Rethinking livestock futures: Integrating climate impacts and genomic technologies into global food security models

Masoud Ghaderi Zefreh[1], Marcos E. Dominguez Viera[2], Saeed Moghayer[2], Zuzana Smeets Kristkova[2,3], Willem-Jan van Zeist[2], Nils Bunnefeld[4,5], Ricardo Pong-Wong[1], Markus Dettenhofer[6], Ioannis Manikas[6], and Andrea Doeschl-Wilson[1]

[1]Roslin Institute, University of Edinburgh, United Kingdom
[2]Wageningen Social and Economic Research, Wageningen University and Research, The Hague, Netherlands
[3]Czech University of Life Sciences, Faculty of Economics, Prague, Czech Republic
[4]Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, UK
[5]Alternet/Eklipse Science-Policy on Biodiversity, Brussels, Belgium
[6]Czech University of Life Sciences, Faculty of Agrobiology, Food and Natural Resources, Prague, Czech Republic

With the projected increase in the global population and food demand on a planet in climate crisis, the debate about the role of livestock continues to intensify. Animals farmed for food are both a victim and a contributor of climate change (CC), with animals suffering from heat stress due to CC but also a major contributor to greenhouse gas emissions (GHG). Livestock studies have demonstrated that novel breeding technologies could partly mitigate these negative effects, yet their wider implications on food security and the socio-economy are not well investigated yet. In this proof-of-concept study we incorporate, 1) the effects of heat stress on livestock's productivity and feed efficiency, and 2) the use of genomic selection as a recently established novel breeding technology, into a global macroeconomic projection model (GMPM) to evaluate their broader impacts on food security. We find that both effects can drastically alter the model projections. In particular, the results suggest that novel breeding technologies can substantially mitigate adverse effects of CC on production, food availability, land use, and GHG, whilst also causing implications for the labour market. The study demonstrates the importance of integrating advances in livestock science and technology into GMPMs for better projections that inform livestock management, policy and consumer decision-making, requiring closer collaboration between livestock scientists and systems modellers.

Keywords: breeding, genomic selection, global macroeconomic projection models, climate change, food security, livestock

1 The evolving role of livestock production in global food security under debate

Livestock have been farmed for food production for over 10,000 years but never has the role of livestock to food security been under as much scrutiny as now. Food security is formally defined by the World Food Summit (1996) as "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [8]. This widely accepted definition underscores that food security is not merely about the presence of food, but also about its accessibility, utilisation, and consistent availability over time, which are the four interconnected pillars of food security [8].

Livestock production is a significant and integral component of the global agricultural economy, with its impact extending far beyond the direct provision of food to include various multipurpose uses. Animal source foods are crucial for global nutrition, supplying essential macro- and micronutrients. They contribute approximately 18% of global calories and a substantial 25% of global protein consumption [10]. These products also provide vital micronutrients such as vitamin B12, iron, and calcium, which are often scarce or less bioavailable in plant-only diets [31]. Beyond nutrition, livestock plays a central role in sustaining the livelihoods particularly in rural areas. It provides direct income, acts as a store of wealth, and offers a form of insurance against economic shocks or crop failures, thereby contributing to household resilience and broader economic growth [9].

A critical, yet often overlooked, aspect of livestock's contribution lies in its resource efficiency. A recent FAO study indicates that a substantial 86% of livestock feed comprises forages, crop residues, and various by-products that are not edible by humans [31]. This highlights livestock's crucial role in converting otherwise unusable biomass into high-value human food, effectively preventing environmental waste and increasing the overall efficiency of the food system. Furthermore, livestock effectively utilises marginal lands, including pastures and rangelands, where crop production is not feasible, thus expanding the productive capacity of the global food system beyond arable land [16]. This multi-functional aspect positions livestock as a key player in resource efficiency and circularity within the agricultural system.

However, in the current climate crisis, the future role of livestock in global food security is heavily under debate. This is because climate change (CC) and livestock production are intricately linked, with significant implications for food security (Figure 1). Livestock production is responsible for 15% of global greenhouse gas (GHG) emissions [12] and 75% of NH3 emissions [57]. Many studies, therefore, advocate a considerable reduction in the production and consumption of animal-based products. For example, The Intergovernmental Panel on Climate Change (IPCC) recommends one portion of meat per week [14]. Yet, the global demand for food is projected to increase by up to 56% [52] by 2050, and current trends suggest that the future demand for animal-based products will follow suit [27]. This is mainly due to the increase in world population and dietary transitions because of GDP growth in lower-income countries [13].

Livestock production is not only a driver of CC, but also negatively affected by it [41]. Indeed, CC poses a global threat to livestock production through various direct and indirect effects: direct effects include, in particular, heat stress impact on animals' metabolism, feed-intake, productivity and reproduction [1]. For example, in the US poultry industry alone, heat stress has been estimated to cause an annual economic loss of 128-156 million USD [56]. Indirect effects associated with CC include reductions in feed and water quality and quantity [1] or changes in the infectious pathogen landscape [45], with negative consequences on animal health and productivity, and increasing mortality. Recent estimates suggest that 20% of livestock production is lost to disease annually [35].

2 Mathematical models are important for assessing climate smart solutions

The above statistics demonstrate the urgent need for innovative climate-smart approaches to livestock production as the status quo is not a viable option to ensure future food security. Unsurprisingly, livestock scientists and industry dedicate considerable efforts into monitoring climatic effects on and from livestock. The intent has been to develop novel agri-tech solutions for mitigating the carbon footprint of livestock production and improving the resilience of livestock systems to heat stress and the other diverse detrimental effects brought on by CC (e.g., pathogen burden and resource shortage, Figure 1). These solutions range from changes in animal feed [17], implementing different animal health and heat stress management strategies, diversifying livestock species and breeds [50], to novel breeding and reproduction technologies [44, 48].

Mathematical prediction models, ranging from the simple, but well-established "breeders' equation" [24] to more complex mechanistic models of nutrient utilisation of animals [7], predict the consequences of implementing these novel solutions on livestock production, health and environmental footprint, thus helping to inform decision-making in the livestock sector. However, the wider implications of these

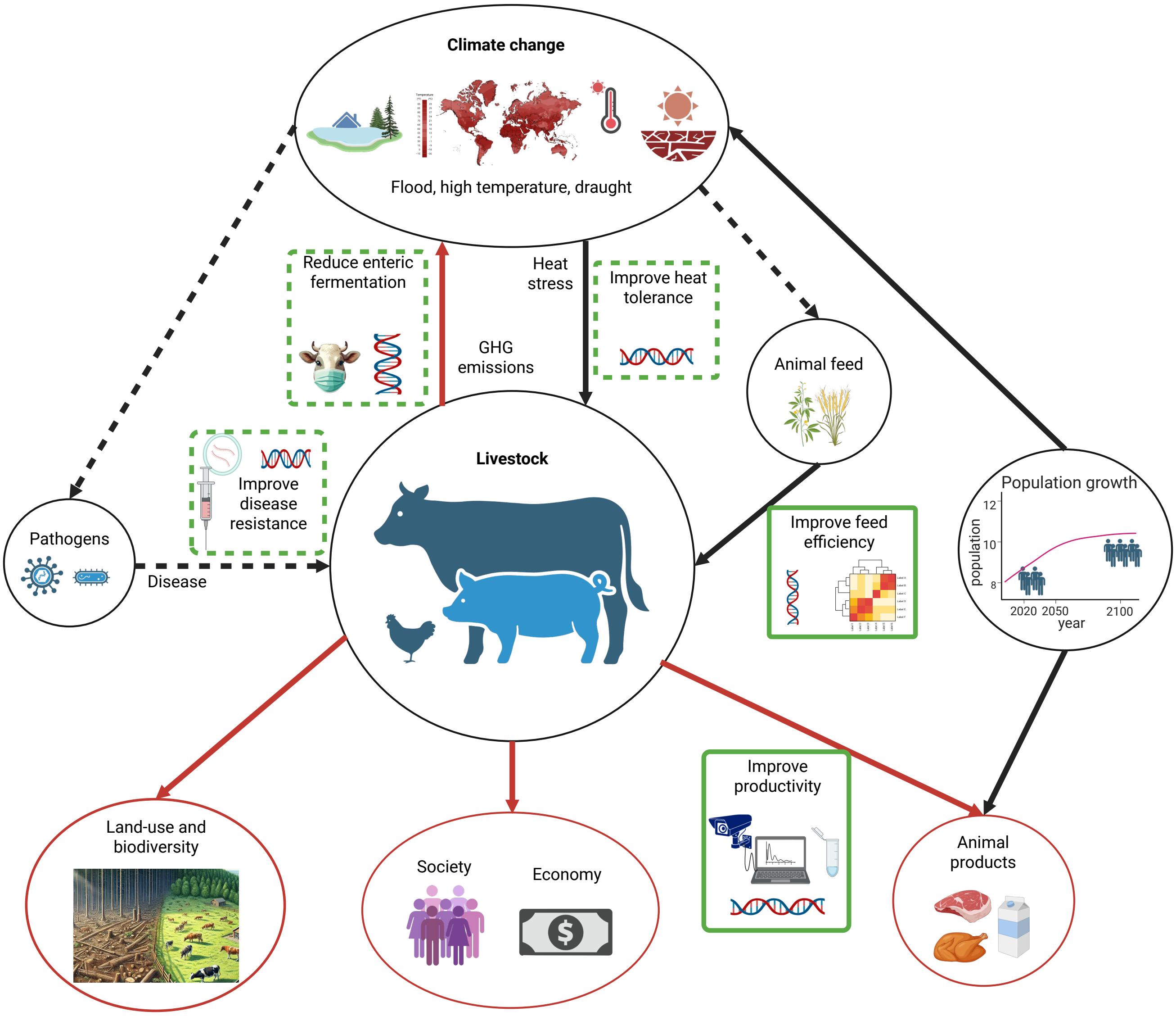

Figure 1: The interaction of livestock and climate change and its impact on environmental, economic and societal aspects and global food security. Some mitigation and adaptation strategies, developed by the animal science community are shown by green boxes. Solid lines indicate factors and improvement strategies integrated in this proof-of-concept study, whereas dashed lines indicate those not yet integrated. Created in https://BioRender.com.

agri-tech innovations to global food security and socioeconomics are currently poorly understood. Understanding these implications typically requires the use of global macroeconomic projection models (GMPMs) that capture the complex interdependencies between various players and stakeholders of the food system and diverse social, economic and environmental factors. For example, IPCC's recommendations for reduced meat consumption are based on results from multiple GMPMs or more broadly Environment-Society-Economy models [53]. These models incorporate technological improvements in different production sectors based on an assumed contextual shared-socioeconomic pathway (SSP) [37, 42]. Different pathways provide different narratives on the level of challenges faced in mitigation and adaptation strategies to tackle CC. Accordingly, technologies associated with different production sectors are projected to improve at different rates and possibly at different directions under each SSP. These improvement assumptions may however not adequately represent the accelerated advances and scientific developments that some production sectors (e.g., livestock production) have recently experienced, and the expected further developments on the horizon. Importantly, as will be demonstrated in this study, incorporating such advances can have a significant impact on the model projections.

In this perspectives paper, we advocate that better integration of recent innovations in livestock science and technologies into large scale GMPMs is vital for accurately assessing the downstream effects of different mitigation and adaptation strategies on global food security and socio-economy. Given the complexity of these models and the high demands on computing and manpower, to our knowledge most GMPMs used to inform policy decisions currently do not incorporate state-of-the-art expert knowledge and relevant novel scientific and technological advances emerging from the livestock sector. The complexity of livestock systems poses a challenge for comprehensive modelling of this sector. Macroeconomic models often simplify the representation of specific sectors and climate stressors [36]. Our hypothesis underpinning this perspectives paper is that shortcomings in integrating these advances could have profound implications on the macroeconomic model projections and its drawn conclusions. Here, we illustrate the importance of integrating these advances in livestock production into GMPMs by showcasing the impact of two opposing key advances on the projections of a GMPM. The key advances chosen in the study refer to the increased scientific understanding of the negative impact of heat stress and the positive impact of genomic breeding technologies on livestock production, as outlined below.

3 The role of heat stress and genomic breeding technologies in climate-conscious livestock production

In our case study below, we integrate the effects of heat stress on animal productivity as one of the major negative consequences of CC on livestock production [49]. We chose heat stress as it negatively affects most global domestic livestock species causing substantial reduction in their health and productivity (e.g., growth rate, milk / egg production), or in the extreme case death [3, 21, 38, 25, 59]. In livestock science, the level of heat stress that animals are exposed to is usually measured by combining the temperature and humidity, also referred to as temperature-humidity index (THI). Various studies have shown severe drops in livestock productivity and health with increasing THI units, with levels differing between species, breeds and as well as individual animals within the same breed. However, to our knowledge heat stress is currently not included as a direct impact of climate to animal production in GMPMs. Yet, THI in some locations is predicted to increase by more than 20 units in 2050 compared to 2023 in the scenario of moderate CC.

In this case study, we also focus on recent technological advances in animal breeding enabled by the genomic revolution as a potential driver of food security and mitigation strategy to reduce the carbon footprint of livestock. Selective breeding has been practised for farmed animals since ancient times and has played a major role in solving food shortages after the World War II. For example, genetic selection has quadrupled milk yield of US dairy cattle since 1960 [55]. Traditionally, selective breeding has been based on information from relatives, and to our knowledge, corresponding projections for genetic improvement in animal productivity have been incorporated into most GMPMs. However, animal breeding is now entering a new era, brought on by the recent technological revolution, which produce a range of promising new opportunities for climate smart livestock production [18]. Specifically, genomic breeding, also known as genomic selection, is a modern breeding approach that utilises genomic data to make more accurate and efficient selection decisions in breeding programs, thus accelerating genetic improvement of animals [28]. This technique involves the use of DNA markers, allowing breeders to identify and select individuals with desirable traits more effectively. For example, a further 50% increase in milk yield in the US has been predicted by 2050, through the use of genomic selection alone [2]. Even larger production increases are forecasted in developing countries, which have only recently started to adopt advanced breeding technologies [33]. Genomic selection for increased productivity and feed efficiency has been recently introduced in breeding programmes for most key farmed animal species (cattle, pigs, poultry, sheep, salmon). It is rapidly becoming the standard breeding methodology for all species. However, whilst current implementation focuses mostly on production and efficiency traits, future genomic selection is expected to also improve complex sustainability traits that have not experienced much improvement in the past, such as GHG emissions and resilience to heat or infectious disease [15]. However, the forecasted effects of current and future genomic improvements have not yet been incorporated into GMPMs.

4 Case study: Assessing the global socio-economic and environmental impact of heat stress and genomic breeding in livestock using the GMPM MAGNET

4.1 Approach

The GMPM used in this case study is MAGNET, a global Modular Applied General Equilibrium Tool, that forms part of the modelling inventory and knowledge management system (MIDAS) of the European Commission. MAGNET is a recursive dynamic, multi-sector and multi-region model calibrated to data from the Global Trade Analysis Project (GTAP) database [5], which captures 160 countries or regions and 129 production sectors (including livestock) and is set up to assess long-term impacts on various environmental and socio-economic factors such as land use, GHG emissions, labour, and capital (see Supplementary Material S1 for further information on MAGNET and modelling livestock in MAGNET). MAGNET has been developed and used to analyse policy scenarios on agricultural economics, bioeconomy, food security and international trade across different sectors and regions [60]. While MAGNET is not specifically tailored for climate modelling, it can incorporate CC scenarios into its analysis [54].

MAGNET implements different climate scenarios based on distinct SSPs. To demonstrate the role of the recent advances in livestock science, we consider a baseline scenario that follows the SSP2 variant towards 2050. SSP2, often referred to as the "middle of the road" scenario, represents a moderate pathway between extremes [11]. The SSP2 narrative offers a plausible and stable scenario that mirrors gradual shifts seen historically, making it relevant for exploring various climate policy impacts and for comparing different mitigation and adaptation efforts on the horizon [11]. Hence, to demonstrate the impact of heat stress and genomic breeding, we consider the SSP2 narrative. The expected GDP growth rates based on SSP2 are used to calibrate expected macroeconomic productivity growth, which is distributed over all sectors of the economy, including animal sectors. This baseline scenario also incorporates calibrations in terms of land productivity and feed efficiency in the livestock sector based on the IMAGE model [47]. Assumed improvements in animal productivity are based on traditional breeding, but not due to genomics. Furthermore, the detrimental impact of heat stress or other climate factors on animal productivity is not considered in the baseline scenario.

Therefore, two scenarios under the SSP2 pathway are considered for 2050 at a global scale (Table1). These two scenarios focus on the sequential integration of the two antagonistic key drivers of sustainable livestock production, i.e. (1) the impact of increased heat stress brought on by CC on animals' productivity and efficiency, and (2) the potential impact of genomic breeding on improved production and efficiency. We chose these two drivers because of their large and contrasting impacts on livestock productivity at a global scale, and because they are focus of much recent research in the animal science community with new results emerging at a fast pace.

The global projections of temperature and humidity for 2050 were obtained from the climate model

Table 1: Scenarios considered in this case study. The contextual socio-economic pathway SSP2 [37] was used as the baseline for both scenarios.

	Scenario 1: Detrimental effect of climate change on livestock production	Scenario 2: Combined detrimental effect of climate change on livestock production, and implementation of genomic selection as adaptation strategy
Incorporate detrimental effect of heat stress on livestock productivity and feed efficiency	Yes	Yes
Incorporate genomic breeding for increased productivity and feed efficiency	No	Yes

EC-Earth3 [6]. The decline in productivity and feed efficiency associated with heat stress in different livestock species were estimated using models from the literature that relate production and feed efficiency to THI. More information on these models, the references used, and the final relative decline in traits are provided in Supplementary Material S2.

For scenario 2, improvement projections for productivity and feed efficiency based on genomic breeding were derived from existing literature and/or historical trends from FAO. These projections were then adjusted for improved genomic selection accuracies due to implementation of genomic selection using the Breeder's equation [24] (see Supplementary Material S3 for more details on improvement projections and references). Note that we did not account for the newly practised breeding targets such as lower methane emission in cattle, or heat and disease resilience in other animals. The projected percentage changes in productivity and feed efficiency for each of the 6 subgroups of terrestrial livestock (dairy cattle, beef cattle, broiler chicken, layer chicken, sheep and goat, pig) for both scenarios were used as inputs into MAGNET via connection variables in the model (i.e., sectoral tech shifters, feed efficiency coefficients). The changes in both traits were introduced as exogenous shocks to the 2050 baseline conditions, which caused the system to attain a new equilibrium for the same period (2050). Comparative-static analysis then provided estimates for the relative impact of both scenarios compared to the baseline SSP2 scenario. Our focus in this assessment was the projected impact of incorporating the advances in science and technology represented in scenarios 1 and 2, respectively on the environment (GHG emission, land use), food security (food affordability, calories per day per capita), and the socio-economy (production, employment, wages) in 2050.

It is crucial to note that the adopted comparative static approach does not analyse the transition path, or the dynamics of how the economy moves between two equilibria; therefore, changes in demand, income, prices, and technological advancements are introduced as direct "shocks" to the system, rather than evolving dynamically. The MAGNET model captures the complex interdependencies between various sectors and factors. Therefore, the observed changes are not merely direct effects but also the knock-on effects across the entire agricultural sector and beyond. Furthermore, the comparative static analysis approach still accommodates changes in demand, income, and prices that occur due to factor market interactions. This is true even if the supply of labour, capital, or economy-wide productivity effects are not dynamically modelled.

4.2 Model results

As would be expected, heat stress in livestock causes detrimental effects on production, food security and on the environment in 2050 compared to the baseline scenario (SSP2) that omits heat stress and genomic improvement (Figure 2). However, at global scale, the changes are relatively small (i.e. below 1%), with the biggest effect (1.2% reduction) observed in global food production. Both land use and fertilisers application are projected with higher values due to higher number of animals or the lower efficiency from animals and therefore more feed required (especially for monogastric animals) which requires more land to be utilised for feed production. However, it is also noted that the reduction in GHG due to animals eating less (and thus producing less) might outweigh the increase from animal numbers in some developing countries, leading to a decline in total emissions in those specific regions (see Supplementary Materials S4 for changes in indicators for each country). This apparent counter-intuitive result is a knock-on effect within the model, where a lower productivity increases prices, reduces competitiveness, causes a reduction in livestock production and therefore lowers output emissions in regions where input use is limited.

GHG emissions are projected to increase by 0.5% when accounting for heat stress. This rise may be due to increased fertiliser use for feed production and more animals needed to meet demand caused by lower feed efficiency. Accounting for heat stress in livestock causes a relative increase of 0.5% and 0.6% in wages and employment (for unskilled workers), respectively. This is driven by reduced productivity which requires more resources including labour to produce livestock and increases the wages of unskilled labour in agriculture. Note that the wages in Figure 2 are for the unskilled agricultural workers whereas the food affordability is defined as the wages from all agricultural workers divided by the food prices. Therefore, since the prices are impacted more by demand than the increase in agricultural worker wages, food affordability decreases (by 1.2%).

Genomic selection offsets and reverses all projected negative effect of heat stress (blue bars in Figure 2). In contrast to heat stress, genomic selection exhibits positive effects on food production and food security and the environment, with projected relative changes between 1.3% (for land use) to 6.4% (for food production). To illustrate with an example, heat stress is projected to cause a reduction of 430 calories per capita per day and an increase of 114000 km2 required land, the latter being equivalent to half the area of the UK. However, when the effects of genomic selection are incorporated, about 2500 more calories per capita per day from livestock products can be produced with 744000 km2 less land required (three times the area of the UK). Incorporation of genomic selection also considerably reduces the carbon footprint of livestock production. A 2.4% reduction in GHG emissions compared to the baseline scenario is projected as a result of genomic selection for increased productivity and feed efficiency alone, and without directly selecting animals for lower genetic GHG emission potential. This is equivalent to about 36 MT of equivalent of CO_2 or 10% CO_2 production of the UK. The increased efficiency from genomic selection reduces the demand for resources, including labour, leading to a reduction in employment and wages for unskilled workers (both by 2.4%). This is a consequence of producing the same quantity with fewer inputs due to higher productivity. The impact, however, is not the same for each country or region (Supplementary Materials S4). When accounting for both heat stress and genomic (Table S5 in Supplementary Material S4), the changes in production, for example, of Sweden is positive while that of Spain is negative due to the impact of the heat stress and genomic improvement on their own as well as their trade partners. Overall, genomic breeding's global improvements in animals' ability to thrive with fewer resources result in the observed profound global impact of this technology on the global environment, food security and economy, and on the strong offset of the detrimental effects of heat stress.

5 Discussion and future directions

The controversy regarding the role of livestock production to the economy, food security and the environment remains to be addressed with specialised tools that are built for this purpose. Global Macroeconomic Projection Models (GMPMs), or more broadly, Environment-Society-Economy models are holistic approaches that are used for policymaking and consumer recommendation [14]. While the results from these models advocate for moderation of animal-based protein, the extent to which livestock production should be limited or change remains under debate, especially in light of new insight and technology. In this paper, we showcased through a simple scenario that integrating advances in livestock science and technologies into a global macroeconomic projection model, MAGNET, can have significant impact on its projections. The changes in the outputs of MAGNET were the result of the complex inter-sectoral interactions that were modified by incorporating the effects of two globally acting forces in livestock production: heat stress and genomic breeding directly affecting productivity and feed efficiency. Whilst incorporation of heat stress had generally only moderate effects on our

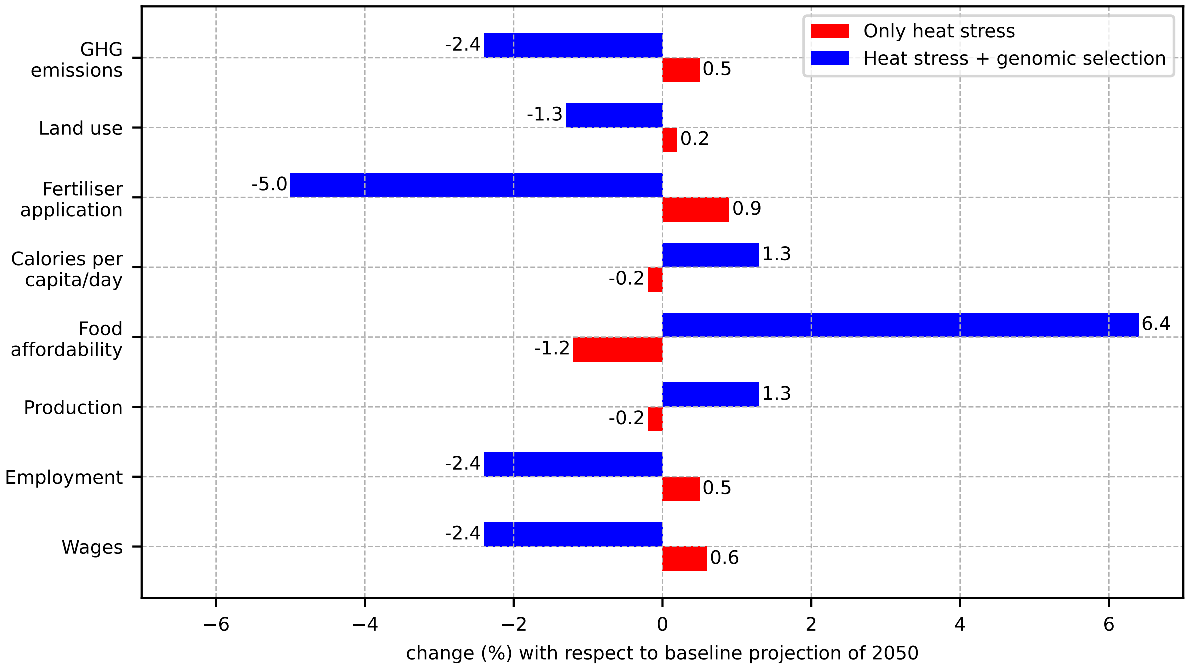

Figure 2: Relative global change (%) in environment (GHG emissions [CO2 equivalent], land use [area], fertiliser application [US$]), food security (calories per capita per day, food affordability [wages/prices in US$]), and economy (production [US$], employment [number of people], wages [US$] - the latter two for unskilled workers) in the agricultural sector from the changes in the livestock production and their knock-on effect in two scenarios: accounting for only heat stress (red) and for both heat stress and genomic breeding(blue). Changes are with respect to baseline conditions without accounting for heat stress or genomic breeding effects on livestock productivity

model projections, implementation of genomic breeding for improved productivity and feed efficiency alone profoundly impacted the model projections for GHG emissions, food security and economic indicators, altering the baseline scenario projections by up to 6.4% and by offsetting the percentage of negative impact of heat stress by a factor of 3 or higher.

One of the potential reasons for the strong projected impact of genomic breeding lies in the global nature of breeding. Indeed, different strategies to mitigate the impact of CC on livestock production or to reduce the environmental footprint on livestock may differ in the scale of disruption they cause on the wider economy, food security, biodiversity and animal health [22]. In the pursuit of climate-smart livestock production, we focused on selective breeding in this case study due to its comparatively low negative impact on other sectors and commodities, distinguishing it from other mitigation strategies that might wield more substantial consequences on animal health or even shock to other sectors [22]. Consider, for instance, the introduction of feed supplements or anthelmintics to expedite growth, reduce enteric methane emissions or combat pathogens. This strategy, though enhancing production or health, requires usage of land, fertilisers and chemicals which can alter externalities such as soil biodiversity or the rise of antimicrobial resistance through the excreted unabsorbed minerals and antibiotics. In contrast, selective breeding of genetically more productive animals with increased feed efficiency constitutes a less disruptive alternative, as it improves animals' ability to thrive with less resources. Breeding practices can contribute to sustainability and climate resilience with minimal collateral consequences [43]. Unlike more localised approaches, breeding offers cumulative [58], permanent and global benefits [46]. Global breeding companies facilitate rapid dissemination of genetic progress into commercial populations at scale, by supplying enhanced brood or seed stock to numerous farms. Hence, selective breeding can be considered as a global and proactive solution, setting itself apart from the more local, temporary, and often reactive nature of its counterparts. This not only ensures a broader impact but also requires less managerial changes from farmers, making breeding a resilient and sustainable force in agricultural practices.

For this proof-of-concept study several simplifying model assumptions were taken as our intention was to demonstrate that it is possible to include novel scientific and technological advances into GMPMs and that their projections can be considerably impacted by this inclusion, rather than quantifying these changes accurately. First, we made various simplifying assumptions in calculating the effect of heat stress on livestock by averaging THI projections over space and assuming that all animals within a species or production system are equally affected by these changes. A logical extension would be to account for breed differences, or regional differences similar to the study done for cattle [49], which assessed the economic loss due to heat stress in worldwide dairy and beef production. However, the average percentage of milk production loss in our study was bounded by the extremes (SSP1 and SSP5) considered in a previous study [49], whereas our estimation of beef production loss is only half of their estimate. Our averaging may have produced conservative estimates for heat stress effects on food security and socio-economy and highlight the need to incorporate heat stress predictions at breed or regional levels in future studies.

Similarly to the heat stress assumptions, we assumed that breeding improvements occur equally between breeds within each species and across the world. However, the gain from advances in breeding is expected to be more pronounced in breeds that have undergone less selection than those with several generations of selection. Hence, the relative gains from genomic breeding are expected to be more significant in developing countries that have not rigorously practised genetic selection, compared with developed countries [33]. Therefore, improvement in production level can significantly differ between species and countries [32]. We also only accounted for gains in prediction accuracies associated with genomic over conventional selection but did not account for the expected shorter generation interval that occurs, e.g., in dairy cattle [19], as a result of genomic selection. Furthermore, in this study, we focused on improvement of only two breeding goal traits: productivity and feed efficiency. However, advances in genomic breeding for complex traits such as reduced methane emission in ruminants [23], reduced nitrogen excretion in pigs [29], or heat- and disease-resilience [20, 4] could further help to mitigate livestock's contribution to CC and to adapt to new conditions. These approaches are only beginning to be utilised and will likely play a role in future breeding objectives. Additionally, there are other novel breeding and reproductive technologies on the horizon or at the early stage of implementation, including gene editing. These innovations along with improvements in precision livestock and artificial intelligence may lead to more drastic improvements than genomic selection. Integrating the potential impacts of these technologies into models will be complex but necessary for long-term projections. We refer to reviews by, e.g., Tait-Burkard et al, Tullo et al and Jones et al [18, 51, 48]. Hence, altogether we expect the projected levels of impact of genomic breeding to be on the conservative side. Furthermore, our understanding of physiology and immunity of animals and their interaction with each other, humans and the environment continues to improve, and we are only starting to acknowledge the consequences of CC. For example, extreme events such as floods cause massive accumulation of parasites for pasturing animals [39] or certain disease prevalence increase with heat stress [56]. CC increases the threat of zoonotic diseases [30] which directly affect livestock and human health, with often massive economic burden [34]. While the technological advances may be represented in different pathways depending on the assumed narrative, to our knowledge new scientific insights about livestock systems have not been included in most GMPMs. Inclusion of these improvements in GMPMs constitutes an important step to enhance future projections for better informed policies and consumer choices.

Based on our model projections, improvements in breeding are predicted to alleviate pressure on land use for agriculture by 1.3%. Land used for livestock leads to habitat loss for biodiversity, which is one of the main drivers of the current biodiversity crisis [40]. Although, MAGNET is not currently directly modelling impacts on biodiversity, the link between land use change and biodiversity has been explored in an extension of the MAGNET model, highlighting the benefits for biodiversity from agriculture and livestock efficiency gains that alleviate pressure on land use [26].

Although our study demonstrated that integration of novel breeding technologies can help reduce the carbon footprint of livestock production, we would like to emphasise that we do not advocate that novel technologies alone can resolve the climate crisis, nor suggest that adjustments in livestock production practices or transitions away from animal-based diets are unnecessary. Our proof-of-concept investigation simply underscores the necessity of integrating advances in livestock science across varying scales to enhance our understanding of the broader implications of recent technological applications. This integration may facilitate resource prioritisation for further development of these technologies and enable the generation of more precise model projections which can strengthen the robustness of analyses and increase the relevance of model outputs for decision-making and foresight analysis. Finally, we only focused on one sector assuming moderate improvement in other sectors (hence, SSP2). Of course, other sectors may have experienced recent impactful scientific or technological advances too (e.g., genomic selection has also been used in crop production) and indeed it is equally important to incorporate those into the GMPMs. Consequently, it is essential to foster an interdisciplinary and collaborative framework between animal scientists and systems modellers as was the case here.

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Rethinking livestock futures: Integrating climate impacts and genomic technologies into global food security models

Supplementary Materials

Masoud Ghaderi Zefreh[1], Marcos E. Dominguez Viera[2], Saeed Moghayer[2], Zuzana Smeets Kristkova[2,3], Willem-Jan van Zeist[2], Nils Bunnefeld[4,5], Ricardo Pong-Wong[1], Markus Dettenhofer[6], Ioannis Manikas[6], and Andrea Doeschl-Wilson[1]

[1]Roslin Institute, University of Edinburgh, United Kingdom
[2]Wageningen Social and Economic Research, Wageningen University and Research, The Hague, Netherlands
[3]Czech University of Life Sciences, Faculty of Economics, Prague, Czech Republic
[4]Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, UK
[5]Alternet/Eklipse Science-Policy on Biodiversity, Brussels, Belgium
[6]Czech University of Life Sciences, Faculty of Agrobiology, Food and Natural Resources, Prague, Czech Republic

S1 MAGNET model

Figure S1 shows a schematic of the MAGNET model. Computable General Equilibrium (CGE) models like MAGNET are valuable for analysing policy scenarios and capturing interdependencies across different sectors. However, global CGE models often require aggregating livestock systems and may have limited detail on specific biological processes or the heterogeneity within the livestock sector, such as breed differences or the use of non-market sourced feeds [26].

S1.1 Modelling livestock in MAGNET

Different production sectors and commodities are usually aggregated in MAGNET to reduce computation time. For the livestock sector, 6 subgroups were defined as dairy cattle, beef cattle, sheep and goat, pigs and broiler chickens and layer chickens (eggs). Modelling livestock production is based on constant elasticity of substitution production function [23] which minimises costs subject to technology constraint. The elasticity of substitution determines the behaviour of the producer - if substitution value is high, one can substitute more expensive inputs such as land or feed with other potentially cheaper ones such as labour or capital. To distinguish animal production technology from crops and other non-agricultural sectors, MAGNET uses a flexible production structure for each technology.

Figure S2 shows how inputs are combined in livestock production in the animal sectors in MAGNET. On the upper level of the nest, intermediate consumption is combined with value added in a fixed proportion (it is not possible to substitute services with labour or feed for instance). Within value added nest (NEST 1), there is a small substitution possible. The lower nests where more similar inputs are combined typically assume higher substitutability (substitution elasticity is 0.5). NESTS 4 and above show how different components of feed are combined - the purchased feed from processing industry and the individual feedstuff from crop sectors which can be produced on farm.

S2 Decline in traits due to climate change

S2.1 Projection of temperature and humidity in 2050

To estimate changes in livestock production, it is necessary to forecast the THI (temperature-humidity index) in extensive livestock regions. The THI is designed to relate a specific sensation of heat to the

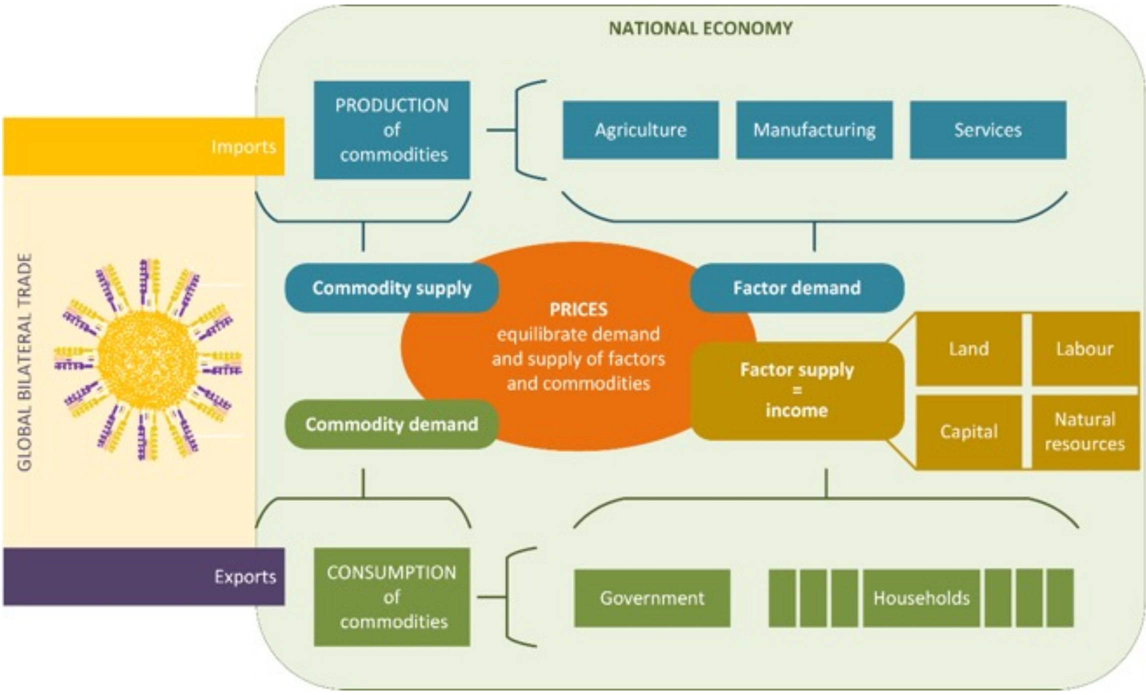

Figure S1: Visual scheme of flows in the MAGNET model

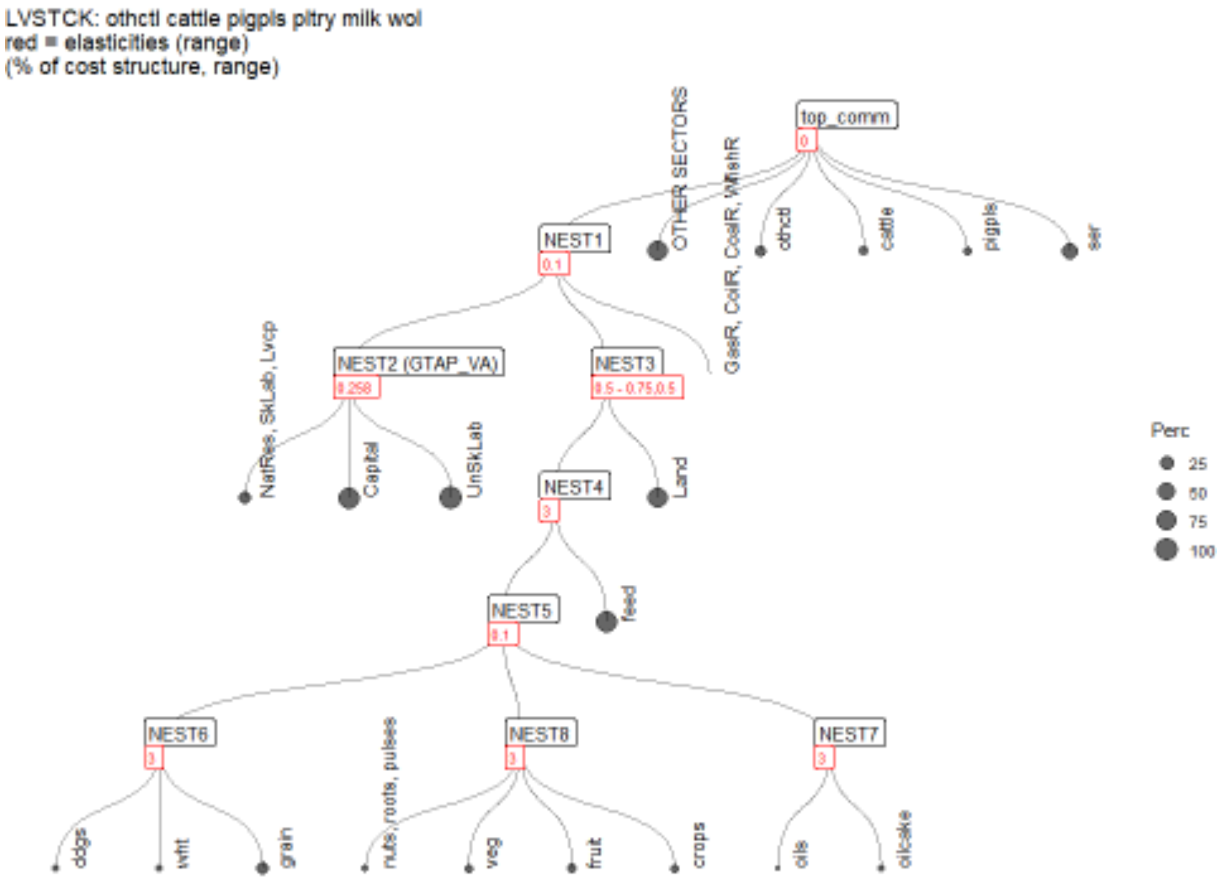

Figure S2: Nested production structure in livestock sector in MAGNET. Note: values in red indicate elasticity of substitution in the respective nest

Table S1: Selections made on the Copernicus Climate Change Service to download the temperature and humidity projections

Group	Selection
Temporal Resolution	Monthly
Experiment	SSP2-4.5
Variables(two separate datasets)	Near-surface air temperature Near-surface relative humidity
Level	N/A
Model	EC-Earth3-CC (Europe)
Year	{2023, ..., 2100}
Month	{Jan, ..., Dec}
Day	N/A
Geographical Area	Whole available region

actual temperature and humidity levels. In other words, two conditions with different levels of humidity and temperature may be perceived equally by livestock. There are various definitions for THI (see [2] for a complete list). Here, we use the following definition

$$\text{THI} = 0.8T + \text{RH}(T - 14.4) + 46.4, \tag{1}$$

where T is the dry-bulb temperature in °C and RH is the relative humidity value between 0 and 1. Hence, to calculate THI, we need both temperature and relative humidity. We used the projections from CMIP6 climate projection (Copernicus Climate Change Service, 2021), and [8]. Table S1 summarise the chosen parameters for downloading the temperature and relative humidity projections, respectively.

The resulting temperature and humidity projections were averaged for each country for 2050. For this proof-of-concept study, the final values were further averaged across the world to obtain an increase of 1.1 unit of THI in 2050 compared to 2023.

S2.2 Decline in traits due to one unit of THI

The majority of studies report a piecewise linear relationship between THI and productivity or efficiency of animals. The range of this comfort window varies largely between species and breeds. However, in estimating the impact of climate change on animals' performance and production, we assumed a linear relationship without any comfort zone.

The values of the changes in the traits were estimated from data in the literature (see Table S2 for the list) where animals' performance and/or production is measured in two different conditions. Hence, changes in the values of trait were regressed over the changes of the THI to obtain the change of train in one unit of THI. Changes were then converted to percentage with respect to production/efficiency at the better condition. Table S2 summarises the percentage changes for each animal and trait that were used in MAGNET model.

S3 Improvement projections

For estimating the additional contribution of genomic prediction on animals' productivity and efficiency the following procedure is employed. First, the improvement in animals productions (milk, bodyweight, egg) and feed efficiency are calculated in terms of relative change for one generation of animals. Here, we assume a generation interval of five years for all animals except chicken for which we assume a generation interval of one year. The relative change can be shown as

$$x = \frac{P_C - P_0}{P_0}, \tag{2}$$

as shown in Figure S3, where P_0 is the original performance prior to selection and P_C is the improved performance after selection using conventional method. One can also use the Breeders' Equation [20]

Table S2: Changes in the trait for production and efficiency (feed-conversion ratio - FCR) of different species

Sector	Trait	Change in trait(%) / THI	References
Dairy cattle	Milk yield	-2.03	[39, 6, 38]
Dairy cattle	FCR	0.10	[5, 37]
Beef cattle	Body weight	-2.26	[12, 18]
Beef cattle	FCR	0.00	[16]
Broiler chicken	Body weight	-1.81	[15, 33]
Broiler chicken	FCR	1.42	[33, 11, 17]
Layer chicken	Egg	-1.30	[27, 35]
Sheep	Body weight	-1.00	[21, 22, 31]
Sheep	FCR	1.47	[21, 28]
Pig	Body weight	-2.88	[14, 25]
Pig	FCR	0.00	[14, 29]

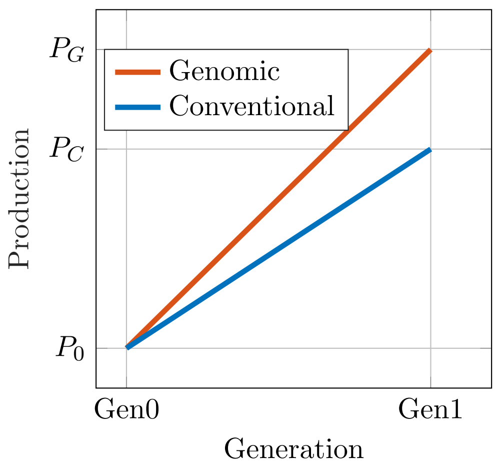

Figure S3: Gain in production from P_0 in one generation following either the conventional method (blue - to P_C) or the new genomic method (red - to P_G).

Table S3: Improvement due to use of genomic selection by 2050 (relative (%) to 2050 if genomic is not used)

Sector	Trait	Improvement	References
Dairy cattle	Milk yield	33.24	[4, 34]
Dairy cattle	FCR	0.00	[3]
Beef cattle	Body weight	7.34	[1, 24]
Beef cattle	FCR	-5.16	[3, 32]
Broiler chicken	Body weight	5.82	[9, 19]
Broiler chicken	FCR	-23.33	[30, 40, 36]
Layer chicken	Egg	5.70	[30, 13]
Sheep	Body weight	9.79	[9, 10]
Sheep	FCR	-2.67	[1]
Pig	Body weight	10.22	[9, 7]
Pig	FCR	-0.22	[7]

to represent P_C as

$$P_C = P_0 + \rho_C p, \tag{3}$$

where ρ_C is the accuracy of the estimated breeding values (EBV) using conventional method and p is the multiplication of selection intensity and the genetic variance.

The productivity/efficiency when genomic information is used can be written using the Breeders' equation similar to conventional method as

$$P_G = P_0 + \rho_G p, \tag{4}$$

as shown in Figure S3. Here, ρ_G is the accuracy of the estimated breeding value when using genomic information. Assuming the GEBV (genomic estimated breeding value) relative increase with respect to EBV is y, we have

$$y = \frac{\rho_G - \rho_C}{\rho_C}. \tag{5}$$

We seek the relative increase in productivity/efficiency with respect to the P_C to estimate the contribution of genomic selection methodology.

$$\begin{aligned} \frac{P_G - P_C}{P_C} &= \frac{(P_0 + \rho_G p) - (P_0 + \rho_C p)}{P_0 + \rho_C p} = \frac{p\,(\rho_G - \rho_C)}{P_0 + \rho_C p} = \frac{\frac{p(\rho_G - \rho_C)}{\rho_C p}}{\frac{P_0 + \rho_C p}{\rho_C p}} \\ &= \frac{\frac{(\rho_G - \rho_C)}{\rho_C}}{\frac{P_0}{\rho_C p} + 1} = \frac{y}{\frac{P_0}{\rho_C p} + 1} \end{aligned} \tag{6}$$

The denominator $\rho_C p$ can be replaced by $P_C - P_0$ from Equation (3) which can be replaced xP_0 following Equation (2). Hence, Equation (6) can further be simplified to

$$\frac{P_G - P_C}{P_C} = \frac{y}{\frac{P_0}{xP_0} + 1} = \frac{xy}{1 + x} \tag{7}$$

Equation (7) shows that the relative contribution of genomic alone can be calculated using the relative change from conventional method together with the accuracy increase due to using genomic selection. The relative change can be calculated from historical data which were obtained either from FAO [9] or literature (see the column references in Table S3). Finally, the relative contribution of genomic selection was compounded for each species and trait from 2023 to 2050 using appropriate generation interval. Table S3 summarises the compounded gain along with literature that was used to obtain the values.

S4 Changes of indicators in each country

Table S4 shows the changes in the environmental and economic indicators for 37 country/regions across the world when only accounting for the effect of heat stress on production and efficiency of livestock. Table S5 shows the changes in the same indicators when both heat stress and genomic selection adaptation are considered. Numbers in both tables are in relative to the baseline projection (SSP2) for 2050 when neither heat stress nor genomic prediction are included in the model.

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Table S4: Changes (%) in indicators for each country with respect to 2050 baseline (SSP2) projection accounting only for the effect of heat stress on production and efficiency of livestock. Columns are W: wages (in agriculture - USD), E: employment (number of people), FA: food affordability (wages/prices), P: production (USD), S: self-sufficiency (production/(production+import-export)), C: calories per capita per day, FE: fertiliser use (USD), LU: land use (km^2), GHG: green-house gas emission (tons of CO_2 equivalent)

Region	W	E	FA	P	S	C	FE	LU	GHG
Austria	1.04	0.73	-0.83	-0.72	-0.05	-0.55	1.12	0.15	0.23
Belgium/Luxembourg	1.58	1.40	-0.51	0.20	0.32	-0.53	1.35	0.23	0.58
Bulgaria	1.17	0.68	-0.78	0.12	0.24	-0.32	0.81	0.04	0.65
Croatia	0.93	0.60	-0.72	-0.04	0.30	-0.39	0.67	0.05	0.57
Czech Republic	1.29	0.78	-0.77	-0.22	-0.07	-0.30	0.55	0.03	0.28
Denmark	1.41	1.14	-0.70	-0.45	0.19	-0.63	0.62	0.01	0.32
Estonia	1.40	0.89	-0.73	-0.22	-0.13	-0.55	0.33	0.03	0.33
Finland	1.65	1.04	-0.62	-0.43	0.08	-0.58	0.75	0.67	0.72
France	1.04	0.83	-0.71	-0.04	0.16	-0.37	0.81	0.05	0.50
Germany	1.23	0.99	-0.67	-0.45	0.05	-0.49	0.76	0.23	0.21
Greece/Cyprus/Malta	0.62	0.36	-0.71	-0.05	0.02	-0.25	0.69	0.06	0.32
Hungary	1.21	0.76	-0.95	-0.05	0.00	-0.35	0.59	0.07	0.39
Ireland	0.66	0.53	-1.04	-1.23	-0.56	-0.67	0.62	0.01	-0.30
Italy	0.79	0.64	-0.80	-0.15	0.10	-0.33	1.12	0.08	0.53
Latvia	1.33	0.87	-0.74	-0.15	0.05	-0.56	0.77	0.06	0.62
Lithuania	1.83	0.87	-0.66	0.18	0.12	-0.27	0.77	0.05	0.55
Netherlands	1.00	0.69	-0.75	0.03	0.09	-0.66	1.10	0.05	0.74
Poland	1.33	0.89	-1.16	-0.37	0.02	-0.29	0.46	0.04	0.39
Portugal	0.94	0.68	-0.66	0.02	0.15	-0.30	0.53	0.06	0.34
Romania	0.81	0.58	-1.08	-0.22	-0.06	-0.27	0.67	0.09	0.41
Slovakia	1.63	1.03	-0.76	-0.06	0.26	-0.37	0.57	0.05	0.46
Slovenia	1.10	0.86	-0.86	0.10	0.53	-0.40	0.80	0.06	1.14
Spain	1.32	0.99	-0.65	0.37	0.13	-0.27	0.85	0.98	0.53
Sweden	1.26	1.01	-0.68	-0.29	0.15	-0.50	0.83	0.03	0.48
Australia/New Zealand	0.70	0.66	-0.73	-0.43	-0.02	-0.57	0.53	0.08	0.06
Brazil	0.79	0.76	-1.28	-0.24	-0.05	-0.26	1.16	0.71	0.37
Canada	1.14	1.12	-0.68	0.27	0.17	-0.34	1.15	0.15	0.93
China	0.42	0.59	-1.14	-0.13	-0.03	-0.36	0.36	0.07	0.26
Former Soviet Union	0.71	0.80	-1.28	-0.08	-0.03	-0.31	1.19	0.14	0.66
India	0.19	0.43	-1.38	-0.26	-0.04	-0.22	0.94	0.06	0.68
Middle East/N. Africa	0.52	0.44	-1.12	-0.23	0.00	-0.17	1.34	0.07	0.60
Other Asia	0.10	0.48	-2.32	-0.53	-0.22	-0.16	1.89	0.08	1.37
Other Europe	0.68	0.46	-0.84	-0.39	0.11	-0.61	0.60	0.02	0.21
Other Latin America	0.86	0.80	-0.96	0.05	0.04	-0.17	0.98	0.69	0.40
South-East Asia	0.51	0.46	-0.61	0.07	0.08	-0.20	0.45	0.28	0.22
Sub-Saharan Africa	-0.46	0.42	-2.62	-0.52	-0.17	-0.03	1.35	0.20	0.28
United States	0.66	0.72	-0.67	-0.33	0.03	-0.42	0.57	0.05	0.23

Table S5: Changes (%) in indicators for each country with respect to 2050 baseline (SSP2) projection accounting for the effect of heat stress as well as worldwide adaptation of genomic selection on production and efficiency of livestock. Columns are W: wages (in agriculture - USD), E: employment (number of people), FA: food affordability (wages/prices), P: production (USD), S: self-sufficiency (production/(production+import-export)), C: calories per capita per day, FE: fertiliser use (USD), LU: land use (km^2), GHG: green-house gas emission (tons of CO_2 equivalent)

Region	**W**	**E**	**FA**	**P**	**S**	**C**	**FE**	**LU**	**GHG**
Austria	-6.06	-4.25	4.66	4.20	0.43	3.04	-5.53	-1.12	-1.05
Belgium/Luxembourg	-8.58	-7.28	2.90	-1.00	-2.04	3.30	-7.65	-1.42	-3.14
Bulgaria	-6.10	-3.55	4.77	-0.47	-1.05	1.88	-4.49	-0.25	-3.44
Croatia	-3.66	-2.36	3.42	-0.19	-1.52	2.00	-4.76	-0.34	-3.66
Czech Republic	-7.28	-4.34	4.39	2.79	1.17	1.72	-2.69	-0.22	-0.92
Denmark	-7.18	-5.80	4.57	3.91	0.48	3.62	-3.29	-0.06	-0.69
Estonia	-9.80	-6.56	4.83	3.05	1.32	3.82	-1.27	-0.24	-1.28
Finland	-11.26	-7.00	4.06	3.17	0.05	3.37	-4.41	-4.32	-5.13
France	-5.80	-4.60	4.07	0.62	-0.82	2.33	-4.47	-0.67	-2.95
Germany	-8.97	-7.06	3.74	1.64	-0.60	3.19	-5.92	-6.33	-2.34
Greece/Cyprus/Malta	-3.36	-2.05	4.36	0.68	0.13	1.51	-3.17	-0.45	-1.71
Hungary	-5.10	-3.21	4.84	-0.23	-0.17	1.48	-3.40	-0.56	-2.28
Ireland	-2.46	-2.06	6.62	10.23	4.52	4.79	-4.13	-0.04	1.87
Italy	-4.28	-3.47	4.08	0.26	-0.63	1.69	-5.77	-0.60	-2.87
Latvia	-9.33	-6.31	5.08	3.19	0.20	4.29	-3.58	-0.40	-2.72
Lithuania	-13.04	-6.06	3.92	-0.26	-0.12	1.51	-4.78	-0.29	-2.94
Netherlands	-6.44	-4.40	4.65	1.63	0.09	3.45	-6.85	-0.42	-1.64
Poland	-6.65	-4.43	6.94	2.73	0.02	1.56	-2.94	-0.63	-2.51
Portugal	-5.35	-3.85	3.58	0.26	-0.71	1.57	-2.57	-0.40	-1.42
Romania	-4.18	-2.99	6.60	1.89	0.47	1.92	-3.57	-0.79	-2.05
Slovakia	-9.58	-5.78	4.37	0.78	-1.43	1.98	-3.14	-0.40	-2.24
Slovenia	-5.41	-4.27	4.95	0.50	-2.71	2.69	-5.15	-0.47	-5.93
Spain	-6.82	-5.07	3.46	-2.03	-0.78	1.70	-4.78	-6.09	-2.90
Sweden	-7.78	-6.14	4.13	2.60	-0.45	3.20	-4.12	-0.21	-2.70
Australia/New Zealand	-5.25	-3.47	4.21	3.39	0.86	3.24	-5.64	-0.41	0.19
Brazil	-3.67	-3.51	6.24	0.28	0.09	1.24	-6.20	-3.77	-3.01
Canada	-5.34	-5.25	3.51	-1.54	-0.69	1.73	-6.48	-0.86	-5.03
China	-1.24	-1.78	4.43	0.33	0.01	1.28	-1.77	-0.36	-1.28
Former Soviet Union	-4.11	-4.39	7.32	0.75	0.27	1.75	-7.55	-0.84	-3.63
India	-1.71	-3.82	12.24	2.86	0.45	1.93	-4.48	-0.45	-1.71
Middle East/N. Africa	-2.23	-1.91	6.55	1.73	0.19	0.80	-8.52	-0.62	-3.49
Other Asia	-1.59	-3.13	15.73	4.00	1.34	1.21	-10.45	-0.58	-7.32
Other Europe	-4.01	-2.02	4.70	2.43	-0.42	3.30	-4.92	-0.14	-1.62
Other Latin America	-3.85	-3.64	4.53	-0.60	-0.28	0.76	-5.48	-3.83	-2.46
South-East Asia	-2.19	-1.92	2.73	-0.58	-0.52	0.93	-2.32	-1.48	-1.24
Sub-Saharan Africa	2.63	-1.79	14.68	3.27	0.88	0.47	-7.88	-1.37	-1.67
United States	-2.55	-2.83	3.30	1.22	-0.23	2.20	-3.78	-0.28	-1.58

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