sustainability

MDPI

Article

Predicting Climate Change Impacts on Agriculture in the Southwest United Kingdom

James Andrew Jackson *, Rick Stafford, Marin Cvitanović and Elena Cantarello

Department of Life and Environmental Sciences, Bournemouth University, Poole BH12 5BB, UK; rstafford@bournemouth.ac.uk (R.S.); mcvitanovic@bournemouth.ac.uk (M.C.)
* Correspondence: jajackson@aub.ac.uk

Abstract: Climate change will create significant challenges to agriculture. The effects on livestock productivity and crop production are highly dependent on weather conditions with consequences for food security. If agriculture is to remain a viable industry and to maintain future food security, the adaptations and the ideal timeframes for their implementation to mitigate against climate change impacts will be essential knowledge. This study aims to show how farms will be affected and will need to adapt to climate change, based on a holistic examination of the entire farming process. A modified Bayesian belief network (BBN) was used to investigate climate change impacts on livestock, crops, soil, water use, disease, and pesticide use through the use of 48 indicators (comprising climate, agricultural, and environmental). The seasonal impact of climate change on all aspects of farming was investigated for three different climate forcing scenarios (RCPs 2.6, 4.5, and 8.5) for four timeframes (2030, 2050, 2080, and 2099). The results suggest that heat stress and disease in both livestock and crops will require adaptations (e.g., shelter infrastructure being built, new crops, or cultivators grown). Pest intensity is expected to rise, leading to increased pesticide use and greater damage to crops and livestock. Higher temperatures will likely cause increased drought and irrigation needs, while increasing rain intensity might lead to winter flooding. Soil quality maintenance will rely increasingly on fertilisers, with significant decreases in quality if unsustainable. Crop yield will be dependent on new crops or cultivators that can cope with a changing climate being successful and market access; failure to do so could lead to substantial decrease, in food security. Impacts are more significant from 2080 onwards, with the severity of impacts dependent on season.

Keywords: climate change; agriculture; food security; Bayesian belief network; adaptation

check for updates

Academic Editors: Piotr Prus, Henrietta Moore and Jacqueline McGlade

Received: 25 January 2025
Revised: 27 March 2025
Accepted: 18 April 2025
Published: 23 April 2025

Citation: Jackson, J.A.; Stafford, R.; Cvitanović, M.; Cantarello, E. Predicting Climate Change Impacts on Agriculture in the Southwest United Kingdom. *Sustainability* **2025**, *17*, 3798. https://doi.org/10.3390/su17093798

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) introduces five new scenarios that facilitate the investigation of alternative future outcomes of climate change and the prediction of its effects at a local level [1]. While climate change will create many challenges to agricultural production, requiring significant adaptations due to changing weather and seasons, the severity of these changes may depend on which scenario we most closely follow.

Challenges may include transitioning to climate resilient crops, addressing soil quality and compactness, flooding episodes, water shortages, and livestock health. These factors will drive changes in farming practices, with consequences for productivity, agricultural economic viability, and food security [1–7]. Agriculture provides food security and fibre generation but is also responsible for the maintenance of ecosystem services such as biodiversity, water quality, soil health, and carbon cycling, especially key for irrigation and crop growth [8–10]. Furthermore, ecosystem services enhance agriculture with pollination and natural pest control [11,12].

Although livestock and certain crops may benefit from a changing climate (e.g., time livestock spend outdoors) in the short term, they will also likely face negative impacts from increasing temperature and increasing rainfall patterns. Crops are sensitive to changing weather events (e.g., high temperatures decreasing crop growth) [13–15] and livestock can also be affected by heat stress [16–19].

Advancing the knowledge on how agriculture will be affected by climate change will be critical to understanding the adaptations required for its mitigation. One way to investigate agriculture and climate change impacts is to use indicators. Previous research has used indicators to assess agriculture and climate change, with indicators such as 'dry days' and 'growing season length' [20], 'grass frost' and 'very dry soil' [21], and 'start of field operations' and 'crop growth duration' [22]. Other research focuses on using indicators to assess specific crops such as wheat [23].

Indicators, in this context, are measurable representations of the farming process, which are either inputs to a system, independent variables (e.g., environmental indicators such as dry days), measurable outputs, or dependent variables (e.g., crop yields or soil quality). As such, the use of measurable indicators lends itself to quantitative studies. For example, models and statistical analysis are often used to assess different climate forcings against agricultural settings.

With multiple indicators, a complex systems approach can be taken, which can be semi-quantitatively modelled using a Bayesian belief network (BBN) due to its ability to integrate ecological, environmental, social, and economic concepts as well as different inputs and outputs to the system and to work with uncertain or incomplete data or knowledge of a system [24]. BBNs have been applied as evaluation tools to investigate climate change impacts or other environmental changes [25–29] and also for agricultural research [30–34].

This study investigates all the interactions within a farm, such as livestock, crops, water, soils, diversification, and field availability, and how they function as a system. This approach will highlight how different areas of a whole farm interact, work in synergy, or possibly impede the impacts of climate change or the adaptations to it. Jackson [35] developed complex system models of how sixty indicators may interact with each other in relation to climate change. This study aims to use a system modelling approach to predict how climate change will affect crops, livestock, and other farming processes. This will establish how the climate change events reported in the IPCC report will result in changes to agriculture in the southwest United Kingdom (UK). Furthermore, this study aims to address which specific practices will need to change and the adaptations to be made.

2. Methods

To assess how climate change impacts will affect agriculture, a mixed farm type was modelled (considers both crops and livestock) using a Bayesian belief network (using the R package BBNet, 36) running in R version 4.3.2 (R Core Team, 2023). The detail of the package, a theoretical framework of how the models work, and practical examples of how the models can be made, as well as specific equations used within the predictions, are described in full in a recent methods paper [36]. A Bayesian belief network (BBN) is a model of a complex system where nodes (these could be physical objects such as crop biomass, environmental parameters such as frost occurrence, or human factors such as health and safety legislation) are connected by directional edges to other nodes. While only direct interactions are modelled, changes can propagate through the system, and system-wide effects of changes or suites of changes can be modelled. The modified BBN used here [36] allows for simplified interactions between multiple nodes to be modelled, as well as feedback loops and reciprocal interactions between nodes.

Only direct interactions between nodes are modelled (for example, an increase in drought leads to a decrease in crop growth rate), but the model behaves as a complex system, so changes to nodes can propagate through the system and provide emergent properties of the network. For example, farm productivity can be calculated, but the final value is likely to depend on many factors, from environmental conditions through to fertiliser use.

We used 48 of the 60 indicators from Jackson [35] as nodes in the BBN (Table 1). The exclusion of 12 nodes was based on replication of outcome (e.g., the 'leaf wetness' indicator is covered by 'crop disease'), a lack of relevance to this study (e.g., day and night scenarios were not investigated, so 'night time air temperature' was redundant), or specific climate variables that did not fit the model use (e.g., 'sunshine' was covered by 'temperature'-type indicators). A more detailed explanation of why indicators were excluded is provided in the Supplementary Information.

Table 1. Indicator nodes used inclusive of the climate nodes modified in the BBN and a brief description.

Indicator	Brief Description	Indicator	Brief Description
Budbreak Date	The time when plant or crop buds unfold and leaves emerge	Livestock Numbers	The stock number of varied species
Conservation Area	Either a specific area set aside for biodiversity or forming part of farming fields	Mean Air Temperature	Average mean air temperature over a calendar month
Crop Disease	Crop pathogens that either kill or harm the crop	Organic Livestock Practices	Likelihood of organic practices in a changing climate
Crop Growth Rate	The ability of crops to grow	Pest Intensity	Pests impact crops and livestock and temperature plays a vital role in their survival
Crop Yield	The harvested production from a farm	Pesticide Use	Protects crops from pests and weeds, whilst also polluting
Drought	A lack of natural water	Pest Migration	New pests migrate due to changing climate
Farm Diversification	Deliberate economic productivity other than farming	Plant Heat Stress	Caused by elevated temperatures limiting crop growth
Farm Insurance	Insurance changing due to farm practices and climate change	Pollinator Abundance	Determines the level of natural pollination ecosystem service
Farm Management	A management decision to be made due to changes from climate change	Precipitation Rate	Main provider of water to agriculture
Fertiliser Use	Adding materials to improve soil quality but also causing potential pollution	Soil Quality	Fundamental component of crop production
Field Availability	Availability of fields due to climate changes, e.g., after flooding	Humidity	A key component of dew and thermal increase in crops influencing growth
Field Cover—New Crops	New crops or cultivators to be grown due to changing climate	Start of Growing Season	Earlier growing season means new crops can be grown but also more water demand and soil quality decline
Field Elevation/Slope	The efficiency of a sloped field after changing weather patterns	Streamflow	Linked to water quality
Fire	The impact of fire on farms, e.g., burnt crops, but also the risk due to climate change	Surface Run-Off	Precipitation that falls to land and flows downhill to soil or watercourses
Flooding	Water submerging land that is usually dry	Total Dairy Production	Total produce from dairy practices

Table 1. *Cont.*

Indicator	Brief Description	Indicator	Brief Description
Forest/Tree Cover	The ecosystem service benefits, e.g., biodiversity and water absorption	Total Meat Production	Total produce from meat production practices
Frost	Ground, air, and hoar frost affecting crop growth and pest survival	Total Productivity	Overall productivity of a farm
Health and Safety Workforce	Health and safety issues associated with a changing climate	Total Utilised Land	Total amount of land creating productivity either farming or alternative
Heatwave	An extended period of hot weather relative to normal	Water Demand	Water requirement to supplement rainfall
Insect Generation per Season	Pest generation as an impact of climate change	Water Quantity	Total water requirement both natural and utility
Irrigation	Non-rainfall watering of crops	Weed Infestation	The likelihood of abundance of weeds changing due to climate
Length of Growing Season	The thermal growing season and likelihood of change due to climate change	Winter Chill Units	Crop exposure to cool temperatures, key to bud development
Livestock Diseases	Zoonotic diseases causing harm or mortality to livestock	Carbon Footprint	Emissions generated during farm operations
Livestock Heat Stress	A decline in performance or mortality due to changing climate	Water Quality	Changes expected due to a changing climate

Following the protocol established in Dominguez Almela et al. [36], edges and edge strengths were established next. The only difference to the procedure referenced above is that edges were directly scored as probabilities rather than on an integer scale, with conversion to probabilities taking place within the BBNet package (strong positive interactions were scored at 0.85, moderate positive at 0.75, and weak positive at 0.65; strong negative interactions were scored at 0.15, moderate at 0.25, and weak at 0.35). These edges have largely been created and parameterised in Jackson [35], but the new connections were rechecked after the removal of some of the original nodes. The full model is available in the Supplementary Information.

The model is used to make predictions of what will happen to a typical farm in the southwest of England (spatial scale of a typical farm). The results indicate the severity of change from the present day (mid 2020s) to the time of the particular scenario. In this case, scenarios considered effects by 2030, 2050, 2080, and 2099, as per IPCC scenarios.

Determining Prior Values for Climatic Change

To obtain predictions from the BBN, 'prior' values need to be provided, which then propagate through the network to provide results. The 'priors' in this case are climate variables of mean temperature, precipitation, frost days, humidity, and heatwaves and are calculated from different Representative Concentration Pathways (RCPs) [37–39] for each season for the years 2030, 2050, 2080, and 2099 respectively. Details of how these were extracted are given in supplementary material, and their values as priors in the BBN model are provided in Table 2.

In addition, fertiliser use was set to 0.15 in all scenarios (as increasing fertiliser use is not a desirable farming practice due to its water contamination and long-term effects on soil health and yield [40]) to assess separately the effect on soil quality.

In running these scenarios, crop yield did not change greatly (see the results), as the model was set to allow new crops to take the place of old crops as conditions changed. In practice, it is likely there may be considerable resistance to changing crops grown. In addition to the scenarios above, the summer RCP 4.5 scenario for 2050 was examined (a mid-duration, mid-severity scenario), with the new crop prior set to 0, to investigate differences in crop yield if no new crops were incorporated.

Table 2. BBN scoring for RCPs 2.6, 4.5, and 8.5 for 2030, 2050, 2080, and 2099 for mean air temperature, precipitation, humidity, frost, and heatwave.

Year/ Season	Mean Air Temperature (RCPs 2.6/4.5/8.5)			Precipitation (RCPs 2.6/4.5/8.5)			Humidity (RCPs 2.6/4.5/8.5)			Frost (RCPs 2.6/4.5/8.5)			Heatwave (RCPs 2.6/4.5/8.5)		
2030															
Winter	0.555	0.555	0.560	0.635	0.625	0.645	0.580	0.565	0.580	0.310	0.310	0.300			
Spring	0.550	0.545	0.555	0.485	0.495	0.490	0.565	0.560	0.570						
Summer	0.600	0.575	0.590	0.360	0.395	0.380	0.575	0.565	0.575				0.925	0.935	0.935
Autumn	0.585	0.570	0.580	0.540	0.555	0.560	0.600	0.575	0.590						
2050															
Winter	0.570	0.585	0.610	0.640	0.645	0.690	0.605	0.605	0.645	0.300	0.290	0.280			
Spring	0.565	0.570	0.595	0.495	0.485	0.480	0.585	0.585	0.615						
Summer	0.625	0.620	0.665	0.305	0.325	0.280	0.590	0.590	0.625				0.935	0.940	0.950
Autumn	0.595	0.600	0.635	0.545	0.565	0.575	0.625	0.615	0.660						
2080															
Winter	0.575	0.625	0.700	0.660	0.750	0.885	0.620	0.680	0.790	0.290	0.265	0.165			
Spring	0.575	0.620	0.690	0.455	0.445	0.435	0.600	0.645	0.725						
Summer	0.635	0.715	0.840	0.295	0.230	0.120	0.590	0.645	0.740				0.940	0.955	0.980
Autumn	0.605	0.670	0.765	0.550	0.575	0.605	0.660	0.710	0.840						
2099															
Winter	0.580	0.660	0.775	0.665	0.810	1.00	0.625	0.760	0.925	0.290	0.215	0.000			
Spring	0.575	0.655	0.760	0.485	0.460	0.450	0.610	0.690	0.815						
Summer	0.660	0.810	1.000	0.250	0.150	0.000	0.610	0.705	0.850				0.940	0.965	1.000
Autumn	0.605	0.720	0.870	0.585	0.600	0.640	0.640	0.805	1.000						

3. Results

Figures 1–4 show the results for the 10 key findings for 2030, 2050, 2080, and 2099 for winter, spring, summer, and autumn, for RCPs 2.6, 4.5, and 8.5, and for soil quality, plant heat stress, pesticide use, pest intensity, livestock heat stress, livestock diseases, irrigation, flooding, drought, and crop yield.

The largest effects of climate change on farms mainly occurred in the summer months and increased with the climate scenario and with the year of prediction (Figures 1–4). However, more unexpected results were also found, with climate impacts becoming evident not just in the summer months. Livestock heat stress increased in autumn, winter, and spring in 2080 (Figure 3) and 2099 (Figure 4), whilst in summer it increased in all three scenarios from 2030 onwards (Figures 1–4). Livestock disease increases in autumn in 2050 (Figure 2), in winter during both 2080 and 2099 (Figures 3 and 4) and 2099 (Figure 4), whilst again in summer increases for all three scenarios occurred from 2030 to 2099 (Figures 1–4).

Pest intensity increases in 2080 and 2099 for both autumn and spring (Figures 3 and 4), and in winter it increases in 2050 and 2080 (Figures 2 and 3) and in 2099 (Figure 4) and in summer from 2030 to 2099 for all three scenarios (Figures 1–4).

Soil quality decreases in summer in all years (Figures 1–4). Soil quality remaining stable in other seasons is reliant on fertiliser use increasing and, where not possible (fertiliser use node set to 0.15), soil quality was likely to decrease (probability of average increase for winter, spring, and autumn = 0.41), with further fertiliser use reductions or more extreme scenarios likely to reduce it further.

Drought decreases in the autumn in 2080 (Figure 3) and 2099 (Figure 4), and in summer it increases from 2030 to 2099 for all three scenarios (Figures 1–4).

Flooding increases in the autumn in 2099 (Figure 4) and in the winter for all years and scenarios. Crop yield remains stable, although this is reliant on new crops or cultivators replacing existing crops that can no longer grow under new climate forcing conditions. If new crops or cultivators cannot be grown (field cover—new crops node set to 0 for RCP 4.5 for summer 2050) crop yield was likely to decrease (probability of increase = 0.23), with longer durations or more extreme scenarios likely to reduce this further.

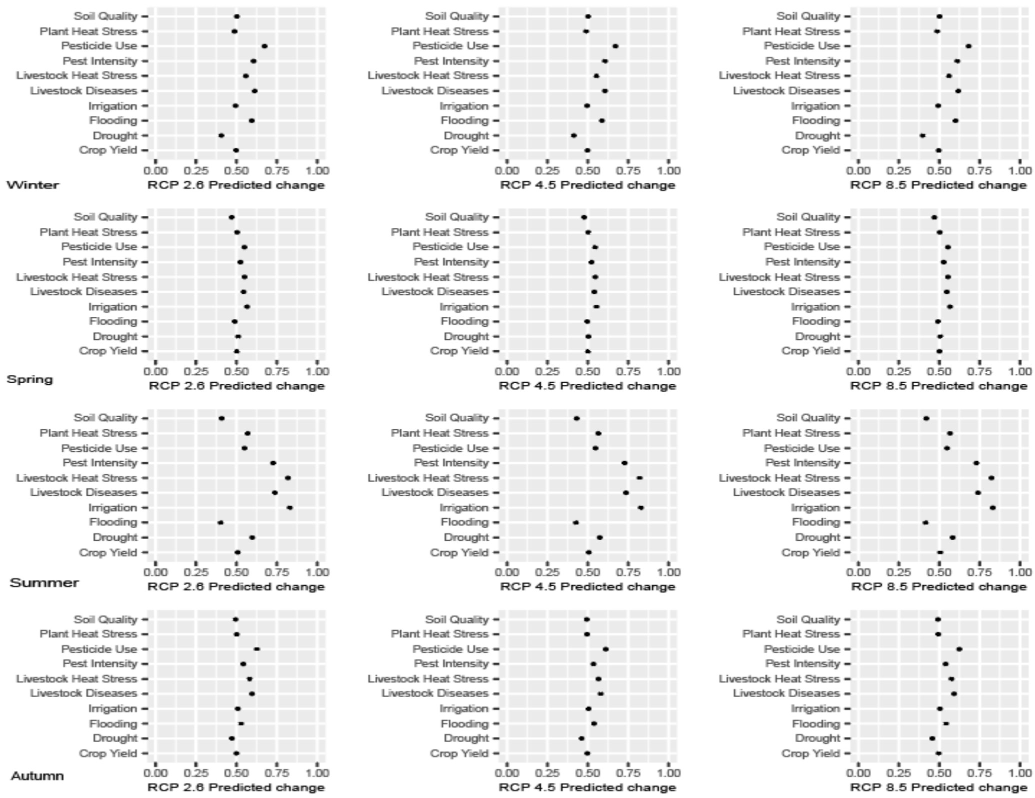

Figure 1. 2030 results for winter, spring, summer, and autumn for RCP 2.6, RCP 4.5, and RCP 8.5.

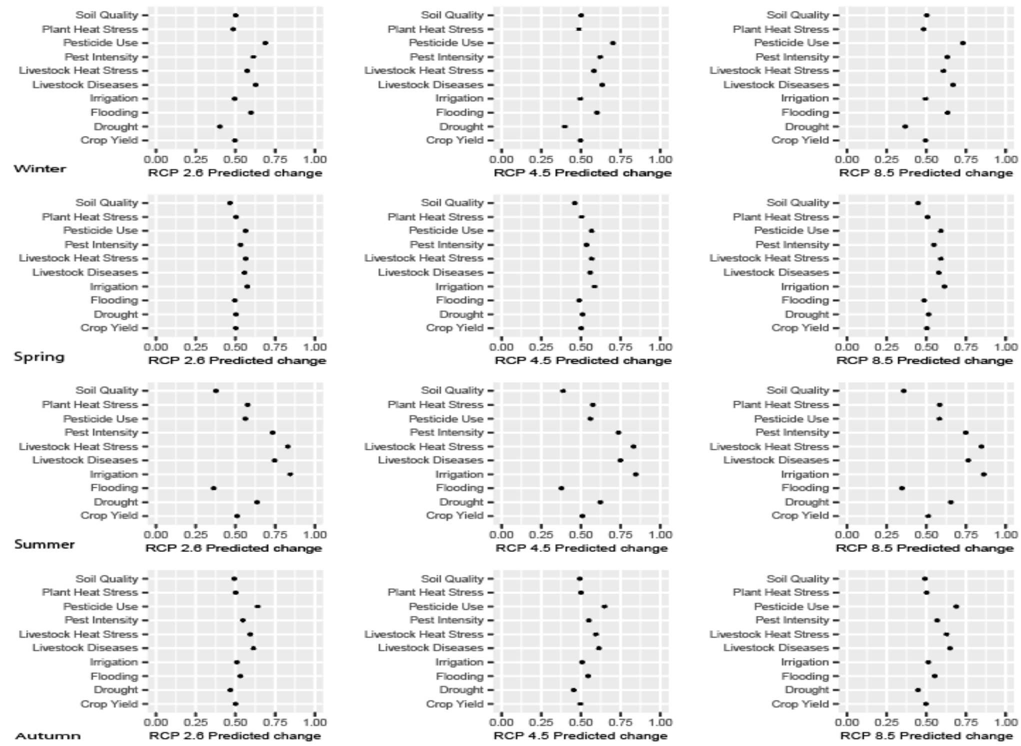

Figure 2. 2050 results for winter, spring, summer, and autumn for RCP 2.6, RCP 4.5, and RCP 8.5.

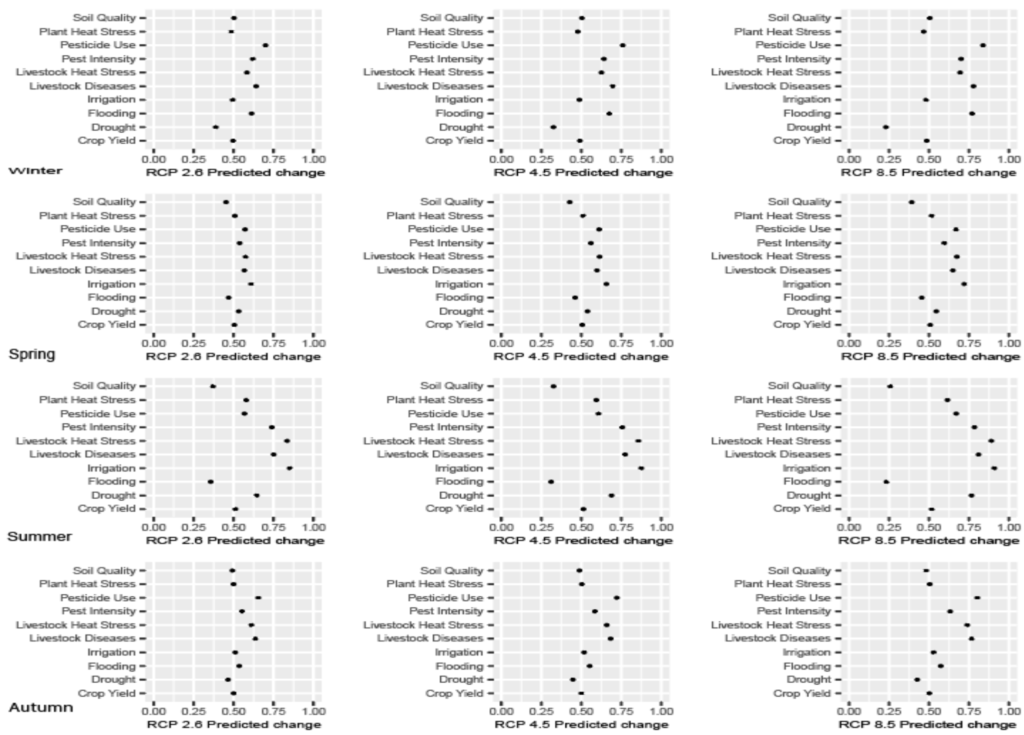

Figure 3. 2080 results for winter, spring, summer, and autumn for RCP 2.6, RCP 4.5, and RCP 8.5.

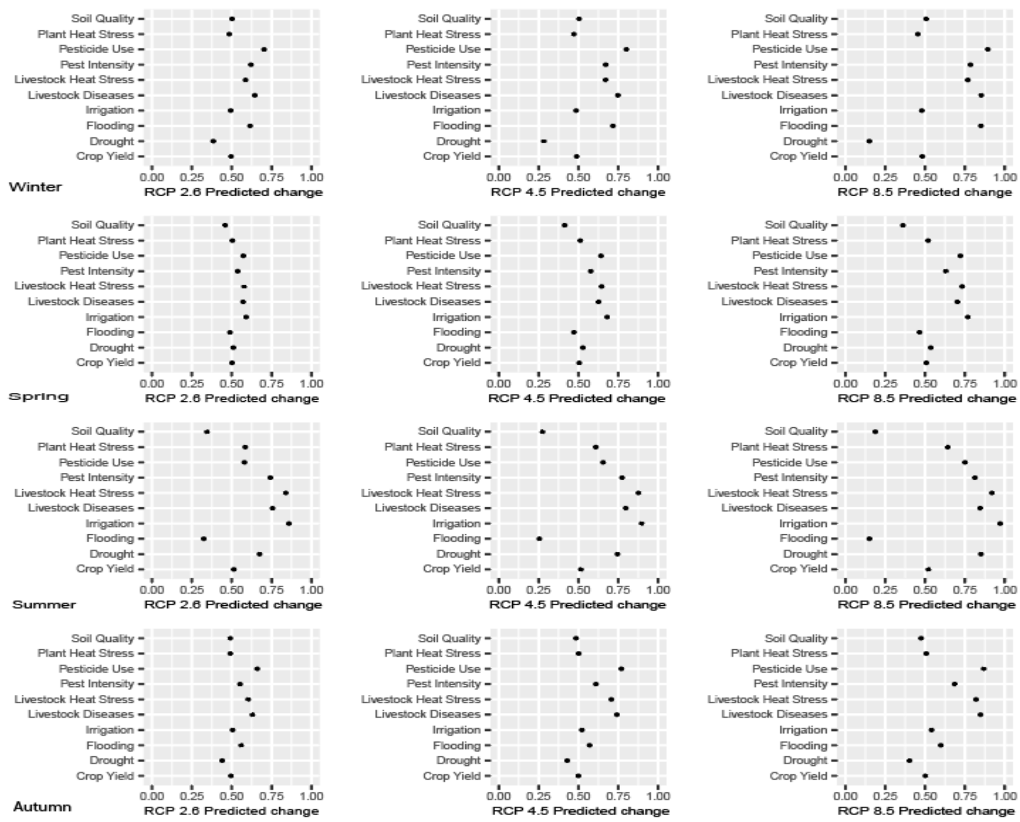

Figure 4. 2099 results for winter, spring, summer, and autumn for RCP 2.6, RCP 4.5, and RCP 8.5.

4. Discussion

Climate change is likely to cause significant impacts. Typical concerns with increased temperatures (and heatwaves) will occur, as will increases in both drought and flooding (seasonally dependent). While these changes are relatively well established [41–45], our model also predicts decreases in soil quality, increases in livestock disease, and in pests and pesticide use, which will increase as climate changes becomes more severe (i.e., greater severity, or longer duration). While livestock heat stress will increase with temperature, plant heat stress and crop yield are relatively unaffected by climate change. However, this assumes that crops grown will reflect new conditions and irrigation and water demand can be met. If this does not happen, large decreases in crop yield are predicted to occur.

4.1. Climate Change Effects on Livestock

Livestock disease has the most impact in the summer. Vector-borne diseases such as Bluetongue and Schmallenberg and parasites such as Helminth and Fasciola hepatica (liver fluke) reduce the productivity of an animal [46,47], and temperature and rainfall increases lower the number of leukocytes (white blood cells) in the immune system that defend against bacteria, viruses, fungi, and parasites [48]. This is then exploited by pathogens such as protozoa, helminths, and vector-borne, foodborne, soilborne, and other zoonotic diseases [49]. Yet increasing temperature could also decrease the prevalence of some diseases, especially in Southern England, such as *Lucilia sericata* ectoparasite (in ewes), although with the possibility they are replaced with other Mediterranean pathogenic agents such as *Wohlfahrtia* spp. [50].

Poultry will also be affected with a likely increase in avian flu [51]. Policy-led disease surveillance technology, such as genome sequencing, DNA fingerprinting, resistance testing, antiviral medications, and cross-breeding will be required to limit productivity loss [52,53].

Heat stress in livestock causes suffering and lowers welfare, reducing yield and fertility and possibly causing death [54]. Arnell and Freeman's [22] results for heat stress align with this study, although a concentration on milk yield effects only likely explains their lower severity. Thornton et al. [53] investigated heat stress differences between the year 2000 and 2090 (exposure days under SSP5-8.5) with cattle increasing from 8 to 69 (days), goats from 6 to 57, sheep from 11 to 77, pigs from 6 to 77, and poultry from 11 to 87. The hot and dry summer of 2018 contributed to 30,000 extra cows slaughtered in the UK [55], and evidence suggests that UK losses in milk yield will be valued at GBP 13.4 million (average) and GBP 33.8 million towards the end of the century [56,57].

Heat stress is caused by a combination of temperature, humidity, solar radiation, and wind speed, with the stress caused to the animal a combination of both indirect effects, e.g., lower feed intake, and direct effects on reproductive physiology, health, energy metabolism and on protein and fat deposition [58]. Animals differ in terms of how heat stress affects them and when production losses start to occur [58–63].

The resilience of each species also depends on the breed, age, genetics, physiological status, nutritional status, size, and level of insulation, e.g., hide thickness, heat evaporation rate, respiration rate, body temperature, previous exposure, standing time, time spent in the shade, and water ingestion [64–68]. Poultry are more suited to intensive production, and this increases heat stress impacts [69] and increases the challenge of maintaining productivity [70].

The results suggest an increase in livestock heat stress by 2030 for the summer months, and therefore it is likely that animals will need cooling by natural shading or by the construction of infrastructure. Higher productivity in hot climates is observed from housed dairy cows compared to non-housed during periods of heat stress [58,71–73].

The least costly option is to use natural vegetation such as trees and hedgerows, while new infrastructure is a further expensive option but a likely requirement in the summer season [74].

The results suggest further cooling will likely be required from 2080 to 2099, especially for RCPs 4.5 and 8.5. Air conditioning is currently energy-intensive and expensive [75], but evaporative cooling systems such as water nozzles, cooling pads, or fogging and misting systems can lower the ambient air in the building [58]. Cooling buildings has been successful in swine production [76,77], closed poultry [58] and pig houses [78], and improving cattle milk production in dairy cattle [79].

Increasing diet energy (for all animals) counters reduced eating by livestock during heat stress [80–82] and will need to be coordinated with antioxidant supplements [83], feed additives [84], pharmaceutical additives [85], and even herbal additives [86]. Changing feeding times and habitats to compensate for eating less during heat stress is affective for poultry and cattle [58].

Further changes to farm practices will help, such as changing livestock mating and sheep shearing season and selecting breeds that have more resilience to heat [54]. Breeds that have higher tolerance to heat tend to correlate with lower productivity [87], but identifying heat tolerant animals with high productivity is viable [64].

Access to drinking water is more critical than cooling systems, e.g., lactating sows given chilled water (10–15 °C) exhibited decreased temperature, improved performance during high temperatures, increased water consumption, increased milk production, decreased respiration rate, increased weaning weight, and increased average daily gain [88].

4.2. Climate Change Effects on Crops

Crop yield results in this study do not change significantly (either a decrease lower than 0.35 or increase higher than 0.65—see the results) for all seasons and scenarios. This is explained by some indicators decreasing crop yield, e.g., crop growth rate, but with others increasing, e.g., field cover—new crops, 'counterbalancing' each other and levelling the result. However, climate change is normally associated with a negative effect on yield [89]. Yet if the new crops indicator is nullified in the model (in the BBN), the results show a significant decrease in crop yield.

Drought lowers the crop growth rate, with temperature increases slowing growth rate [90], although this depends on its growth stage [91]. Water stress causes a decrease in leaf water potential, stomatal opening, and photosynthesis [92].

The increase in the start (and length) of the growing season is not always advantageous, with negligible effects on wheat yield compared with growth rate [93], and furthermore depends on the location and type of crop [94]. Arnell and Freeman [22] estimated, in higher climate forcing scenarios, that the growing season would begin between 30 and 50 days earlier by 2080 in Southern England. Harding et al. [20] predict 10- to 11-month growing seasons towards the end of the century, which matches the results here with length of the growing season increasing in probability for RCP 8.5 in 2080 and RCP 4.5 in 2099.

Increasing winter temperature supports the likelihood of pest survival, although activities on the farm itself also determine intensity [95]. Pesticide use will likely increase, with benefits for crop survival and negative impacts for biodiversity and pollution.

Crop disease will also affect crop yield, with fungal pathogen prevalence and effectiveness related to temperature variance, radiation, carbon dioxide levels, and stage of harvest [96–101]. Disease resistance crops are not quick-win solutions [102] and give time for plant pathogens to evolve and limit effectiveness [103].

Double cropping is an adaptation if water and light factors are not limiting, with multiple harvesting possible from the same field [104]. Furthermore, earlier sowing may allow crop maturity to be reached earlier, ensuring harvesting happens before peak summer temperatures [40,105]. Suitable growth conditions will allow new crops to be grown, and current crops such as potatoes will become problematic due to the rise in temperature and drought [106]. New crops are being introduced into crop rotation in Europe, although in cooler areas current crop portfolios are maintained with new cultivators [89].

Rainfall and run-off affect soil quality [107], especially soil organic carbon, aggregation, porosity, infiltration, leaching, and yield [108]. This contributes to decreasing soil quality alongside suboptimal field operations, livestock grazing, late harvesting crops, machinery weight, and agricultural intensification [109]. The results of Arnell and Freeman [22] and Rivington et al. [21] agree with this study in that soil quality (they used soil moisture) decreases in the summer season and continues into autumn even though rainfall increases, likely due to soil moisture deficits from the summer. Soil fertility for agriculture supplies essential nutrients for crop growth, supports a diverse biotic community, and supports soil structure, allowing for undisturbed decomposition [110].

To maintain soil quality and improve crop growth, fertiliser use is increased, improving the physical properties of the soil via reducing solidity, bulk density, water infiltration rate, acidity, and increasing porosity and aeration [111]. Yet it is impractical to keep increasing fertiliser and once a continuous increase is restricted; the results show soil quality significantly decreasing from 2030. Crop rotation, with crops that are biological fixers, can help lower the need for fertilisation, e.g., forage crops such as clover (*Trifolium* spp.), lucerne (*Medicago* spp.), and arable crops such as peas (*Pisum sativium*) and beans (*Vicia faba*) [112].

5. Conclusions

Pressures on food production from climate change will cause significant challenges to agriculture. The results from this study show that temperature, drought, and flooding increases will affect crops and livestock but also result in a decrease in soil quality and an increase in livestock diseases, pests, and pesticide use. Also, crop productivity is reliant on new crops or cultivators being grown, irrigation water demands being met, and market access.

This study demonstrates that there are adaptations that farms can make to mitigate against unwanted climate change outcomes. Key to these changes are measures to protect animals from direct heat stress, the ability to change crop cultivars as environmental conditions change, and awareness and better management measures to mitigate decreases to soil quality and increases in crop and livestock pests and diseases.

Adaptations to ensure food security will also need top-down support. Government mechanisms such as benefits for farmers (e.g., subsidies), connected and innovative policies (e.g., agricultural with drought, flooding, and climate policies), investment and reward provision for early adapters, focus on technology, efficiency of existing resources, and further research and development funding are required [113,114]. The results from this study can be used to inform the practices, measures, and adaptations required to direct policy to the key areas of support required for agriculture against climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17093798/s1, Table S1. Indicator nodes used inclusive of the climate nodes modified in the BBN. 'Physical' indicators are highlighted in orange, 'biological' in green, and 'human-driven' in blue. Table S2. The indicators from Jackson (35) that are excluded with justification. References [115–117] are cited in the supplementary materials or in main text.

Author Contributions: Conceptualization, J.A.J.; Methodology, J.A.J., R.S., M.C. and E.C.; Software, R.S.; Formal analysis, J.A.J. and R.S.; Investigation, J.A.J.; Data curation, J.A.J. and R.S.; Writing—original draft, J.A.J.; Writing—review & editing, J.A.J., R.S., M.C. and E.C.; Visualization, J.A.J. and R.S.; Supervision, R.S., M.C. and E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; pp. 3–32. [CrossRef]
2. Garry, F.K.; Bernie, D.J.; Davie, J.C.; Pope, E.C.D. Future climate risk to UK agriculture from compound events. *Clim. Risk Manag.* **2021**, *32*, 100282. [CrossRef]
3. Kiss, T.B.W.; Chen, X.; Ponting, J.; Sizmur, T.; Hodson, M.E. Dual stresses of flooding and agricultural land use reduce earthworm populations more than the individual stressors. *Sci. Total Environ.* **2021**, *754*, 142102. [CrossRef] [PubMed]
4. Seppelt, R.; Klotz, S.; Peiter, E.; Volk, M. Agriculture and food security under a changing climate: An underestimated challenge. *iScience* **2022**, *25*, 105551. [CrossRef]
5. Benitez-Alfonso, Y.; Soanes, B.K.; Zimba, S.; Sinanaj, B.; German, L.; Sharma, V.; Bohra, A.; Kolesnokova, A.; Dunn, J.A.; Martin, A.C.; et al. Enhancing climate change resilience in agricultural crops. *Curr. Biol.* **2020**, *33*, 1246–1261. [CrossRef] [PubMed]
6. Khalfaoui, R.; Goodell, J.W.; Mefteh-Wali, S.; Chishti, M.Z.; Gozgor, G. Impact of climate risk shocks on global food and agricultural markets: A multiscale and tail connectedness analysis. *Int. Rev. Financ. Anal.* **2024**, *93*, 103206. [CrossRef]
7. Wen, Y.; Fei, Y.; Fan, Y.; Yang, A.; Wang, B.; Gao, P.; Scott, D. Development of a probabilistic agricultural drought forecasting (PADF) framework under climate change. *Agric. For. Meteorol.* **2024**, *350*, 109965. [CrossRef]
8. Hardaker, A.; Pagella, T.; Rayment, M. Ecosystem service and dis-service impacts tree cover on agricultural land by land-sparing and land-sharing in the Welsh uplands. *Ecosyst. Serv.* **2021**, *48*, 101253. [CrossRef]
9. Felix, L.; Houet, T.; Verburg, P.H. Mapping biodiversity and ecosystem service trade-offs and synergies of agricultural change trajectories in Europe. *Environ. Sci. Policy* **2022**, *136*, 387–399. [CrossRef]
10. Villa-Cox, G.; Bucaram-Villacís, S.J.; Goethals, P.; Speelman, S. Mapping linkages between ecosystem services and agricultural and landscape management using structural topic modelling of scientific literature. *Ecosyst. Serv.* **2023**, *61*, 101525. [CrossRef]
11. Kratschmer, S.; Hauer, J.; Zaller, J.G.; Dürr, A.; Weninger, T. Hedgerow structural diversity is key to promoting biodiversity and ecosystem services: A systematic review of Central European studies. *Basic Appl. Ecol.* **2024**, *78*, 28–38. [CrossRef]
12. Thomasz, E.O.; Kasanzew, A.; Massot, J.M.; García-García, A. Valuing ecosystem services in agriculture production in southwest Spain. *Ecosyst. Serv.* **2024**, *68*, 101636. [CrossRef]
13. Deryng, D.; Conway, D.; Ramankutty, N.; Price, J.; Warren, R. Global crop yield response to extreme heat stress under multiple climate change futures. *Environ. Res. Lett.* **2014**, *9*, 034011. [CrossRef]
14. Trnka, M.; Rotter, R.P.; Ruiz-Ramos, M.; Kersebaum, K.C.; Olesen, J.E.; Žalud, Z.; Semenov, M.A. Adverse weather conditions for European wheat production will become more frequent with climate change. *Nat. Clim. Change* **2014**, *4*, 637–643. [CrossRef]
15. Powell, J.P.; Reinhard, S. Measuring the effects of extreme weather events on yields. *Weather Clim. Extrem.* **2015**, *12*, 69–79. [CrossRef]
16. Herrero, M.; Wirsenius, S.; Henderson, B.; Rigolot, C.; Thornton, P.; Havlík, P.; De Boer, I.; Gerber, P. Livestock and the environment: What have we learned in the past Decade? *Annu. Rev. Environ. Resour.* **2015**, *40*, 177–202. [CrossRef]
17. Hristov, A.N.; Degaetano, A.T.; Rotz, C.A.; Hoberg, E.; Skinner, R.H.; Felix, T.; Li, H.; Patterson, P.H.; Roth, G.; Hall, M.; et al. Climate change effects on livestock in the Northeast US and strategies for adaptation. *Clim. Change* **2018**, *146*, 33–45. [CrossRef]
18. Sloat, L.L.; Gerber, J.S.; Samberg, L.H.; Smith, W.K.; Herrero, M.; Ferreira, L.G.; Godde, C.M.; West, P.C. Increasing importance of precipitation variability on global livestock grazing lands. *Nat. Clim. Change* **2018**, *8*, 214–218. [CrossRef]
19. Hempel, S.; Menz, C.; Pinto, S.; Galán, E.; Janke, D.; Estellés, F.; Müschner-Siemens, T.; Wang, X.; Heinicke, J.; Zhang, G.; et al. Heat stress risk in european dairy cattle husbandry under different climate change scenarios-uncertainties and potential impacts. *Earth Syst. Dyn.* **2019**, *10*, 859–884. [CrossRef]
20. Harding, A.E.; Rivington, M.; Mineter, M.J.; Tett, S.F.B. Agro-meteorological indices and climate model uncertainty over the UK. *Clim. Change* **2015**, *128*, 113–126. [CrossRef]
21. Rivington, M.; Matthews, K.B.; Buchan, K.; Miller, D.G.; Bellocchi, G.; Russell, G. Climate change impacts and adaptation scope for agriculture indicated by agro-meteorological metrics. *Agric. Syst.* **2013**, *114*, 15–31. [CrossRef]
22. Arnell, N.W.; Freeman, A. The effect of climate change on agro-climatic indicators in the UK. *Clim. Change* **2021**, *165*, 40. [CrossRef]
23. Harkness, C.; Semenov, M.A.; Areal, F.; Senapati, N.; Trnka, M.; Balek, J.; Bishop, J. Adverse weather conditions for UK wheat production under climate change. *Agric. For. Meteorol.* **2020**, *282–283*, 107862. [CrossRef] [PubMed]

24. Dominguez Almela, V.; Croker, A.R.; Stafford, R. Creating simple predictive models in ecology, conservation and environmental policy based on Bayesian belief networks. *PLoS ONE* **2024**, *19*, e0305882. [CrossRef]
25. Franco, C.; Hepburn, L.A.; Smith, D.J.; Nimrod, S.; Tucker, A. A Bayesian Belief Network to assess rate of changes in coral reef ecosystems. *Environ. Model. Softw.* **2016**, *80*, 132–142. [CrossRef]
26. Moe, J.; Jackson-Blake, L.; Haande, S.; Solheim, A.L. Linking climate and land-use scenarios to ecological status of lakes: A Bayesian network approach. *Geophys. Res. Abstr.* **2019**, *21*, 17247.
27. Rankinen, K.; Holmberg, M.; Aroviita, J. Climate change, land use change and ecological status of Finnish rivers: A Bayesian network approach. *Geophys. Res. Abstr.* **2019**, *21*, 13785.
28. Sperotto, A.; Molina, J.L.; Torresan, S.; Critto, A.; Pulido-Velazquez, M.; Marcomini, A. Water Quality Sustainability Evaluation under Uncertainty: A Multi-Scenario Analysis Based on Bayesian Networks. *Sustainability* **2019**, *11*, 4764. [CrossRef]
29. Chanapathi, T.; Thatikonda, S. Evaluation of sustainability of river Krishna under present and future climate scenarios. *Sci. Total Environ.* **2020**, *738*, 140322. [CrossRef]
30. Mihunov, V.V.; Lam, N.S.N. Modeling the dynamics of drought resilience in South-Central United States using a Bayesian Network. *Appl. Geogr.* **2020**, *120*, 102224. [CrossRef]
31. Kaghazchi, A.; Hashemy Shahdany, S.M.; Roozbahani, A. Simulation and evaluation of agricultural water distribution and delivery systems with a Hybrid Bayesian network model. *Agric. Water Manag.* **2021**, *245*, 106578. [CrossRef]
32. Tao, J.; Wang, Y.; Qiu, B.; Wu, W. Exploring cropping intensity dynamics by integrating crop phenology information using Bayesian networks. *Comput. Electron. Agric.* **2022**, *193*, 106667. [CrossRef]
33. Mahmood, S.A.; Karampoiki, M.; Hammond, J.P.; Paraforos, D.S.; Murdoch, A.J.; Todman, L. Embedding expert opinion in a Bayesian network model to predict wheat yield from spring-summer weather. *Smart Agric. Technol.* **2023**, *4*, 100224.
34. Martinez-Megias, C.; Mentzel, S.; Fuentes-Edfuf, Y.; Moe, S.J.; Rico, A. Influence of climate change and pesticide use practices on the ecological risks of pesticides in a protected Mediterranean wetland: A Bayesian network approach. *Sci. Total Environ.* **2023**, *878*, 163018. [CrossRef]
35. Jackson, J.A. Climate Change Impacts on Agriculture and Adaptations: A Focus on Dorset. Ph.D. Thesis, Bournemouth University, Poole, UK, 2024.
36. Dominguez Almela, V.; Stafford, R. BBNet: Simple Predictive Models on Bayesian Belief Networks. 2024. Available online: https://eprints.soton.ac.uk/490390/ (accessed on 20 July 2024).
37. Thomson, A.M.; Calvin, K.V.; Smith, S.J.; Kyle, G.P.; Volke, A.; Patel, P.; Delgado-Arias, S.; Bond-Lamberty, B.; Wise, M.A.; Clarke, L.E.; et al. RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Clim. Change* **2011**, *109*, 77–94.
38. van Vuuren, D.P.; Stehfest, E.; den Elzen, M.G.J.; Kram, T.; van Vliet, J.; Deetman, S.; Isaac, M.; Klein Goldewijk, K.; Hof, A.; Mendoza Beltran, A.; et al. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2 °C. *Clim. Change* **2011**, *109*, 95–116. [CrossRef]
39. Schwalm, C.R.; Glendon, S.; Duffy, P.B. RCP8.5 tracks cumulative CO(2) emissions. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 19656–19657.
40. Cho, K.; Falloon, P.; Gornall, J.; Betts, R.; Clark, R. Winter wheat yields in the UK: Uncertainties in climate and management impacts. *Clim. Res.* **2012**, *54*, 49–68. [CrossRef]
41. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M.T.; Yao, Y.T.; Bassu, S.; Ciais, P.; et al. Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9326–9331. [PubMed]
42. Orimoloye, I.R. Agricultural Drought and Its Potential Impacts: Enabling Decision-Support for Food Security in Vulnerable Regions. *Front. Sustain. Food Syst.* **2022**, *6*, 838824.
43. Davie, J.C.S.; Falloon, P.D.; Pain, D.L.A.; Sharp, T.J.; Housden, M.; Warne, T.C.; Loosley, T.; Grant, E.; Swan, J.; Spincer, J.D.G.; et al. 2022 UK heatwave impacts on agrifood: Implications for a climate-resilient food system. *Front. Environ. Sci.* **2023**, *11*, 1282284. [CrossRef]
44. Kim, K.; Iizumi, T.; Hosokawa, N.; Tanoue, M.; Hirabayashi, Y. Flood impacts on global crop production: Advances and limitations. *Environ. Res. Lett.* **2023**, *18*, 054007. [CrossRef]
45. Savari, M.; Eskandari Damaneh, H.; Eskandari Damaneh, H. Managing the effects of drought through the use of risk reduction strategy in the agricultural sector of Iran. *Clim. Risk Manag.* **2024**, *45*, 100619. [CrossRef]
46. Fox, N.J.; White, P.C.; McClean, C.J.; Marion, G.; Evans, A.; Hutchings, M.R. Predicting impacts of climate change on Fasciola hepatica risk. *PLoS ONE* **2011**, *6*, e16126. [CrossRef] [PubMed]
47. Skuce, P.J.; Morgan, E.R.; van Dijk, J.; Mitchell, M. Animal health aspects of adaptation to climate change: Beating the heat and parasites in a warming Europe. *Animal* **2013**, *7*, 333–345. [CrossRef] [PubMed]
48. Bagath, M.; Krishnan, G.; Devaraj, C.; Rashamol, V.P.; Pragna, P.; Lees, A.M.; Sejian, V. The impact of heat stress on the immune system in dairy cattle: A review. *Res. Vet. Sci.* **2019**, *126*, 94–102. [CrossRef]
49. McIntyre, K.M.; Setzkorn, C.; Hepworth, P.J.; Morand, S.; Morse, A.P.; Baylis, M. Systematic Assessment of the Climate Sensitivity of Important Human and Domestic Animals Pathogens in Europe. *Sci. Rep.* **2017**, *7*, 7134. [CrossRef]

50. Wall, R.; Rose, H.; Ellse, L.; Morgan, E. Livestock ectoparasites: Integrated management in a changing climate. *Vet. Parasitol.* **2011**, *180*, 82–89. [CrossRef]
51. Seekings, A.H.; Slomka, M.J.; Russell, C.; Howard, W.A.; Choudhury, B.; Nunez, A.; Londt, B.Z.; Cox, W.; Ceeraz, V.; Thoren, P.; et al. Direct evidence of H7N7 avian influenza virus mutation from low to high virulence on a single poultry premises during an outbreak in free range chickens in the UK, 2008. *Infect. Genet. Evol.* **2018**, *64*, 13–31. [CrossRef]
52. Perry, B.; Sones, K. *Global Livestock Disease Dynamics over the Last Quarter Century: Drivers, Impacts and Implications*; FAO: Rome, Italy, 2009.
53. Thornton, P.; Nelson, G.; Mayberry, D.; Herrero, M. Increases in extreme heat stress in domesticated livestock species during the twenty-first century. *Glob. Change Biol.* **2021**, *27*, 5762–5772. [CrossRef]
54. Wreford, A.; Topp, C.F.E. Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. *Agric. Syst.* **2020**, *178*, 102737. [CrossRef]
55. Wheeler, R.; Lobley, M. Managing extreme weather and climate change in UK agriculture: Impacts, attitudes and action among farmers and stakeholders. *Clim. Risk Manag.* **2021**, *32*, 100313. [CrossRef]
56. Dunn, R.J.H.; Mead, N.E.; Willett, K.M.; Parker, D.E. Analysis of heat stress in UK dairy cattle and impact on milk yields. *Environ. Res. Lett.* **2014**, *9*, 064006. [CrossRef]
57. Fodor, N.; Foskolos, A.; Topp, C.F.E.; Moorby, J.M.; Pasztor, L.; Foyer, C.H. Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom. *PLoS ONE* **2018**, *13*, e0197076. [CrossRef] [PubMed]
58. Renaudeau, D.; Collin, A.; Yahav, S.; de Basilio, V.; Gourdine, J.L.; Collier, R.J. Adaptation to hot climate and strategies to alleviate heat stress in livestock production. *Animal* **2012**, *6*, 707–728. [CrossRef]
59. Tesseraud, S.; Temim, S. Modifications metaboliques chez le poulet de chair en climat chaud: Consequences nutritionnelles. *INRA Prod. Anim.* **1999**, *12*, 353–363. [CrossRef]
60. Finocchiaro, R.; van Kaam, J.B.C.H.; Portolano, B.; Misztal, I. Effect of heat stress on production of Mediterranean dairy sheep. *J. Dairy Sci.* **2005**, *88*, 1855–1864. [CrossRef]
61. Mauger, G.; Bauman, Y.; Nennich, T.; Salathé, E. Impacts of Climate Change on Milk Production in the United States. *Prof. Geogr.* **2014**, *67*, 121–131. [CrossRef]
62. Koluman Darcan, N.; Silanikove, N. The advantages of goats for future adaptation to Climate Change: A conceptual overview. *Small Rumin. Res.* **2018**, *163*, 34–38. [CrossRef]
63. Sejian, V.; Silpa, M.V.; Reshma Nair, M.R.; Devaraj, C.; Krishnan, G.; Bagath, M.; Chauhan, S.S.; Suganthi, R.U.; Fonseca, V.F.C.; Konig, S.; et al. Heat Stress and Goat Welfare: Adaptation and Production Considerations. *Animals* **2021**, *11*, 1021. [CrossRef]
64. Gaughan, J.B.; Holt, S.M.; Hahn, G.L.; Mader, T.L.; Eigenberg, R. Respiration Rate—Is It Good Measure of Heat Stress in Cattle? *Asian-Aus. J. Anim. Sci.* **2000**, *13*, 329–332.
65. Mader, T.L.; Gaughan, J.B.; Johnson, L.J.; Hahn, G.L. Tympanic temperature in confined beef cattle exposed to excessive heat load. *Int. J. Biometeorol.* **2010**, *54*, 629–635. [CrossRef] [PubMed]
66. Rashamol, V.P.; Sejian, V.; Pragna, P.; Lees, A.M.; Bagath, M.; Krishnan, G.; Gaughan, J.B. Prediction models, assessment methodologies and biotechnological tools to quantify heat stress response in ruminant livestock. *Int. J. Biometeorol.* **2019**, *63*, 1265–1281. [CrossRef] [PubMed]
67. Saeed, M.; Abbas, G.; Alagawany, M.; Kamboh, A.A.; Abd El-Hack, M.E.; Khafaga, A.F.; Chao, S. Heat stress management in poultry farms: A comprehensive overview. *J. Therm. Biol.* **2019**, *84*, 414–425. [CrossRef]
68. Godde, C.M.; Mason-D'Croz, D.; Mayberry, D.E.; Thornton, P.K.; Herrero, M. Impacts of climate change on the livestock food supply chain; a review of the evidence. *Glob. Food Sec.* **2021**, *28*, 100488. [CrossRef] [PubMed]
69. Robinson, T.; Thornton, P.; Franceschini, G.; Kruska, R.; Chiozza, F.; Notenbaert, A.; Cecchi, G.; Herrero, M.; Epprecht, M.; Fritz, S. *Global Livestock Production Systems*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy; International Livestock Research Institute (ILRI): Nairobi, Kenya, 2011.
70. Carvajal, M.A.; Alaniz, A.J.; Gutierrez-Gomez, C.; Vergara, P.M.; Sejian, V.; Bozinovic, F. Increasing importance of heat stress for cattle farming under future global climate scenarios. *Sci. Total Environ.* **2021**, *801*, 149661. [CrossRef]
71. Bubsy, D.; Loy, D. Heat stress in feedlot cattle: Producer survey results. *Iowa State Univ. Anim. Ind. Rep.* **1996**, 108–110. Available online: https://www.iastatedigitalpress.com/air/article/id/7271/ (accessed on 17 April 2025).
72. Brown-Brandl, T.M.; Eigenberg, R.A.; Nienaber, J.A.; Hahn, G.L. Dynamic Response Indicators of Heat Stress in Shaded and Non-shaded Feedlot Cattle, Part 1: Analyses of Indicators. *Biosyst. Eng.* **2005**, *90*, 451–462. [CrossRef]
73. Hill, D.L.; Wall, E. Dairy cattle in a temperate climate: The effects of weather on milk yield and composition depend on management. *Animal* **2015**, *9*, 138–149. [CrossRef]
74. Khongdee, S.; Sripoon, S.; Chousawai, S.; Hinch, G.; Chaiyabutr, N.; Markvichitr, K.; Vajrabukka, C. The effect of modified roofing on the milk yield and reproductive performance of heat-stressed dairy cows under hot-humid conditions. *Anim. Sci. J.* **2010**, *81*, 606–611. [CrossRef]

75. West, J.W. Effects of heat-stress on production in dairy cattle. *J. Dairy Sci.* **2003**, *86*, 2131–2144. [CrossRef]
76. Nichols, D.A.; Ames, D.R.; Hines, R.H. Evaporative cooling systems for swine. *Kans. Agric. Exp. Stn. Res. Rep.* **1979**, 6–9. [CrossRef]
77. Haeussermann, A.; Hartung, E.; Jungbluth, T.; Vranken, E.; Aerts, J.M.; Berckmans, D. Cooling effects and evaporation characteristics of fogging systems in an experimental piggery. *Biosyst. Eng.* **2007**, *97*, 395–405. [CrossRef]
78. Panagakis, P.; Chronopoulou, E. Preliminary Evaluation of the Apparent Short-term Heat Stress of Dairy Ewes Reared under Hot Summer Conditions. *Appl. Eng. Agric.* **2010**, *26*, 1035–1042. [CrossRef]
79. Ryan, D.P.; Boland, M.P.; Kopel, E.; Armstrong, D.; Munyakazi, L.; Godke, R.A.; Ingraham, R.H. Evaluating two different evaporative cooling management systems for dairy cows in a hot, dry climate. *J. Dairy Sci.* **1992**, *75*, 1052–1059. [CrossRef]
80. Wang, J.P.; Bu, D.P.; Wang, J.Q.; Huo, X.K.; Guo, T.J.; Wei, H.Y.; Zhou, L.Y.; Rastani, R.R.; Baumgard, L.H.; Li, F.D. Effect of saturated fatty acid supplementation on production and metabolism indices in heat-stressed mid-lactation dairy cows. *J. Dairy Sci.* **2010**, *93*, 4121–4127. [CrossRef] [PubMed]
81. Ghasemi, H.A.; Ghasemi, R.; Torki, M. Periodic usage of low-protein methionine-fortified diets in broiler chickens under high ambient temperature conditions: Effects on performance, slaughter traits, leukocyte profiles and antibody response. *Int. J. Biometeorol.* **2014**, *58*, 1405–1414. [CrossRef] [PubMed]
82. Wang, X.; Peebles, E.D.; Zhai, W. Effects of protein source and nutrient density in the diets of male broilers from 8 to 21 days of age on their subsequent growth, blood constituents, and carcass compositions. *Poult. Sci.* **2014**, *93*, 1463–1474. [CrossRef]
83. Chauhan, S.S.; Celi, P.; Leury, B.J.; Clarke, I.J.; Dunshea, F.R. Dietary antioxidants at supranutritional doses improve oxidative status and reduce the negative effects of heat stress in sheep. *J. Anim. Sci.* **2014**, *92*, 3364–3374. [CrossRef]
84. Zimbelman, R.B.; Collier, R.J.; Bilby, T.R. Effects of utilizing rumen protected niacin on core body temperature as well as milk production and composition in lactating dairy cows during heat stress. *Anim. Feed. Sci. Technol.* **2013**, *180*, 26–33. [CrossRef]
85. Liu, D.-Y.; He, S.-J.; Jin, E.-H.; Liu, S.-Q.; Tang, Y.-G.; Li, S.-H.; Zhong, L.-T. Effect of daidzein on production performance and serum antioxidative function in late lactation cows under heat stress. *Livest. Sci.* **2013**, *152*, 16–20. [CrossRef]
86. Pan, L.; Bu, D.P.; Wang, J.Q.; Cheng, J.B.; Sun, X.Z.; Zhou, L.Y.; Qin, J.J.; Zhang, X.K.; Yuan, Y.M. Effects of Radix Bupleuri extract supplementation on lactation performance and rumen fermentation in heat-stressed lactating Holstein cows. *Anim. Feed. Sci. Technol.* **2014**, *187*, 1–8. [CrossRef]
87. Hoffmann, I. Climate change and the characterization, breeding and conservation of animal genetic resources. *Anim. Genet.* **2010**, *41*, 32–46. [CrossRef] [PubMed]
88. Jeon, J.H.; Yeon, S.C.; Choi, Y.H.; Min, W.; Kim, S.; Kim, P.J.; Chang, H.H. Effects of chilled drinking water on the performance of lactating sows and their litters during high ambient temperatures under farm conditions. *Livest. Sci.* **2006**, *105*, 86–93. [CrossRef]
89. Olesen, J.E.; Trnka, M.; Kersebaum, K.C.; Skjelvåg, A.O.; Seguin, B.; Peltonen-Sainio, P.; Rossi, F.; Kozyra, J.; Micale, F. Impacts and adaptation of European crop production systems to climate change. *Eur. J. Agron.* **2011**, *34*, 96–112. [CrossRef]
90. Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurralde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D. Climate Impacts on Agriculture: Implications for Crop Production. *Agron. J.* **2011**, *103*, 351–370. [CrossRef]
91. Hatfield, J.L.; Prueger, J.H. Temperature extremes: Effect on plant growth and development. *Weather. Clim. Extrem.* **2015**, *10*, 4–10. [CrossRef]
92. Osakabe, Y.; Osakabe, K.; Shinozaki, K.; Tran, L.S. Response of plants to water stress. *Front. Plant Sci.* **2014**, *5*, 86. [CrossRef]
93. Slafer, G.A.; Savin, R.; Sadras, V.O. Wheat yield is not causally related to the duration of the growing season. *Eur. J. Agron.* **2023**, *148*, 126885. [CrossRef]
94. Porter, J.R.; Xie, L.; Challinor, A.J.; Cochrane, K.; Howden, S.M.; Iqbal, M.M.; Lobell, D.B.; Travasso, M.I. Food security and food production systems. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; pp. 485–533.
95. Emery, S.E.; Jonsson, M.; Silva, H.; Ribeiro, A.; Mills, N.J. High agricultural intensity at the landscape scale benefits pests, but low intensity practices at the local scale can mitigate these effects. *Agric. Ecosyst. Environ.* **2021**, *306*, 107199. [CrossRef]
96. Bebber, D.P.; Ramotowski, M.A.T.; Gurr, S.J. Crop pests and pathogens move polewards in a warming world. *Nat. Clim. Change* **2013**, *3*, 985–988. [CrossRef]
97. Sadyś, M.; Kennedy, R.; West, J.S. Potential impact of climate change on fungal distributions: Analysis of 2 years of contrasting weather in the UK. *Aerobiologia* **2015**, *32*, 127–137. [CrossRef]
98. Cavicchioli, R.; Ripple, W.J.; Timmis, K.N.; Azam, F.; Bakken, L.R.; Baylis, M.; Behrenfeld, M.J.; Boetius, A.; Boyd, P.W.; Classen, A.T.; et al. Scientists' warning to humanity: Microorganisms and climate change. *Nat. Rev. Microbiol.* **2019**, *17*, 569–586. [CrossRef] [PubMed]
99. Magyar, D.; Tischner, Z.; Páldy, A.; Kocsubé, S.; Dancsházy, Z.; Halász, Á.; Kredics, L. Impact of global megatrends on the spread of microscopic fungi in the Pannonian Biogeographical Region. *Fungal Biol. Rev.* **2021**, *37*, 71–88. [CrossRef]

100. Hanson, M.C.; Petch, G.M.; Ottosen, T.B.; Skjoth, C.A. Climate change impact on fungi in the atmospheric microbiome. *Sci. Total Environ.* **2022**, *830*, 154491. [CrossRef] [PubMed]
101. Raza, M.M.; Bebber, D.P. Climate change and plant pathogens. *Curr. Opin. Microbiol.* **2022**, *70*, 102233. [CrossRef]
102. Newbery, F.; Qi, A.; Fitt, B.D. Modelling impacts of climate change on arable crop diseases: Progress, challenges and applications. *Curr. Opin. Plant Biol.* **2016**, *32*, 101–109. [CrossRef]
103. Yang, L.N.; Ren, M.; Zhan, J. Modeling plant diseases under climate change: Evolutionary perspectives. *Trends Plant Sci.* **2023**, *28*, 519–526. [CrossRef]
104. Mueller, B.; Hauser, M.; Iles, C.; Rimi, R.H.; Zwiers, F.W.; Wan, H. Lengthening of the growing season in wheat and maize producing regions. *Weather. Clim. Extrem.* **2015**, *9*, 47–56. [CrossRef]
105. Liu, Z.; Hubbard, K.G.; Lin, X.; Yang, X. Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. *Glob. Change Biol.* **2013**, *19*, 3481–3492. [CrossRef]
106. Daccache, A.; Keay, C.; Jones, R.J.A.; Weatherhead, E.K.; Stalham, M.A.; Knox, J.W. Climate change and land suitability for potato production in England and Wales: Impacts and adaptation. *J. Agric. Sci.* **2011**, *150*, 161–177. [CrossRef]
107. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; de Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; et al. Soil quality—A critical review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [CrossRef]
108. Du, X.; Jian, J.; Du, C.; Stewart, R.D. Conservation management decreases surface runoff and soil erosion. *Int. Soil Water Conserv. Res.* **2022**, *10*, 188–196. [CrossRef]
109. Peake, L.R.; Dawson, L.A.; Price, J.P.N.; Aller, M.F.; Bhogal, A.; Doody, D.G.; Gregory, A.S.; McKinley, J.M. Priorities for UK soils. *Geoderma Reg.* **2022**, *29*, e00512. [CrossRef]
110. Mäder, P.; Fließbach, A.; Dubois, D.; Gunst, L.; Fried, P.; Niggli, U. Soil Fertility and Biodiversity in Organic Farming. *Science* **2002**, *296*, 1694–1697. [CrossRef] [PubMed]
111. Singh, T.B.; Ali, A.; Prasad, M.; Yadav, A.; Shrivastav, P.; Goyal, D.; Dantu, P.K. Role of Organic Fertilizers in Improving Soil Fertility. *Contam. Agric.* **2020**, 61–77. Available online: https://link.springer.com/chapter/10.1007/978-3-030-41552-5_3 (accessed on 17 April 2025).
112. Rial-Lovera, K.; Davies, W.P.; Cannon, N.D. Implications of climate change predictions for UK cropping and prospects for possible mitigation: A review of challenges and potential responses. *J. Sci. Food Agric.* **2017**, *97*, 17–32. [CrossRef]
113. Howden, S.M.; Soussana, J.-F.; Tubiello, F.N.; Chhetri, N.; Dunlop, M.; Meinke, H. Adapting agriculture to climate change. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19691–19696. [CrossRef] [PubMed]
114. Puertas, R.; Marti, L.; Calafat, C. Agricultural and innovation policies aimed at mitigating climate change. *Environ. Sci. Pollut. Res.* **2023**, *30*, 47299–47310. [CrossRef]
115. Hanlon, H.M.; Bernie, D.; Carigi, G.; Lowe, J.A. Future changes to high impact weather in the UK. *Clim. Change* **2021**, *166*, 50. [CrossRef]
116. NASA. Heatwave. 2023. Available online: https://www.earthdata.nasa.gov/topics/atmosphere/weather-events/heat-wave (accessed on 4 October 2023).
117. Met Office. Heatwaves. 2023. Available online: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave (accessed on 16 October 2023).