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To cite this article before publication: Pete Falloon *et al* 2022 *Environ. Res. Lett.* in press <https://doi.org/10.1088/1748-9326/ac68f9>

Manuscript version: Accepted Manuscript

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

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In light of the publication of Henry Dimbleby’s National Food Strategy (<https://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 system¹, underlining the importance of preparedness across the food

chain². 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 extremes⁵ on primary food production⁶. The major knowledge gaps therefore concern post-primary production dimensions⁴, notably food system activities between the 'farm-gate' and consumption – which are the core focus of this paper (Supplementary Material S1). 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.

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

[Figure 1 here]

Risks to domestic and overseas primary production

Future changes in weather and climate extremes⁵ (Supplementary Material S2.1) could have wide-ranging impacts on the UK food system (Figure 1, Supplementary Table S1a,b), including well-established impacts on domestic and overseas primary production (Supplementary Material S2), i.e. agriculture, horticulture and fisheries¹⁴

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 food¹⁶. While there is much less information available on the impact of weather and climate change shocks on post-primary production aspects (Figure 1, Supplementary Table S1a,b), there is sufficient evidence to raise concerns¹⁶. 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 transport⁴;
- 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 risks¹³ – this will increase energy use leading to a positive feedback whereby changing climate increases energy consumption and hence GHG 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 damage⁴. 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 unpredictability¹⁷. Storm surges and flooding can disrupt port facilities and other transport infrastructure (rail and roads), causing delays, depreciation of goods and additional costs¹⁵ 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.

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 Table S1a,b) highlights the need for systems approaches to adaptation and mitigation¹⁸. 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 pandemics¹⁹) and system-wide risk transmissions, interactions and cascades²⁰. Potential candidates are discussed in Supplementary Material S3.1.

[Figure 2 here]

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.

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 made significant progress by taking an interdisciplinary approach across academia, government, business and civil society organizations. '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 6-fold increase in computing capacity for the first five years alone (<https://www.metoffice.gov.uk/about-us/press-office/news/corporate/2021/met-office-and-microsoft-announce-supercomputer-project><https://www.metoffice.gov.uk/about-us/press-office/news/corporate/2021/met-office-and-microsoft-announce-supercomputer-project>). This will, which could 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 (<https://foodlossnetwork.com/>), funded by the Biotechnology and Biological Sciences Research Council (BBSRC), 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 (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 (<https://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.

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.

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3 1 Greater integration of climate, biophysical, social, political and economic research is required
4 2 to characterise geo-political influences on food system climate resilience. A key knowledge
5 3 gap to be addressed is whether long-term climate change will drive countries, including the
6 4 UK, towards greater self-sufficiency or greater dependence on global food supply systems²².
7
8 5 As part of Defra's priorities to ensure a secure, environmentally sustainable and safe supply
9 6 of food in the face of future challenges, Defra published a comprehensive assessment of UK
10 7 Food Security in 2010, the UK Food Security Assessment (UKFSA:
11 8 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
12 9 for assessing UK food security. As a statutory duty under the Agriculture Act 2020, Defra
13 10 produced a UK Food Security Report (UKFSR:
14 11 <https://www.gov.uk/government/statistics/united-kingdom-food-security-report-2021>) in
15 12 December 2021 and updates will be produced at least every three years thereafter. The
16 13 UKFSR presents data and case studies across five themes (global food availability, UK
17 14 supply sources, UK supply chain resilience, household food security and food safety &
18 15 consumer confidence), and includes case studies on the impacts of weather and climate
19 16 shocks on food supply. There are opportunities to include future climate-related indicators in
20 17 subsequent releases of the UK-FSR, which would help raise awareness of, and
21 18 preparedness for weather and climate shocks.
22 19
23 20 Here, we have only considered the direct impacts of weather and climate extremes on the
24 21 UK food chain. Further work is needed to assess adaptation actions needed in response,
25 22 and their knock-on trade-offs and consequences across sectors, and their interactions to lay
26 23 the foundations for the next generation of research. For adaptation, there is a need for
27 24 applied, industry-inclusive interdisciplinary approaches involving social, political and
28 25 economic sciences to help address challenges in uptake of new approaches and tools. It is
29 26 also needed to address the socio-cultural issues associated with this change²³ such as
30 27 farming attitudes towards maintaining land in production, the rural economy and nature of
31 28 the production base, dietary changes towards Net Zero goals^{22,24}, and to understand the
32 29 links with food poverty in low-income groups. Future changes in population, wealth and diet
33 30 will indirectly affect exposure and vulnerability to domestic and international climate hazards
34 31 through links to trading patterns, and these factors need to be robustly assessed.
35 32
36 33 There is also, potentially, a very wide range of trade-offs and consequences stemming from
37 34 food chain adaptation to weather and climate extremes that need to be assessed, including
38 35 for water and energy security and ecosystems/biodiversity. These will lead to, for example,
39 36 conflicts with other policy goals and actions and off-site impacts of food production systems.
40 37 Future changes in trade-offs and consequences should be assessed since they will differ for
41 38 the UK itself, and in key international supply regions. There is also a need to account for
42 39 changes in other sectors as they adapt to climate change and to meet targets set under the
43 40 UK 25-year Environment Plan, with knock-on consequences for food systems. It is therefore
44 41 critical that planned climate adaptation of the food system avoids unintended consequences
45 42 on health and wellbeing, both for humans and ecosystems.
46 43
47 44 The challenges identified here suggest the need for challenge-led, connective,
48 45 interdisciplinary approaches to future funding initiatives in support of achieving food system
49 46 resilience to weather and climate shocks. In particular, further support is needed to underpin
50 47 understanding of climate shocks on the "missing middle" of the food chain, and towards
51 48 developing a full systems view, along with the priority areas identified above.
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54 51 **Acknowledgements**
55 52 PF was supported by the Met Office Hadley Centre Climate Programme funded by BEIS and
56 53 Defra. CD was supported by an Independent Research Fellowship from the Natural

Environment Research Council (Grant No. NE/N01524X/1). TN was supported by grants from the Natural Environment Research Council (NE/R010811/1) and the Economic and Social Research Council (ES/S008160/1), and by a University Research Fellowship from the Royal Society (UF150526). PF would like to thank Sean Milton and Helen Mako-Yule (Met Office, UK) and the Global Food Security Programme's Programme Coordination Group (<https://www.foodsecurity.ac.uk/about/governance/>) for discussions that helped inform the development of this paper. The discussions that led to this paper were part of a Met Office Academic Partnership (<https://www.metoffice.gov.uk/research/approach/collaboration/partnership>) activity with logistical support from Shannon Jackson and Verity Payne (Met Office, UK).

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.

Competing Interests statement

The authors declare no competing interests.

Data availability statement

No new data were created or analysed in this study

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



- Changing weather and climate extremes cause impacts across the UK food system
- Major knowledge gaps exist post-primary production - the 'missing middle between' farm gate and retail



	Heatwaves and hot extremes	High rainfall and flooding	Low rainfall and drought	Wind, storm and storm surge
 Producing	• Increase in crop and grass heat stress, damage and failure, and the need for irrigation^{7,9} • Increased livestock heat stress^{9,12} • Reduced nutrient content and milk yields^{9,10} • Increased food safety risks for shellfish	• Inundation of farmland and soil erosion¹⁴ • Reduced soil fertility¹⁴ • Crop and grass damage⁷ • Reduced access to farmland • Increasing risk of disease in livestock	• Reduced arable and livestock feed-crop productivity and increased risk of crop failures⁷ • Reduced grazing productivity and quality • Reduced supplies of livestock drinking water • Increased need for irrigation	• Arable and livestock feed-crop damage⁷ • Soil erosion • Inundation, leading to salinity issues for agricultural land¹⁴ • Flushing of accumulated nutrient stores from soils into nearby waters
 Processing & Packaging	• Workforce heat stress¹¹ • Increased risk of supply variability and delay	• Increased risk of supply variability and delay	• Increased risk of supply variability and delay	• Damage to buildings and infrastructure • Increased risk of supply variability and delay
 Transporting	• Infrastructure damage⁸ • Livestock heat stress during transit¹²	• Increased risk of delays • Reduced access in flood-affected areas	Risks unidentified/unknown	• Road and rail disruption and delays⁸ • Port disruption and delays¹⁵
 Storing	• Increased need for temperature-controlled 'cold chain'¹³ • Higher energy use and reduced efficiency	• Increased energy use and cost to dry grain • Increased toxins in grain	Risks unidentified/unknown	• Damage to buildings and infrastructure • Inundation and spoilage of exposed grain
 Retailing	• Workforce heat stress and impacts on working conditions	• Increased risk of supply variability and delay	• Increased risk of supply variability and delay	• Damage to buildings and infrastructure • Increased risk of supply variability and delay
 Consuming	• Reduced nutritional quality of crop-based food types¹⁰ • Increased risk of road damage with impacts for food deliveries • Increased demand for 'barbeque food'	• Reduced access to food and deliveries for flood-affected populations	• Reduced nutritional quality¹⁰	• Delay and cancellation of deliveries • Reduced access to food in storm, surge and inundated-affected areas
 Disposing & Re-using	• Increased volumes due to greater levels of damage and wastage • Reduced shelf life of food types stored at room temperature	• Increased volumes due to greater levels of damage and wastage	• Increased volumes due to greater levels of damage and wastage	• Increased volumes due to greater levels of damage and wastage

Figure 1: Key risks to UK food system activities from climate change and weather extremes. 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.

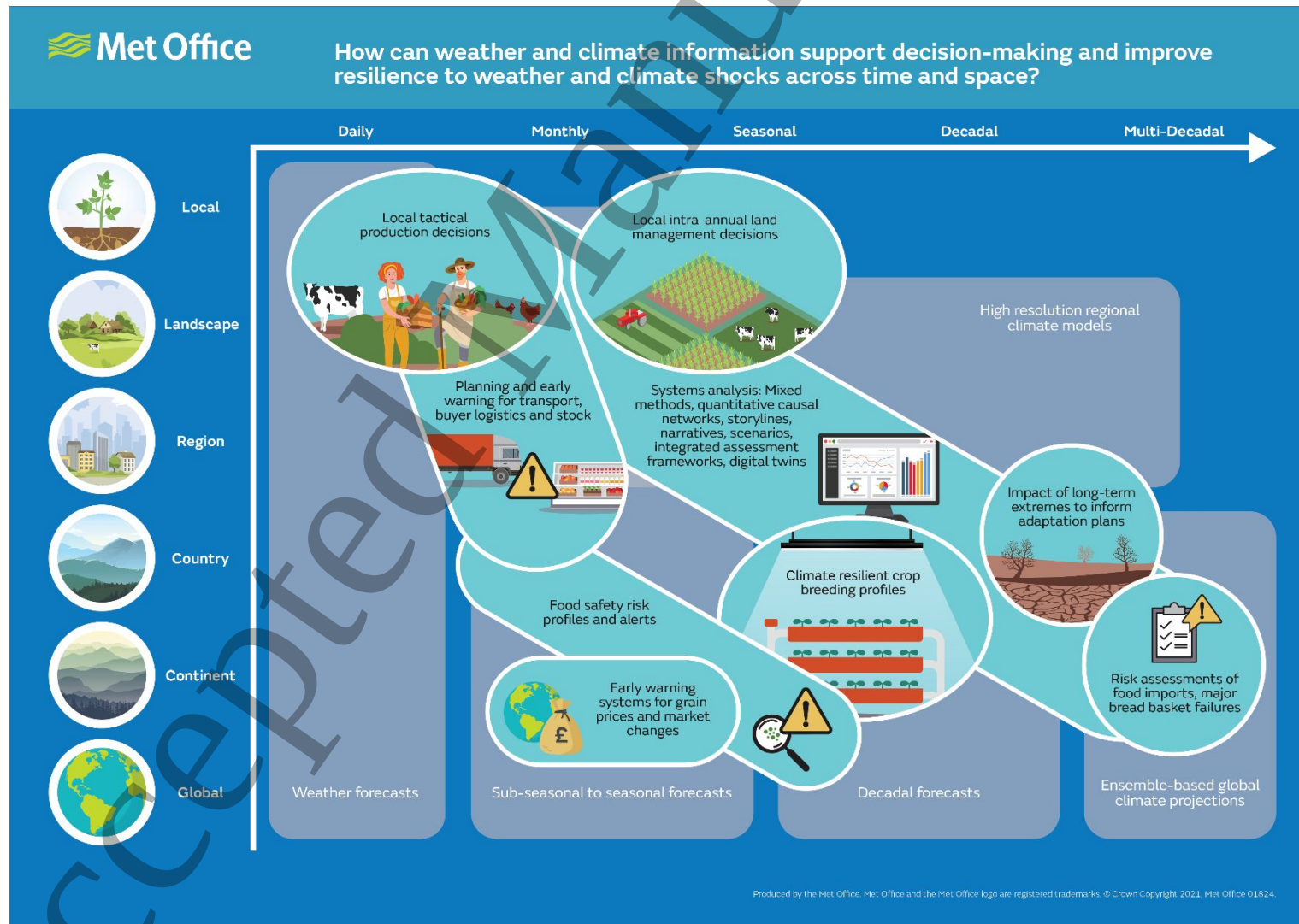


Figure 2. The potential for weather and climate information to support decision making in agricultural and food system-related activities, and improved resilience to weather and climate shocks across time and space scales. Grey background boxes represent generalised meteorological capabilities; Light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