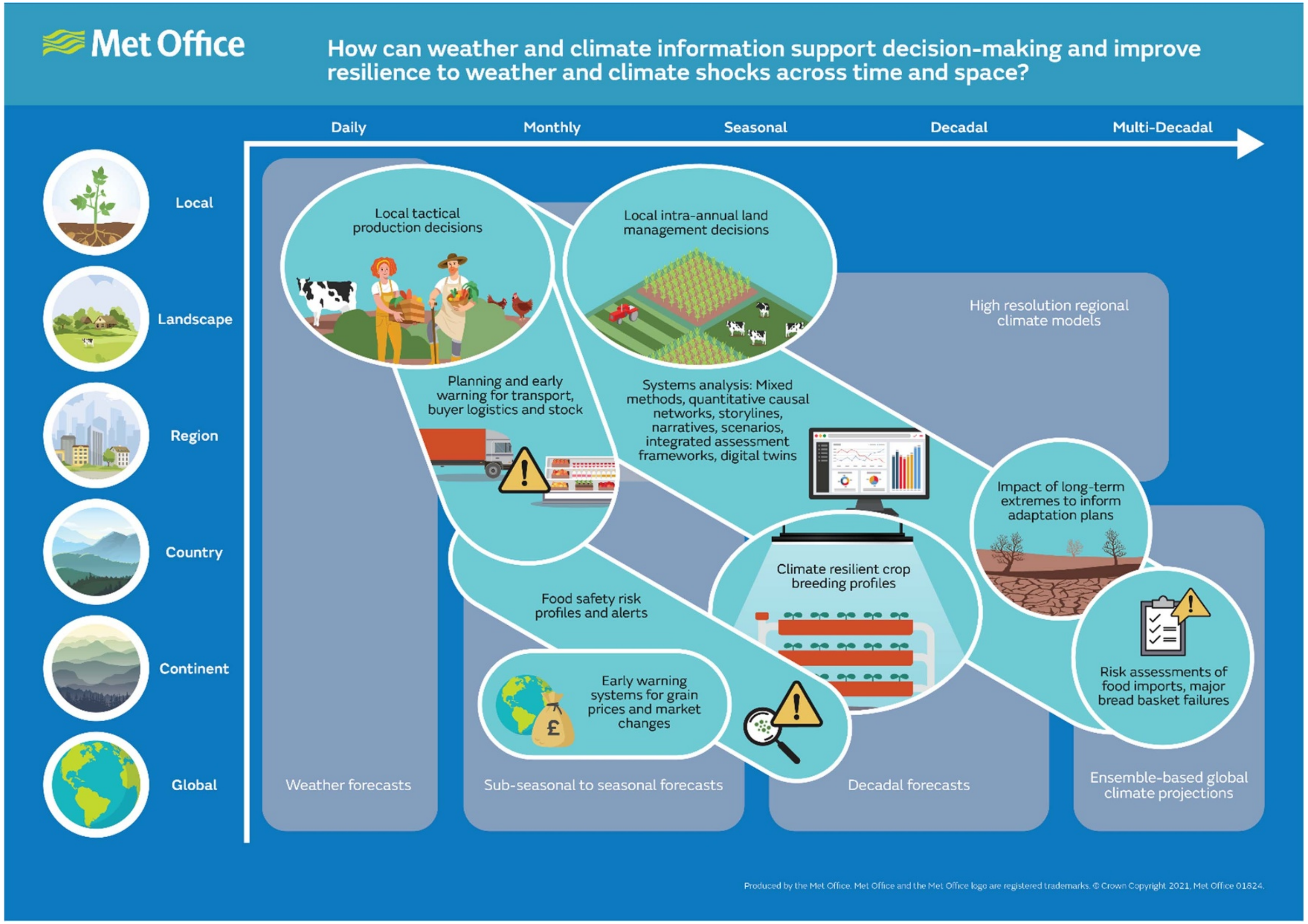

Figure 2. The potential for weather and climate information to support decision making in agricultural and food system-related activities, and improved resilience to weather and climate shocks across time and space scales. Grey background boxes represent generalised meteorological capabilities; light blue ellipses with white outlines denote potential applications. © Crown Copyright 2021, Met Office.

made significant progress by taking an interdisciplinary approach across academia, government, business and civil society organisations. 'Resilience of the UK Food System in a Global Context' (GFS-FSR) [21] focuses on understanding major vulnerabilities in the UK food system and how resilience to shocks can be enhanced, while 'Transforming the UK food system for healthy people and a healthy environment' (TUKFS) [3] focuses on transformational change of the UK's food system for healthy people and environment.

The recent £1.2bn UK government investment in weather and climate supercomputing will provide a six-fold increase in computing capacity for the first 5 years alone (https://www.metoffice.gov.uk/about-us/press-office/news/corporate/2021/met-office-and-microsoft-announce-supercomputer-project). This will provide significant opportunities to underpin the aim of increased weather, climate and food chain data application in support of improved decision-making and resilience.

The UK's Horticultural Quality and Food Loss Network, funded by the Biotechnology and Biological Sciences Research Council, aims to tackle food loss through research and promoting improved horticultural crop quality and could help address knowledge gaps in the post-harvest impacts of weather and climate extremes. The UK Government, through the Government Department for Environment, Food and Rural Affairs (Defra), is also funding international research on food system climate resilience through the Horizon 2020 ERA-NET co-fund on Food Systems and Climate (www.foscera.net/en/foscera/About-FOSC.htm) which focuses on assessing climate change risks for food value chains, promoting innovative food technology deployment and resilience to climate change across Africa, Latin America and Europe. Given the need to build resilience across the food chain, there is also a need to consider potential links to private funding, including from the (re)insurance and risk sectors.

Developing an overall, holistic framework and understanding of the food system, and connecting individual strands of work remains a challenge beyond GFS-FSR. For both GFS-FSR and TUKFS the focus is not specifically on resilience to future climate shocks. A recent UKRI funding initiative in response to the COVID-19 pandemic (https://strategicfutures.org/TopicMaps/UKRI/research_map.html) furthered knowledge around shorter-term UK resilience, including for the food system, but a gap remains in understanding longer-term resilience to system shocks. Challenge-led funding initiatives are key to making progress and ensuring fit to objectives in this area. It would be beneficial to consider different approaches to their design and funding such as *a priori* approaches to connecting individual projects across research domains and food system activities.

4. Conclusion and recommendations

Future shocks and stresses due to changes in weather and climate extremes will have significant impacts on the UK food system. Key knowledge gaps remain in our understanding of their impacts on non-cereal crops, livestock and fisheries production, on the food chain beyond primary production, on the longer-term impacts, and in an integrated, full system view of impacts that accounts for cumulative impacts, interactions, feedbacks and the interplay between domestic and overseas elements of the UK food system. These knowledge gaps need to be urgently addressed to ensure future climate resilience of the UK food system.

There are several areas where research could better support decision-making towards increased resilience to weather and climate shocks in both food policy and business sectors. We note the need for a step change in the collection, quality, synthesis and application of a broad range of weather and food chain data and information across time and space. There is a need to develop tools to support the inclusion of the 'missing middle' of food chain and policy discussions that incorporate weather and climate impacts: processing/packaging, transport, storage, wholesale, retail and disposing/reusing. Such efforts should also aim to support decision-making to enhance climate resilience across policy domains, given the potential for interactions between policy objectives in different areas. Research is needed to provide evidence to address the challenge of decision-making to improve climate resilience under deep uncertainty, and in support of dynamic policy decision-making to reflect changing circumstances and avoid lock-ins. Effective integration of quantitative and qualitative information on the food chain impacts of meteorological shocks across researchers and stakeholders will be central to these efforts.

Greater integration of climate, biophysical, social, political and economic research is required to characterise geo-political influences on food system climate resilience. A key knowledge gap to be addressed is whether long-term climate change will drive countries, including the UK, towards greater self-sufficiency or greater dependence on global food supply systems [22].

As part of Defra's priorities to ensure a secure, environmentally sustainable and safe supply of food in the face of future challenges, Defra published a comprehensive assessment of UK Food Security in 2010, the UK Food Security Assessment (UKFSA: https://webarchive.nationalarchives.gov.uk/20130402160926tf_/http://archive.defra.gov.uk/foodfarm/food/security/index.htm). The UKFSA analysed a wide range of indicators and evidence for assessing UK food security. As a statutory duty under the Agriculture Act 2020, Defra produced a UK Food Security Report (UKFSR: www.gov.uk/government/statistics/united-kingdom-food-security-report-2021) in December 2021 and updates will be produced at least every 3 years thereafter. The UKFSR presents data and case studies across five themes (global food availability, UK supply sources, UK supply chain resilience, household food security and food safety and consumer confidence), and includes case studies on the impacts of weather and climate shocks on food supply. There are opportunities to include future climate-related indicators in subsequent releases of the UK-FSR, which would help raise awareness of, and preparedness for weather and climate shocks.

Here, we have only considered the direct impacts of weather and climate extremes on the UK food chain. Further work is needed to assess adaptation actions needed in response, and their knock-on trade-offs and consequences across sectors, and their interactions to lay the foundations for the next generation of research. For adaptation, there is a need for applied, industry-inclusive interdisciplinary approaches involving social, political and economic sciences to help address challenges in uptake of new approaches and tools. It is also needed to address the socio-cultural issues associated with this change [23] such as farming attitudes towards maintaining land in production, the rural economy and nature of the production base, dietary changes towards Net Zero goals [22, 24], and to understand the links with food poverty in low-income groups. Future changes in population, wealth and diet will indirectly affect exposure and vulnerability to domestic and international climate hazards through links to trading patterns, and these factors need to be robustly assessed.

There is also, potentially, a very wide range of trade-offs and consequences stemming from food chain adaptation to weather and climate extremes that need to be assessed, including for water and energy security and ecosystems/biodiversity. These will lead to, for example, conflicts with other policy goals and actions and off-site impacts of food production systems. Future changes in trade-offs and consequences should be assessed since they will differ for the UK itself, and in key international supply regions. There is also a need to account for changes in other sectors as they adapt to climate change and to meet targets set under the UK 25 year Environment Plan, with knock-on consequences for food systems. It is therefore critical that planned climate adaptation of the food system avoids unintended consequences on health and wellbeing, both for humans and ecosystems.

The challenges identified here suggest the need for challenge-led, connective, interdisciplinary approaches to future funding initiatives in support of achieving food system resilience to weather and climate shocks. In particular, further support is needed to underpin understanding of climate shocks on the 'missing middle' of the food chain, and towards developing a full systems view, along with the priority areas identified above.

Data availability statement

No new data were created or analysed in this study.

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Conflict of interest

The authors declare no competing interests.

Author contributions

PF led discussions that informed the initial development of the paper and took overall editorial and writing responsibility. PF, DB, CD, JI, DM, TH, PJ, TN, AC, JF, MG, CP, RC, RB, EP, AE and AB contributed both to discussions that informed the paper development, and to the drafting of the paper itself. AW and KMcN conceptualised the figures which were designed by AH.

ORCID iDs

Pete Falloon https://orcid.org/0000-0001-7567-8885
Daniel P Bebber https://orcid.org/0000-0003-4440-1482
Carole Dalin https://orcid.org/0000-0002-2123-9622
John Ingram https://orcid.org/0000-0001-9365-1889
Dann Mitchell https://orcid.org/0000-0002-0117-3486

Penny J Johnes https://orcid.org/0000-0003-1605-6896
Tim Newbold https://orcid.org/0000-0001-7361-0051
Andrew J Challinor https://orcid.org/0000-0002-8551-6617
Marcelo V Galdos https://orcid.org/0000-0002-6080-0726
Celia Petty https://orcid.org/0000-0001-8178-2574
Ros Cornforth https://orcid.org/0000-0003-4379-9556
Riaz Bhunnoo https://orcid.org/0000-0003-3646-0474
Edward Pope https://orcid.org/0000-0002-8295-2667
Aiduan Borrion https://orcid.org/0000-0002-9869-1887
Amy Waterson https://orcid.org/0000-0002-5620-0269

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