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The role of local knowledge in enhancing climate change risk assessments in rural Northern Ireland

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A R T I C L E I N F O

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A B S T R A C T

Climate risk modelling provides valuable quantitative data on potential risks at different spatiotemporal scales, but it is essential that these models are evaluated appropriately. In some cases, it may be useful to merge quantitative datasets with qualitative data and local knowledge, to better inform and evaluate climate risk assessments. This interdisciplinary study maps climatic risks relating to health and agriculture that are facing rural Northern Ireland. A large range of quantitative national climate risk modelling results from the OpenCLIM project are scrutinised using local qualitative insights identified during workshops and interviews with farmers and rural care providers. In some cases, the qualitative local knowledge supported the quantitative modelling results, such as (1) highlighting that heat risk can be an issue for health in rural areas as well as urban centres, and (2) precipitation is changing, with increased variability posing challenges to agriculture. In other cases, the local knowledge challenged the national quantitative results. For example, models suggested that (1) potential heat stress impacts will be low, and (2) grass growing conditions will be more favourable, with higher yields as a result of future climatic conditions. In both cases, local knowledge challenged these conclusions, with discomfort and workplace heat stress reported by care staff and recent experience of variable weather having significant impacts on grass growth on farms across the country. Hence, merging even a small amount of qualitative local knowledge with quantitative national modelling projects results in a more holistic understanding of the local climate risk.

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1. Introduction

Climate change is a global challenge that manifests with environmental and societal impacts on all scales, from planetary, to regional and local. Climate impacts and risk research at a range of scales has highlighted areas or sectors at particular risk and where adaptation interventions or enhanced resilience could be prioritised (e.g. Frieler et al., 2017; Navarro-Racines et al., 2020; Bednar-Friedl et al., 2022; Edwards et al., 2022; Paulik et al., 2023). While modelling approaches are valuable for providing quantitative data on potential risks, it is essential that they are evaluated appropriately (Wagener et al., 2022). A potential confounding issue is that climate risk assessments may lack data to validate results particularly regarding impacts (e.g. Speretto et al., 2017; Reyes-García et al., 2023). In many cases, this is due to quantitative impacts data not being routinely reported and accessible to researchers at appropriate scales comparable with broad-scale model results (Rising et al., 2022).

Other sources of information besides quantitative datasets are therefore both useful and necessary for informing and evaluating climate risk modelling – for example qualitative data and local knowledge (Perkins, 2011; Conway et al., 2019; Reyes-García et al., 2023). Indigenous and local knowledge is often cited as a valuable data source (e.g. Filho et al., 2022; McAllister et al., 2023). However, it can be unclear who the holders of such knowledge are and/or how to access this knowledge in many regions (Petzold et al., 2020), including the UK/Europe, meaning effective use of this information is neglected (Ford et al., 2016). The latest UK Climate Change Risk Assessment acknowledges that high quality evidence makes "use of relevant indigenous and local knowledge" (CCRA3 Technical Report, p. 40, Table 2.4; Betts & Brown, 2021), though this is not discussed further in the report.

This lack of integration of local knowledge with data-driven, usually national, climate risk assessments represents an important research gap in the UK, but also likely in many contexts around the world. Over-reliance on top-down deterministic modelling and data products risks simplifying climate change impacts and adaptation as a singular, convergent problem, whereas the reality in many cases is a divergent problem with plural, conditional solutions (Rodrigues & Shepherd, 2022). The first objective of this study is to showcase two examples of how qualitative local knowledge can be integrated with and compliment a national (UK) model-based climate risk assessment. This will be done using rural Northern Ireland as a case study. By integrating this data, the plurality and complexity of climate change impacts at a local scale can be better understood than by using quantitative modelling approaches alone. Understanding this complexity is vital to support effective adaptation actions (Rodrigues & Shepherd, 2022).

Northern Ireland (NI) is a devolved administration of the UK (alongside England, Scotland and Wales) and is largely rural, with over a third of the population defined as living in rural areas (DAERA, 2022). Rural NI and its industry sectors, including agriculture and community care, face multiple challenges in the coming years and decades. Among these, climate change poses both direct and indirect challenges. For example, recent summer heatwaves have set record temperatures (Kendon, 2021), posing direct challenges to care providers (as will be discussed in this paper), while new national legislation (the Climate Act 2022) sets an ambitious net zero target that will be a challenge for agriculture due to its current high emissions (Climate Change Committee, 2022). A number of recent academic studies have focussed on climate impacts in the UK on health and care (e.g. Jenkins et al., 2022; Gupta et al., 2021) and agriculture (e.g. Garry et al., 2021, Arnell et al., 2021b). However, none of these focussed specifically on NI, despite recognition that devolved UK administrations have their own unique circumstances (Steentjes et al., 2023).

NI's marine, temperate climate is usually cool and relatively wet. However, there is some notable local variability within NI, with wetter conditions in the west and in the uplands, and milder, drier conditions in the east. Direct weather and climate impacts in rural NI are multiple and varied, including but not limited to flooding, drought, high summer temperatures, cold winter temperatures, snowy/icy conditions and storms (Climate NI, 2022). Despite NI warming less rapidly than the rest of the UK (Murphy et al., 2018; Christidis et al., 2020; Kennedy-Asser et al., 2021), the occurrence of these extremes and their impacts is expected to change along with shifts in more 'moderate' or typical climatic conditions. The 2018 UK Climate Projections (UKCP18) show a variety of changes in precipitation for NI, with the central ensemble projection having wetter winters, drier summers and a little change in summer rainfall extremes (Murphy et al., 2018). However, there is a considerable range within the UKCP18 ensemble members, particularly for the extreme rainfall, with some ensemble members showing opposing wetting and drying signals (Murphy et al., 2018, Fig. 4.10).

In addition to the first research objective, this interdisciplinary study addresses a second research objective to map selected climatic risks relating to health and agriculture facing rural NI. To do this, the study primarily uses quantitative climate risk modelling results from the OpenCLIM project using UKCP18 climate model projections (Murphy et al., 2018; Kendon et al., 2019) and UK-SSP (Shared Socioeconomic Pathways) data (Pedde et al., 2021). In addition, the study utilises qualitative insights from workshops and interviews with farmers and rural care providers carried out as part of embedded research with Climate NI. This combination of quantitative and qualitative data is used to answer a number of specific research questions within the two wider objectives of the study, including:

1. How is heat-related mortality projected to change due to future warming in rural NI (and NI as a whole)?
2. How is heat-related discomfort projected to change across NI and is this consistent with currently reported qualitative data?
3. How might agricultural productivity in terms of yields of different crops or livestock be affected by a changing climate?
4. How is precipitation variability changing across NI and how is this affecting agricultural operations?
5. What other climate-related metrics of interest arise and require calculation following the qualitative study of local knowledge?

In answering these two objectives and five research questions, this study has conducted a first multi-sectoral climate risk assessment for NI. This novel study highlights the utility of interdisciplinary methods for (1) evaluating models where quantitative observations are unavailable and (2) effectively understanding climate impacts at the local scale. Our focus on NI represents a scale large enough to have multiple actors and stakeholders involved, for example national and local government, large business sectors and a considerable population, but small enough that local knowledge can be effectively utilised to interrogate quantitative results that were initially produced at a larger (UK) scale as part of an integrated climate risk assessment. It shows how such results can be reused at smaller scales and support focused regional to local risk assessments.

2. Methods

This research began as a quantitative multi-sector climate impact modelling study, with opportunities to carry out qualitative research arising throughout the research process. The modelling of climate hazards and impacts therefore represents a larger proportion of the analysis and is detailed in Section 2.1. The relatively smaller research component of qualitative data collection and analysis is described in Section 2.2.

2.1. Climate hazards and impacts

The climate hazards and impacts modelling component of this paper was carried out by a range of modelling groups as part of the OpenCLIM project and/or work with Climate NI. The individual risks are grouped by climate hazard and outlined in Table 1.

The OpenCLIM project has produced a set of risk metrics across a range of sectors (including impacts of temperature on health, hydrology and changes in crop yields) using consistent land use, population and climate scenarios (Tyndall Centre, 2024). The majority of the methods and results are fully accessible and reproducible through the DAFNI platform (login required; DAFNI, 2024; see also Matthews et al., 2023). A subset of OpenCLIM results that are directly relevant for understanding climate risks in rural NI will be explored here. Where OpenCLIM model results have been previously published as part of other assessments this is specified in Table 1.

Climate data is provided by UKCP18 (Murphy et al., 2018); specifically the 12 km resolution regional ensemble of 12 ensemble members, forced with historical emissions to 2005 and then the RCP8.5 emissions scenario to 2080. Future global warming levels were selected using a time-slice approach (Arnell et al., 2021a; Hanlon et al., 2021), noting that this is an approximation of the true equilibrium warming level (King et al., 2020). Depending on the sector, different bias correction methods have been applied as not all bias correction methods are equally appropriate for all climate variables, as detailed below.

2.1.1. Heat and cold related impact metrics

Heat-related mortality calculations used the exposure–response model described in Jenkins et al. (2022), known as HEAT-HARM in OpenCLIM. However, this paper provides more detailed evaluation of these results for NI than was previously possible on the national scale. Additionally, the baseline period has been updated from Jenkins et al. (2022). The method assumes that NI has a similar population response to temperature (minimum mortality temperature and relative risk) as the Northwest of England, with heat-related mortality increasing above mean temperature of 17.3 °C and cold-related mortality increasing below 11.9 °C (Hajat et al., 2014; Vardoulakis et al., 2014). UKCP18 temperature and humidity data were both bias corrected to ERA5 data (Hersbach et al., 2020) using the ISIMIP2b bias correction method (Freiler et al., 2017; Lange, 2018).

Population data used in the heat-related mortality calculation for the main analysis is from historic data for the baseline and UK-SSP5 (Pedde et al., 2021), which is characterised by high fossil fuel development, large increases in population resulting in rapidly expanding cities and urban sprawl. UK-SSP2 and UK-SSP4 were included for some analysis in the supplementary material. For presenting mortality results, areas were categorised as rural or urban based upon the land use fraction assigned in the UKCP18 model. Areas which have more than 2.5 % as urban tile fraction were classed as urban, aligning with Belfast, Bangor, Lisburn, Derry-Londonderry and Newry – the major cities in NI.

Three further threshold-based metrics were assessed also using the HEAT-HARM model. Firstly, residential discomfort, which indicates when indoor bedroom temperatures exceed 26 °C between the hours of 10 pm and 7am, can be approximated across household types relative to mean outdoor temperatures. The mean outdoor temperature thresholds for the baseline, assuming no

Table 1
List of modelled climate related impacts, all carried out as part of OpenCLIM except for that marked*.

Climate hazard theme	Impact	Unit/measure	Reference/author lead
Heat	Heat-related mortality	Average deaths per year	Jenkins et al. (2022) / K. Jenkins, A.T. Kennedy-Asser, O. Andrews
	Heat stress	Days when mean sWBGT > 26.8	K. Jenkins, A.T. Kennedy-Asser, O. Andrews
	Residential discomfort	Days when mean temperature > 22.0 °C	K. Jenkins, A.T. Kennedy-Asser, O. Andrews
Cold	Hard frost days	Days when mean temperature < 0 °C	Harding et al., 2016, Arnell et al., 2021b / K. Jenkins, A.T. Kennedy-Asser, O. Andrews
Agriculture (crops)	Perennial rye grass yield	t/ha	Hayman et al., 2024 / R. Pywell, M. Brown, J. Redhead
	Winter wheat yield	t/ha	Hayman et al., 2024 / R. Pywell, M. Brown, J. Redhead
	Oilseed rape yield	t/ha	Hayman et al., 2024 / R. Pywell, M. Brown, J. Redhead
Agriculture (livestock)	Milk yield loss*	Litres per cow per year	Wildridge et al., 2018 / A.T. Kennedy-Asser
Hydrology	Catchment discharge flows	Q1, Q50, Q99	Smith et al., 2024 / B. Smith, E. Lewis, S. Birkinshaw, He, H.

retrofit of shading devices to limit heat gains, range from 21.0-21.6 °C for four main housing types (Ferguson et al., 2023). Furthermore, stakeholder-led work by the UK Met Office identified that for Belfast, days above 22 °C saw increased water consumption and energy demand for cooling, both likely in response (at least partially) to discomfort (Ramsey et al., 2024). Therefore, to ensure consistency with recent and locally relevant stakeholder-led research (Ramsey et al., 2024), days with daily mean temperatures (T_{mean}) above 22.0 °C were taken as an approximate threshold for residential discomfort in rural settings. We note, however, that this could produce a conservative estimate compared to lower thresholds (Ferguson et al., 2023).

Secondly, following discussion with stakeholders (detailed further in Sections 2.2.1 and Section 3.1), it was deemed important to include a metric relating to cold weather due to their concerns and impacts caused by these conditions. Days with T_{mean} below 0 °C were taken as 'hard frost days' when there is additional risk of cold impacts, including but not limited to transport disruption (with indirect effects on social isolation in rural settings) and frost damage to crops (Arnell et al., 2021b). Note that Arnell et al. (2021b) use the metric of daily minimum temperatures falling below 0 °C, therefore the T_{mean} threshold used here is colder.

Finally, a basic metric of outdoor heat stress, simplified Wet Blub Globe Temperature (sWBGT), was calculated following Zhao et al. (2015). Heat stress risk was based upon the threshold identified in Costa et al. (2016) as days when daily maximum sWBGT > 26.8 °C, which is lower than the 'slight' heat stress threshold used previously in the global study of Zhao et al. (2015; sWBGT = 28). It is important to note that the sWBGT heat stress metric, and other metrics like it, are relatively poor approximations of Wet Bulb Globe Temperature (Kong & Huber, 2022). Therefore, this metric is calculated for illustrative purposes only.

It is important to note some caveats concerning the heat-related mortality modelling presented here (see also Jenkins et al., 2022). Firstly, the method expects a linear relationship between the relative risk of increased mortality above the minimum mortality temperature for heat-related mortality. This is conceptually simplified compared to more sophisticated models, such as distributed lag non-linear models (e.g. Lo et al., 2022). However, it produced similar results when compared to heat-related mortality reporting from UK Health Security Agency and Public Health England (Jenkins et al., 2022). A further caveat is that the model used here was calibrated on data for the Northwest of England, not NI, based upon the availability of data for the model (which followed Hajat et al., 2014), however, climatically the two regions are relatively similar. Provided the uncertainties are well understood, we believe these heat-related mortality results offer important climate information for NI – a region which is underrepresented in research and analysis.

2.1.2. *Agriculture related impact metrics*

Projected potential crop yields for perennial rye grass, winter wheat and oilseed rape were calculated using the CropNet model (Hayman et al., 2024) through OpenCLIM. The majority of NI's agricultural land is used for grazing, so the results will primarily focus on perennial rye grass. Winter wheat and oil seed rape are also of interest, with the latter being the only significant oil crop produced in NI. CropNet accounts for variation in daily temperature, sunlight hours, precipitation, water limitation, heat stress, CO_2 fertilisation effect and sowing date. This model used CHESS-SCAPE for driving data (Robinson et al., 2023), which is a 1 km downscaled version of UKCP18. Due to the computational demands of this model, it was not possible to use all 12 UKCP18 RCM simulations. Instead, only four were used (ensemble members 01, 04, 06 and 15). Results are all presented as ensemble mean of these four simulations. It should be noted that, like the heat-related mortality model, the crop model used here has been calibrated with data for England and Great Britain. Future research should prioritise incorporating NI observational yield data into crop models like CropNet to improve accuracy.

In addition to these climate impact analyses from OpenCLIM, some further agricultural heat stress metrics were calculated as part of embedded research work with Climate NI and these have been made available through a ShinyApp (AgricultureNI, 2024). This included the dairy cattle heat stress metric Temperature Humidity Index (THI) (Dunn et al., 2014; Garry et al 2021) and the associated impact this has on milk yield (Wildridge et al., 2018), the equations of which are provided in the supplementary material. Percentage decrease in milk yield was calculated assuming current average milk yield per cow per year in the UK of 8,000 L (AHDB, 2024).

2.1.3. *Hydrology related impact metrics*

Hydrology, in terms of high (Q01 – the flow exceeded 1 % of the time), low (Q99) and median (Q50) river discharge flows, was calculated by the SHETRAN model (Ewen et al., 2000) and HBV model (Bergström, 1995; He et al., 2022) for 30 catchments across NI for moving 30 year time periods from 1980 to 2080. The periods closest aligning to 2 and 4 °C warming above pre-industrial for each of the 12 RCMs are shown here. Catchments that had any missing data and any catchments where the Nash–Sutcliffe model efficiency coefficients (NSE) were < 0.7 for either the calibration or validation period were not included. Bias correction was performed for the meteorological model inputs, quantile mapping the climate data to historical data (1985–2010) on a monthly basis to better capture seasonal patterns.

Given the potential diversity of simulated responses from the 12 UKCP18 simulations driving 2 hydrological models, caution is required when interpreting the ensemble mean changes in catchment flow shown in the supplementary materials. It is important to note that for some catchments there is poor model agreement on the direction of trend (i.e. wetting or drying), particularly for those in the north of the country in terms of Q01 flows. However, for median flows and at higher levels of warming, there is very consistent model behaviour. A full analysis of the hydrological changes over NI is beyond the scope of this paper.

2.2. *Qualitative research and stakeholder engagement*

In addition to the quantitative assessment, qualitative analysis of relevant climate-related impacts was also performed to enrich the study through semi-structured interviews with rural care providers and focus groups with farmers. These came about through an opportunity to do embedded research with boundary organisation Climate NI.

2.2.1. Semi-structured interviews

Semi-structured interviews with care providers in the rural town of Castlederg were carried out in July 2022. This study location was chosen as Castlederg currently holds the record for both NI's hottest and coldest recorded temperatures. Care providers included three managers of care facilities for older adults ranging from a sub-acute hospital to independent sheltered accommodation, and three in positions of care with children, including day care for infants and pre-school children and staff at a secondary school. A full report of this work can be found in Kennedy-Asser (2022). Ethics approval was granted for this work by the School of Geographical Sciences at University of Bristol in June 2022. Interviews were chosen as an appropriate method due to the relatively small number of interviewees in the town, the richness of data interviews provide and to allow flexibility for interviewees to fit the research into their schedules. The interviews followed the format outlined below.

Theme 1: Hot extremes

- Thinking about hot extremes, like the summer of 2021, did you notice impacts on your professional life?
- Personally, how did you feel during the high temperatures last summer? (How did these compare to what you were used to throughout your life?)
- Professionally or personally did you change behaviours/would you change behaviour in the event of a future heat wave?

Theme 2: Cold extremes

- Thinking about cold extremes, like the winter of 2010, did you notice impacts on your professional life?
- Personally, how did you feel during the cold temperatures in 2010 or 2018? (How did these compare to what you were used to throughout your life?)
- Professionally or personally did you change behaviours/would you change behaviour in the event of a future cold snap?

Theme 3: Comparison and advice

- Which of hot or cold extremes (or another weather phenomenon) are better or worse for you, personally or professionally?
- If you could offer one piece of advice to the rest of NI about how to deal with extreme temperatures, what would it be?

2.2.2. Farm workshops

Four workshops were organised with members of the farming community across NI in winter 2022/2023. These were held in Omagh (targeting farmers from the west), Ballymoney (targeting farmers in the north), Ballynahinch (targeting farmers from the southeast) and Dungannon (targeting farmers from mid-Ulster). The workshops were advertised via a number of networks including Ulster Farmers' Union, Dale Farm, Nature Friendly Farming Network, Rural Support, College of Agriculture, Food and Rural Enterprise (CAFRE), AgriSearch and NI Grain Trade Association.

Farmers were represented from a range of farm types, including predominantly dairy ($\sim$ 25 % farms), beef ($\sim$ 30 % farms) or mixed farms (including suckler, tillage and sheep; $\sim$ 35 % farms), and from a range of farm sizes ($\sim$ 40 % farms $<$ 50 ha, $\sim$ 60 % farms $>$ 50 ha). Attendees were from a range of age groups, although the youngest category (under 35) was under-represented ($\sim$ 10 % attendees) and approximately half of the attendees were aged 35–55. Note, this information was only recorded for pre-registered attendees – for others who attended on the day this information was not captured. The number of attendees across all workshops was 75, however the Dungannon group was notably smaller (8). Results from the Dungannon group are not analysed in isolation but combined with NI aggregate.

At the workshops, farmers individually responded to a series of prompt questions, before going into group discussions around two further questions. The prompt and discussion questions are in Supplementary Table 1. The question of "What impact on your farm have you noticed as a result of changes in extreme weather patterns?" is of greatest interest here. To avoid groupthink or certain narratives dominating discussion, individual responses to questions were written first on post-it notes before opening up into the group discussions. Post-it responses were subsequently collated for deductive thematic analysis, identifying responses that were predominantly temperature related, precipitation related and unpredictability related. Unpredictability related, for example, would relate to changing of typical seasonal patterns, such as unseasonal frosts or periods of heavy rain that are abnormal based on their local, historical experience.

It is important to note that there could be overlap, for example the response 'Some dry and warm summers' is both temperature and precipitation related. Participants could provide multiple responses if they wanted, so the total number of responses (113) exceeds the total number of participants. The two members of the project team involved with these workshops independently carried out this deductive thematic analysis, before discussing and agreeing upon the final groupings. The exact responses and their aggregation for the weather-related question are provided as an example in Supplementary Table 2.

2.2.3. Integration of local knowledge

Due to the qualitative nature of the local knowledge collected, it was not used to directly calibrate the quantitative models. For example, indoor temperatures were not recorded at care homes and crop or milk yield data was not collected from individual farms. While this information would be extremely valuable, it was beyond the scope of this study. Instead, the discussions with these stakeholders during the interviews and discussion sections of the workshops helped guide further analysis of the quantitative modelling results. Specifically, this involved focussing on temperature thresholds of particular importance and understanding temporal variability in impacts as will be discussed in Section 3.

3. Results

3.1. Heat and cold impacts

Heat-related mortality is currently unreported in NI and is likely to be below the magnitude that is statistically significant. The first research question is to provide an estimate of how this risk may increase in NI in the future. The projected heat-related mortality is shown here in Fig. 1a-e. The exposure–response model detailed in Section 2.1.1 projects ~ 2 deaths per year (1–4 5th and 95th percentile) for a 1981–2000 baseline in UKCP18 data. Applying the exposure–response model to observed data (HadUK-Grid; Hollis et al., 2019) for the major 2018 heatwave using the same method as Jenkins et al., 2022, suggests that the heatwave likely caused ~ 7 excess deaths. By 2080 assuming a population change consistent with the high population growth SSP5 scenario, in a 2 °C warmer world ~ 22 annual heat related deaths would occur (16–36, 5th and 95th percentile), while in a 4 °C warming world ~ 98 annual heat-related deaths could occur (61–142, 5th and 95th percentile). At 2 °C warming, 72–73 % of mortality is projected to occur in rural areas despite having a low population density, dropping to 66–68 % at 4 °C warming (Supplementary Fig. 1). At the higher level of warming, coastal cities such as Belfast, Derry-Londonderry and Bangor also start to experience more days exceeding the minimum mortality temperature.

The second research question focussed on heat-related discomfort, how it could change in future and if modelled results are consistent with present day experience in NI. Modelled residential discomfort days (daily mean temperature > 22.0 °C) are shown in Fig. 1f-h. Residential discomfort is shown to not currently be an issue in this bias corrected UKCP18 data, with no days for the baseline period exceeding daily mean temperatures of 22 °C. With warming, it is projected to increase particularly in inland areas. At 2 °C warming, temperatures in parts of NI will start to exceed 22 °C, mainly around south and central Lough Neagh. It is notable that Castlederg and the west of NI is not one of the regions highlighted. By 4 °C warming, days of residential discomfort are projected to become widespread, with the most days (approx. 1 week per year) occurring in the region between Lough Neagh and the southern

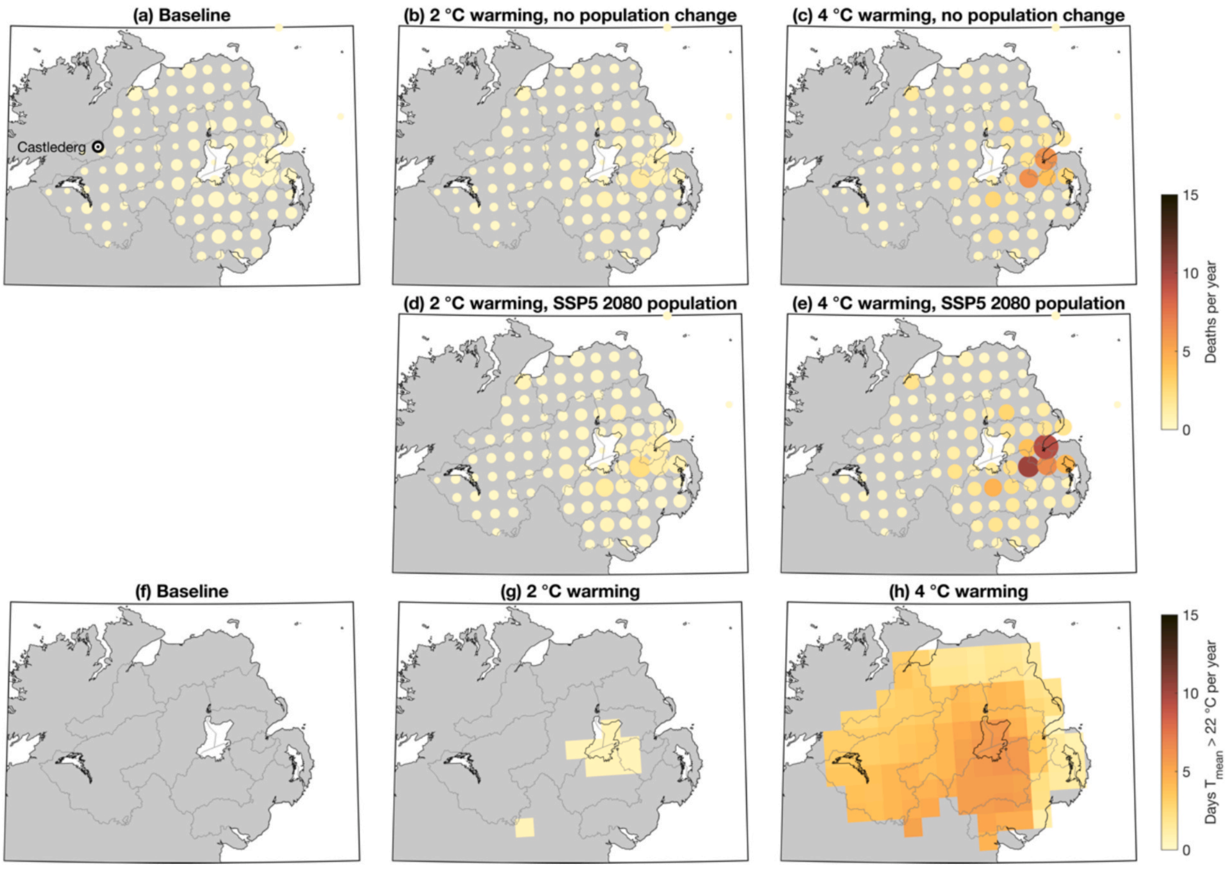

Fig. 1. Modelled heat-related mortality over Northern Ireland for (a) the historic baseline, (b) 2 °C warming with no population change, (c) 4 °C warming with no population change, (d) 2 °C warming with a future population for 2080 from UK-SSP5 and (c) 4 °C warming with a future population for 2080 from UK-SSP5. Dots are scaled proportionally to the population size. Modelled number of days exceeding 22.0 °C are shown for (f) the historic baseline, (g) 2 °C warming and (h) 4 °C warming.

border with the Republic of Ireland. As well as affecting rural areas, this region includes some notable urban areas including Lisburn, Portadown, Craigavon, Armagh and Newry. There are no days modelled to have heat stress in NI (daily mean sWBGT > 26.8), even under a 4 °C warming scenario (not shown).

Under 4 °C warming, projected heat-related mortality for NI is highest in urban areas of Belfast due to the high population density, as shown in Fig. 1a-e. However, projected absolute temperature increases are greater in the central, southern and western parts of the country away from the Belfast region and coastal areas (Fig. 1f-h). Notwithstanding that there could be an urban heat island effect in towns and cities (Ramsey et al., 2024) that is poorly captured in the climate model used here (Keat et al., 2021), the spatial patterns of projected warming suggest that the greatest risk in terms of health and discomfort to individuals could likely be in rural areas. A similar result of greater heat risk in southwest NI was also shown in Kennedy-Asser et al. (2022).

A series of semi-structured interviews were carried out with care providers in Castlederg, highlighted in Fig. 1a. A full discussion of these interviews can be found in the report written for Climate NI (Kennedy-Asser, 2022), however there are three key findings of relevance here. Firstly, it was noted that care work particularly for the old and vulnerable was physically exerting work, often performed in a warm setting by staff wearing personal protective equipment (PPE). There is further stress particularly on those who work night shifts and who had to sleep in the heat of the day. As a result, additional staff breaks were regularly required during warm periods in recent summers. This is an example of a response to workplace heat stress which was not identified by heat stress metric applied here. sWBGT is typically applied as an outdoor heat stress metric, therefore it is unsurprising that it is inconsistent with the specific conditions of this indoor setting. However, this result highlights the need for more appropriate metrics to be developed for this scale in future research.

Secondly, care staff managers reported that during the summers there could be 3–4 days *per week* which they class as 'hot days' when residents were uncomfortable and extra precautions must be taken, for example increasing fluids provided to residents. This suggests the 22 °C threshold for residential discomfort is underestimating risk and highlights that temperatures do not need to be extreme to have impacts – a similar point was raised in terms of heat-related mortality by Jenkins et al. (2022). Aggregate modelling even at high resolution misses the granularity of individual buildings, where heat-related impacts can be amplified. UKCP18 climate data suggests that summer temperatures will increase across the country, particularly in areas like Castlederg (Kennedy-Asser et al., 2022), thus, heat-related adaptation options need to be considered.

Finally, staff noted that very cold conditions, particularly those associated with heavy snowfall and frost can be particularly impactful by making roads impassable. This can have implications for staff commuting to work and for providing community care for those in rural locations. This prompted our fifth research question and led to further quantitative analysis of hard frost days when the average temperature does not rise above 0 °C. The results of this further analysis, shown in Fig. 2, identified this to be a particular issue in the west of NI (up to 8 days per year for the baseline period), highlighting why this is a concern for those living and working in this region. The chance of hard frost days decreases substantially with future warming, but will remain a potential issue in the west (only up to 2 days per year for the 4 °C scenario).

3.2. *Agriculture and hydrology impacts*

Moving to the third research question, the crop model used in OpenCLIM suggests that general growing conditions for perennial rye grass will improve in NI with increased levels of global warming, as shown in Fig. 3. At 2 °C warming, the increase is modest (<10 %), however at 4 °C warming, increases could exceed 30 %. Potential winter wheat and oil seed rape yields are shown in Supplementary Fig. 2. Wheat yields are also projected to increase across NI, by up to around 50 % with 4 °C warming, however, areas of the Ards Peninsula that are currently some of the more suitable parts of the country for wheat production could see declines in yield at 4 °C warming. These results account for a CO_2 fertilisation effect in future. If the CO_2 fertilisation effect is removed, crop yield increases are smaller and level off at around 2 °C warming, as shown in Fig. 4 for NI council areas.

Heat stress impacts on dairy cattle (milk yield per cow) were also calculated for individual council areas of NI, shown in Fig. 4. Typically, the impacts of projected warming are small, causing a reduction of less than ~ 0.5 % of the recent past annual total milk production even under a 4 °C warming scenario. Consistent with the impacts due to extreme heat shown in Fig. 1, areas in the south and central parts of NI such as Mid Ulster and Armagh City, Banbridge and Craigavon council areas show larger impacts than councils

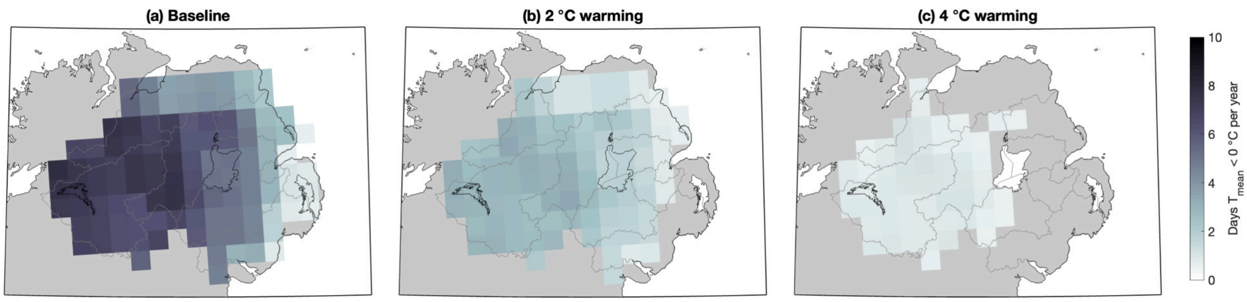

Fig. 2. Number of hard frost days per year with daily mean temperatures < 0 °C for (a) the historic baseline, (b) 2 °C warming and (c) 4 °C warming.

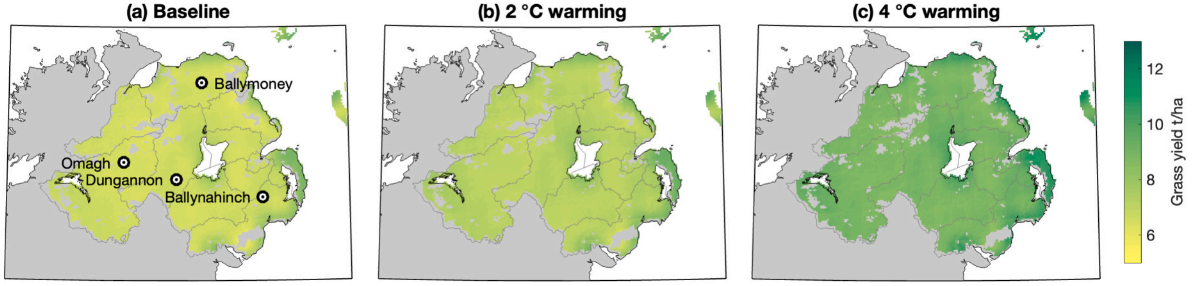

Fig. 3. Modelled perennial rye grass yield over Northern Ireland for (a) the historic baseline, (b) 2 °C warming and (c) 4 °C warming, assuming CO_2 fertilisation effects.

such as Causeway Coast and Glens and Ards and North Down in the north and east, as shown in Fig. 4.

To gain further insight into the impact of weather and climate at farm level, four workshops were organised with members of the farming community across NI in Omagh, Ballymoney, Ballynahinch and Dungannon, highlighted in Fig. 3a. Farmers were asked "What impact on your farm have you noticed as a result of changes in extreme weather patterns?". A summary of the responses to this question is provided in Table 2, with the full set of responses provided in Supplementary Table 2.

Of the 113 responses provided to this question across the workshops, precipitation related impacts were the most reported across all workshops, and for Omagh and Ballynahinch (i.e. in the west and east) they accounted for ~ 40–50 % of responses. Across all workshops, and for Omagh and Ballynahinch individually, this was followed by unpredictability related impacts (~ 30 %) then temperature related impacts (~ 6–12 %). Ballymoney in the north was notably different, with an approximately equal rate of reporting for precipitation, unpredictability, and temperature related impacts. Importantly, there is often significant overlap between these groupings, particularly as the unpredictability typically relates to when the weather is dry enough to harvest, wetter than normal in the summer or colder than normal in the spring. 45 responses noted explicit impacts: the most reported impact was extended housing for cattle throughout the year, with further impacts noted on animal health and disease risk (e.g. pneumonia) due to housing and/or unpredictable weather. Impacts on grass growth were also commonly reported, with increased poaching of fields (i.e. damage to grass and soil due to trampling by livestock while fields are too wet), increased need for re-seeding and reduced silage quantity and/or quality all reported.

In general, the unpredictability and associated impacts were mainly related to precipitation changes, prompting our fourth research question. OpenCLIM hydrological modelling results suggest both increased drying of dry periods and increased precipitation in wet periods due to climate change, shown in Fig. 5 and Supplementary Fig. 3 (consistent with Kay et al., 2021, 2023). However, there is notably more disagreement between the two OpenCLIM hydrological models in the wetting trends compared to the drying trends. Agreement between models on direction of change is generally stronger in the west of NI.

Some individual responses at the workshops quoted heat-related impacts, including cattle heat stress (reported in Ballymoney), adapting sheds for warmer conditions, increased warm and dry extremes requiring additional energy and water inputs. Heat impacts therefore appear small but non-negligible. With regards to the cattle heat stress, there was no specific mention of milk yields being reduced and so it is unclear if the impact was on milk production, animal health, reproduction rates, or if it was something that could be managed by the farmer to mitigate any further impact.

This is broadly consistent with a recent study also suggests that NI currently has a low risk of dairy cattle heat stress. Garry et al. (2021) calculate that the 1998–2017 baseline heat stress in dairy cattle was very low in NI, resulting in a very large future increase in percentage terms of almost 3,000 %. The results here (Fig. 4), presented as a percentage reduction in the approximate annual milk yield of cattle (a relatively small value), provides a very different picture to the large relative change reported by Garry et al.. It will be important to record with further quantitative and qualitative data in future if concern about cattle heat stress increases in NI.

One question raised by farmers and a local dairy co-operative (who assisted in advertising the workshops) concerned the temporal variability of changes in dairy heat stress risk: i.e. would a 0.5 % reduction in milk production be experienced every year, or would it be a 5 % reduction once in every 10 years? Management of these two scenarios would be very different. Subsequent quantitative analysis highlighted that although there is some interannual variability, the impact appears to be relatively consistent across years in the 30-year model scenarios, as shown in Fig. 6. For all UKCP18 model simulations at 4 °C warming, most years are shown to have some days exceeding a THI of 68 when yields are modelled to decrease, with no disproportionately large one-off heatwaves dominating the signal.

Finally, there were also some opportunities or benefits noted, including warmer summers being better suited for vegetable growing, longer growing seasons and some usually wet/mossy fields being improved, along with some general comments about 'good' weather. However, these responses made up a small minority of the total. Supplementary Table 2 shows all of the responses, giving a sense of the balance of positive and negative comments.

4. Discussion and conclusions

For over a decade, the international research community has called for the use of indigenous and local knowledge in climate risk assessment (Perkins, 2011; Strauss, 2015; Reyes-Garcia et al., 2015, 2023, Conway et al., 2019). There are some studies in the UK

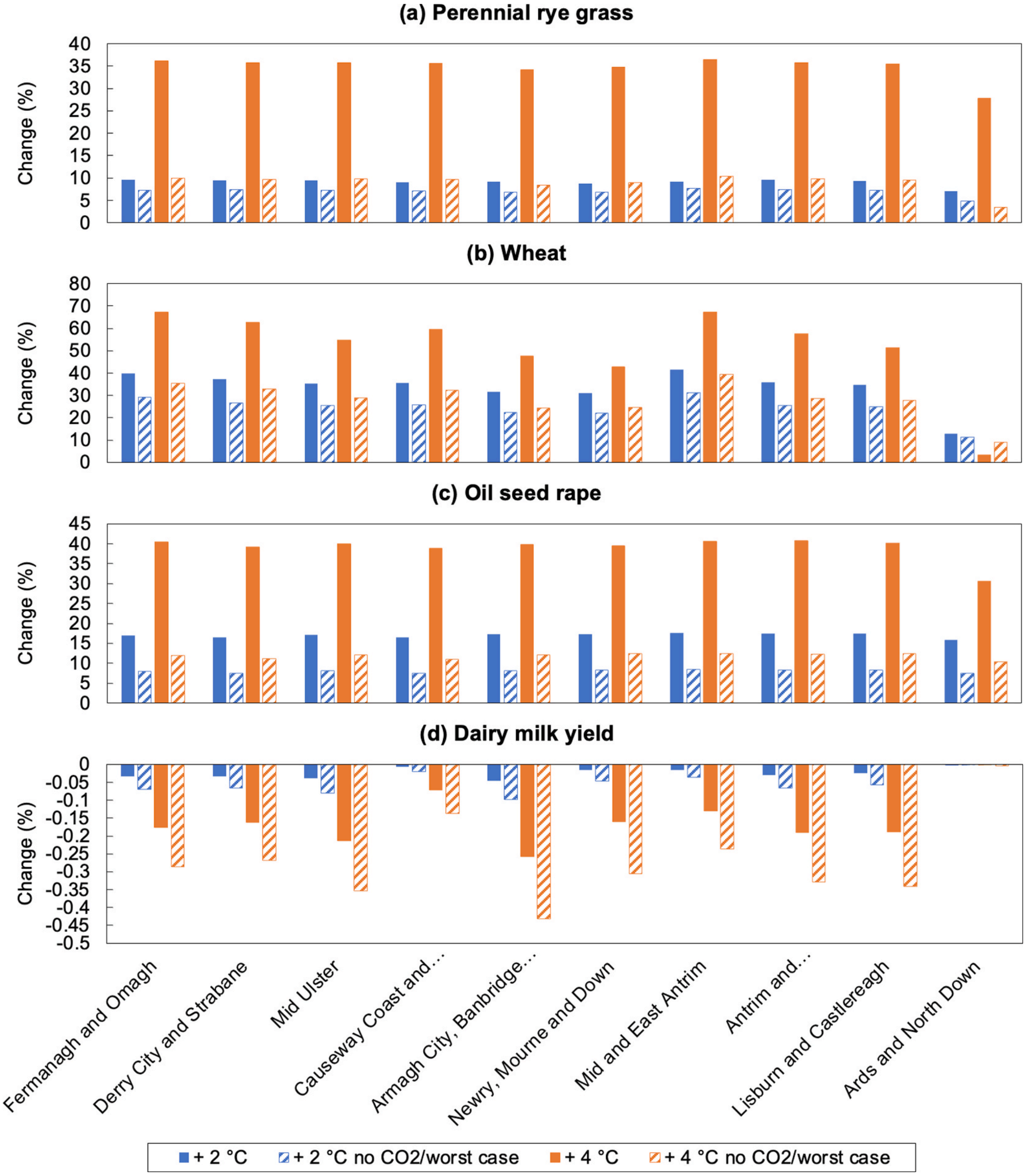

Fig. 4. Projected changes in agricultural metrics at different levels of global warming for council areas in NI. For crop yields (a-c), solid bars show yield change accounting for CO_2 fertilisation while hatched bars show yield change if there is no CO_2 fertilisation effect. For dairy milk yield (d), solid bars show the UKCP18 ensemble mean reduction and the hatched bars show ensemble maximum reduction for 'worst case' yield decline.

utilising local data through co-production or stakeholder input (e.g. Ramsey et al., 2024). However, studies in the UK rarely acknowledge the potential value of these data and methods (e.g. Dale, 2022) or use them in risk assessment studies, which are often based on quantitative metrics (e.g. Arnell et al., 2021a,b; Kennedy-Asser et al., 2022). The local knowledge incorporated here, like place-based approaches (Howarth et al., 2021; Garry et al., 2024), provides an 'on the ground' or bottom-up perspective on the impacts of climate change from people who manage those impacts currently. We point to studies such as Lonsdale et al. (2024), Ramsey et al. (2024) and our own methods presented here to showcase how these methods can be applied in practice to enhance the risk assessment process.

Our first objective was to showcase how qualitative local knowledge can be integrated with and enhance a model-based climate risk assessment in a UK context. Initially, the engagement with local knowledge holders was not considered, but was subsequently developed through embedded research. Ultimately, even this relatively small amount of qualitative local data significantly enhanced the outcomes and fundamentally shaped the direction of this study. Here, we reflect on this process.

In some cases, the qualitative local knowledge supported the quantitative modelling results. For example, qualitative data

Table 2
Summary of responses to the question "What impact on your farm have you noticed as a result of changes in extreme weather patterns?" across four workshops.

Omagh	Temperature related	Precipitation related	Unpredictability related	Impact explicitly mentioned
47 responses	3	18	15	19
Top reported impacts	*Housing cattle longer* (n = 7)			
	Shorter windows to get field work done (n = 6)			
	Harder to plan ahead (n = 5)			
	Longer/altered growing season (grass may be left over at end of season) (n = 4)			
	Reduced grass/silage quality when wet (requires supplementary feeding) (n = 4)			
	Wetter winters (n = 4)			
Ballynahinch	Temperature related	Precipitation related	Unpredictability related	Impact explicitly mentioned
33 responses	4	17	10	13
Top reported impacts	*Harder to plan grass growth, field operations* (e.g. *fertiliser and slurry application) and/or general decisions* (n = 6)			
	Regular/increased summer drought (n = 4)			
	Hotter & drier summers (need more water for potatoes, streams drying out) (n = 4)			
	Mild winters (ewes out longer, no deep frosts) (n = 3)			
	Increased surface water in fields/water logging (more reseeding required) (n = 3)			
Ballymoney	Temperature related	Precipitation related	Unpredictability related	Impact explicitly mentioned
26 responses	5	6	5	9
Top reported impacts	*Mild wet winters (less snow)* (n = 3)			
	Some poor summer weather means cattle need housed (n = 3)			
	Animal health can be affected during housing (n = 3)			
	Negative impacts on grass and crop growth (n = 2)			
Dungannon	Temperature related	Precipitation related	Unpredictability related	Impact explicitly mentioned
7 responses	1	1	5	4
Top reported impacts	*Change from years ago* (e.g. *hay making used to be easier)* (n = 2)			
	Unpredictability of dates in farming calendar (n = 2)			
	Warmer weather throughout year driving increased power usage (n = 1)			
	Flash flooding from river (n = 1)			
	Periods of unusually good weather (n = 1)			

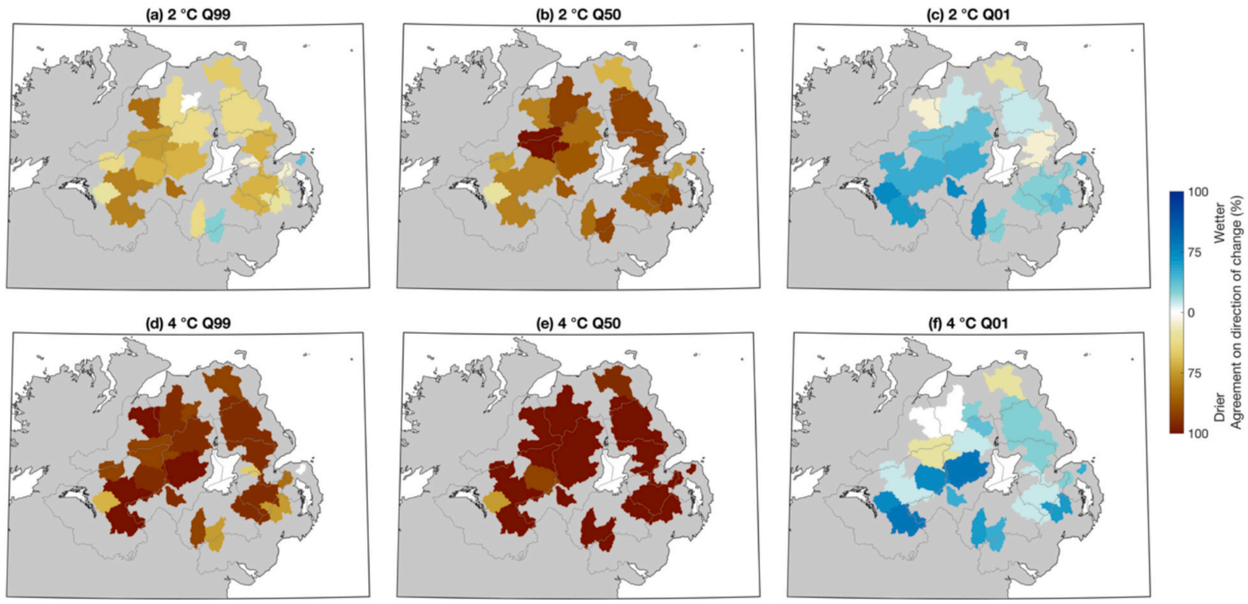

Fig. 5. Model simulation agreement on direction of projected changes in median (Q50), high (Q1) and low (Q99) river flows for catchments at 2 °C and 4 °C warming from the two OpenCLIM hydrological models when each forced by 12 UKCP18 ensemble members. Dark brown (blue) values indicate 100 % of simulations (i.e. all 24) showing drying (wetting). White colours (0 % agreement) indicate 12 simulations are wetting and 12 are drying. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

highlighted that heat risk can be an issue for health and health care in rural areas and is not limited to urban centres (in agreement with heat-related mortality modelling), and that precipitation is changing and becoming increasingly erratic, posing challenges to agriculture (in broad agreement with modelled hydrological changes). In other cases, the local knowledge challenged the quantitative results, for example regarding the potential heat-related discomfort and heat stress impacts in workplaces (which models suggest to be negligible) and the suggestion from models that grass growing conditions will be more favourable, with higher yields as a result of

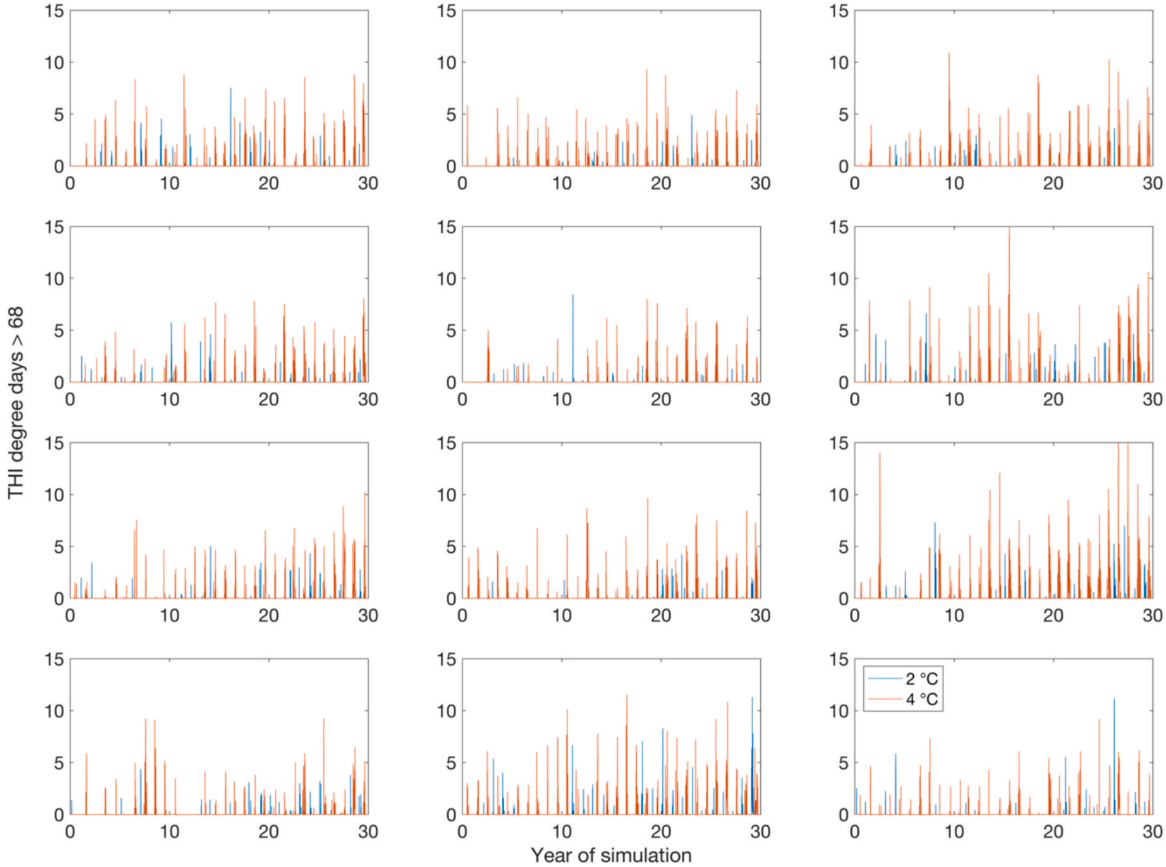

Fig. 6. Annual degree days when THI > 68 for each UKCP18 ensemble member at 2 °C (blue) and 4 °C warming (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

future climatic conditions, contrary to current local experience.

The negative impact of extreme weather on grass yields is supported by other ongoing non-academic research. For example, there has been a notable decline in grass growth across the Agrisearch GrassCheck NI network due to a combination of hot and dry conditions (Agrisearch, 2024), with the impacts of heatwaves during the summers of 2018 and 2021 clearly identifiable compared to the long-term 10-year average. Meanwhile, in the other seasons farmers reported potentially good grass growth, but the ground was too wet for it to be grazed. It should be noted that this could be due to the temporal scale on which results are presented. For example, if individual summers were extracted from the crop model and assessed at the weather time scales that farmers reported having issues, then the crop model might agree that there will be unseasonal periods of poor growth. However, a climate risk assessment at regional to national scales necessitates that overall long-term average climate shifts are reported, which are unlikely to align with the week-to-week impacts that are experienced by farmers.

In this study we asked a research question: what other climate-related metrics of interest arise and require calculation following the qualitative study of local knowledge? Engagement with local knowledge holders helped shape the analysis of model results. Without the engagement of local farmers, the variability in modelled dairy cattle heat stress may not have been explored. Likewise, the semi-structured interviews with care providers also prompted investigation of a new threshold-based metric: potential changes in hard frost days. Analysis showed that such events are likely to decline in frequency but cannot be completely ruled out even under 4 °C warming scenarios, and a need to be ready for them remains. Finally, integrated risk modelling initiatives such as OpenCLIM produce a huge amount of data, only a fraction of which can be reported in a single paper. Despite not being part of the original research proposal, it was the discussions with local knowledge holders that shaped which research questions were addressed and which model data was interrogated in this paper.

Although this is a regional case study of a small country, we would argue that it is necessary to take such a focus to apply these methods. By its definition, local knowledge requires engagement at small or the community scale, with previous studies for example working at city scale (e.g. O'Hare, 2021; McClure et al., 2023).

OpenCLIM modelling results are available at the national UK scale. However, already at this scale it becomes increasingly difficult to both incorporate local knowledge and include multiple sectors. For example, previous studies including stakeholder engagement at a national scale (Ibbetson et al., 2021; Garry et al., 2021) focussed only on a single sector (experiences in care homes in England and Wales, and agriculture respectively). Cross sectoral studies at national scale typically do not include detailed stakeholder engagement (e.g. Arnell et al., 2021a,b).

At an even larger scale, for example continental or global, it is increasingly difficult to incorporate nuanced local knowledge in a balanced way with quantitative modelling results that are relatively easy to produce at scale and often focus on high impact events (Ford et al., 2016). Therefore, a key recommendation from this study is that both large-scale quantitative and local-scale qualitative research are needed to properly understand climate risk and improve climate adaptation decision making. Quantitative results allow (often) transparent intercomparison between regions. However, qualitative research provides a vital check on the quantitative data, ensuring conclusions are supported and support stakeholders, who ultimately can use this information in their decision making processes.

The second objective of this research was to provide a climate risk assessment for health and agriculture sectors in NI. This is important as NI in general has poorer availability of data and research studies than the rest of the UK. This work is also significant and novel as it is the first interdisciplinary risk assessment for NI. Here, we summarise the research questions answered through this risk assessment:

1. Heat-related mortality is expected to increase significantly with projected future warming, in the most extreme case to 98 (61–142; 5th-95th percentile) deaths per year with a population in line with SSP5 in 2080 and 4 °C warming. Approximately 65–75 % of these deaths would occur in rural areas.
2. Heat-related discomfort is projected to increase across NI, becoming a widespread issue at 4 °C warming. However, there are concerns that the current modelling underestimates this risk as heat-related impacts on comfort and productivity were already recorded in rural NI in recent years.
3. Modelled yields of crops including perennial rye grass are generally projected to improve as a result of global warming, increasing by up to 30–50 % at 4 °C warming if taking into account the effect of CO_2 fertilisation. Without CO_2 fertilisation, yield increases between 4 °C compared to 2 °C are less.
4. However, experience of farmers in recent years highlighted that changes in weather variability, particularly in terms of precipitation, have often negatively affected field operations. Hydrological model results support that dry extremes will get drier and wet extremes wetter with future warming.

It is worth noting that there are many caveats to the modelling results carried out, found in detail in Section 2. For example, the heat-related mortality exposure–response function uses Northwest England as an analogue region – an approximation that will introduce some error. The relatively simplistic threshold-based temperature metrics aim to approximate some inherently subjective quantities such as discomfort and require further local and sector-specific tuning. The crop model has been calibrated with data for England and only covers 3 crops with many other important crops for NI (such as barley) not assessed. Finally, only a limited number of climate model input datasets (all deriving from UKCP18) were used to drive these impact models and other global or regional climate models could produce alternative future climates for the British Isles.

The qualitative data too has limitations. The semi-structured interviews were with care facility managers, but further valuable insights would come from interviewing staff and residents. The regions and demographics sampled by farmers attending the workshops will not be fully representative of all farmers, farm types and regions. Finally, only a small amount of research time could be committed to this element of the project, meaning a great amount of local knowledge remains unexplored. These important caveats highlight areas that could be further explored with calibration, evaluation and sensitivity analysis in terms of the quantitative modelling and additional data collection for the qualitative research.

This research was made possible through a knowledge exchange/embedded research project. These methods of embedding and deep stakeholder engagement are time intensive but also build trust, which is essential for effective sharing and understanding of local knowledge (Pretorious et al., 2019, Lonsdale et al., 2024) and ultimately pave the way to a more holistic and transdisciplinary understanding of climate risk (McClure et al., 2023). Not all climate change impacts occur at the extremes: many occur under relatively moderate conditions in the communities and fields around us, and yet remain under-reported as those impacted have not had a chance to tell their story and be heard.

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CRediT authorship contribution statement

Alan T. Kennedy-Asser: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Oliver D. Andrews:** Writing – review & editing, Conceptualization. **Jill Montgomery:** Writing – review & editing, Methodology, Conceptualization. **Katie L. Jenkins:** Writing – review & editing, Data curation. **Ben A.H. Smith:** Data curation. **Elizabeth Lewis:** Data curation. **Stephen J. Birkinshaw:** Data curation. **Helen He:** Data curation. **Richard F. Pywell:** Data curation. **Matt J. Brown:** Data curation. **John W. Redhead:** Data curation. **Rachel Warren:** Writing – review & editing. **Craig Robson:** Software. **Adam J.P. Smith:** Writing – review & editing. **Robert J. Nicholls:** Writing – review & editing, Funding acquisition. **Donal Mullan:** Writing – review & editing. **Ryan McGuire:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2025.100702.

Data availability

All quantitative OpenCLIM modelling data is available through the DAFNI website (https://www.dafni.ac.uk). Further analysis code including the dairy milk yield calculation is available via GitHub (https://github.com/ATK-A/NI_CRM).

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