Department of Animal Science

CLIMATE CHANGE IMPACTS LIVESTOCK PRODUCTION, INCREASES WATER SCARCITY

November 2023

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Impacts of climate change on livestock production and water scarcity are serious threats to society and expected to worsen in the future as global population continues to increase. As a result, a critical question regarding humanity's future is whether there is enough freshwater in the global system to meet the demands of tomorrow's world population. Currently, more than two-thirds of the global population lives under water scarcity (Mekonnen and Hoekstra, 2016). Limited water supplies inhibit economic growth, pose societal health risks and endanger ecosystems (Marston et al., 2021). Despite Norman Borlaug's Green Revolution (the increase in agricultural production made possible by the use of new crop varieties and new farming methods, especially in developing countries), large parts of dry climatic regions of the world have remained poor, undernourished and hungry. In addition, the Green Revolution had unintended yet harmful consequences on agriculture, human health and the environment due to intensified usage of chemicals and irrigation, etc. (John and Babu, 2021). Can precision agriculture (PA)/precision livestock farming (PLF) (which utilizes technology and data-driven solutions to optimize crop and livestock production and management) reverse these consequences and increase production, reduce labor requirements and ensure the efficient management of fertilizers, pesticides, irrigation and livestock production? There is a need for a system approach in dealing with food insecurity and malnutrition not only in developing countries but also in many developed countries around the world. However, the impacts of climate change on current livestock production systems and water scarcity worldwide are a major concern and a threat to global food security.

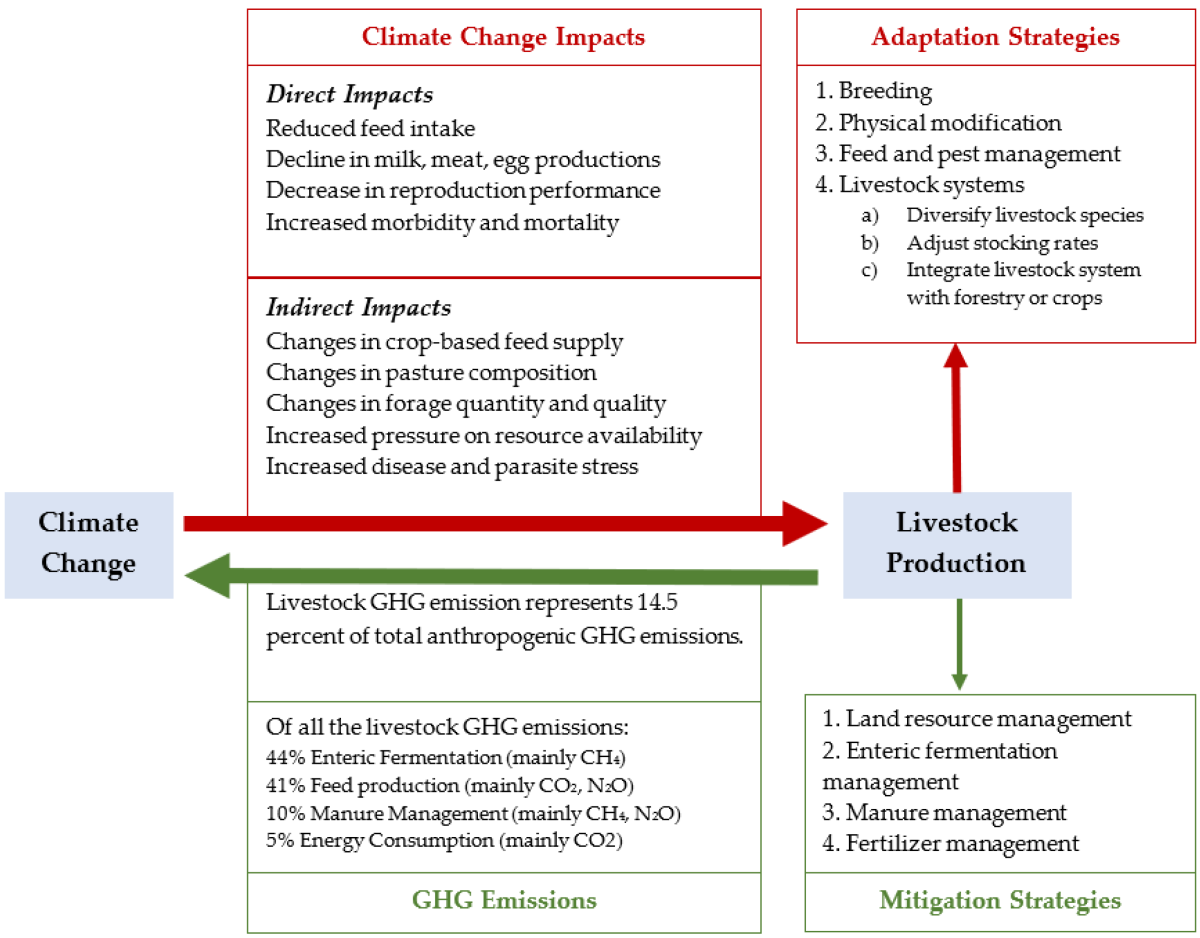
Livestock production

Demand for livestock products is growing rapidly, driven by population and income growth around the world and increasing urbanization, particularly in developing countries. Livestock provide 33 percent of the global protein and 17 percent of global calories consumed (Cheng et al., 2022). Livestock systems vary greatly across animal species, products and geographies. Production occurs in a wide range of ecosystems, from those relatively undisturbed, such as open range and grasslands, through food-producing landscapes with mixed degrees of human involvement, to production environments that are intensively modified and closely managed by humans (Steinfeld et al, 2019). However, livestock production is facing increasing pressure from climate change effects, such as rising temperatures, more variable precipitation patterns, more frequent extreme events and increasing carbon dioxide (CO_2) concentrations (IPCC, 2014). Such changes have been found to impact livestock performance across many regions and are projected to have growing impacts (Cheng et al., 2022), with predictive models broadly indicating the impacts will be negative (Escarcha et al., 2018).

The future of the livestock sector will be increasingly challenging with the projected scarcity of resources crucial for production, particularly land and water, being affected by climate change (Weindl et al., 2015). Climate change leads to reductions in livestock productivity by directly depressing animals' adaptive response mechanisms, altering the spread and prevalence of diseases (Bett et al., 2017), and causing heat stress and related welfare issues (Morignat et al., 2014); and indirectly by compromising the availability of feed grain crops and quality of forages (Kandalam and Samireddypalle., 2015). However, climate change also has implications for the processing, storage, transport, retaining and consumption of livestock products. Therefore, the ability of current livestock systems to support livelihoods and meet the increasing demand for livestock products is threatened (Godde et al., 2021). Environmental impacts of climate change have been somewhat mitigated by productivity increases in livestock that have been the result of the broad application of science and advanced technology (i.e., advanced PA and PLF techniques) in areas such as feeding and nutrition, genetics and reproduction, and animal health, along with general improvements in animal husbandry and overall food supply chain management. These innovations have led to transitions from low-input, low-output systems to more efficient and productive intensive livestock systems in many parts of the world. However, the overall environmental burden of the livestock sector at the global level continues to increase (Davis et al., 2016).

The thermal environment is the major climatic factor affecting livestock production. In today's current global climatic conditions, heat stress is more problematic than cold stress (Collier et al., 1982; Maibam et al., 2018). Heat stress occurs when animals are not able to dissipate sufficient heat to maintain homeothermy (Daramola et al., 2012), leading to increased respiration, pulse and heart rate, and a rise in body temperature. Animals possess several adaptive mechanisms which are helpful for their survival during these harsh environmental conditions. However, their productive performance is compromised while these adaptive mechanisms are in place (Rashamol et al., 2018). Reduced feed intake is often noted as the first response to high environmental temperatures among several livestock species. Poultry have exhibited a 9.5 percent drop in feed intake when ambient temperatures increase from 21.1 to 32.2 °C (Syafwan et al., 2011). Hogs have demonstrated feed intake decreases of 10.9 percent when temperatures increase from 20 to 35 °C (Lopez et al., 1991). Ruminants experience reduced appetite, gut motility and rumination under increased heat stress (Baile and Forbes, 1974; Yadav et al., 2013). Greenhouse gas emissions (GHG) are another concern associated with livestock production. On one hand, climate change can affect livestock production directly through increased heat stress and indirectly through impacts on quality and quantity of forage and crop-based feeds as well as land and water availability. On the other hand, livestock production influences climate change by contributing 14.5 percent of the global anthropogenic GHG emissions (Cheng et al., 2022). There are mitigation measures that reduce livestock GHG emissions. Gerber et al. (2013) indicated that livestock emission intensities vary greatly between production systems and regions, and the mitigation potential lies in the gap between the management techniques that result in the lowest and highest emission intensities. Mitigation strategies from the livestock side could address enteric emissions and improve manure management, along with more emission efficient feed production through reduced use of N-fertilizer and land carbon sequestration (Figure 1).

Figure 1. Overview of the relationship between climate change and livestock production. Source: Cheng et al., 2022.



The effects of climate change on resources will continue to lead to shifts in the global agricultural area as well as changes in seasonality and crop and livestock suitability (Godde et al., 2021). King et al. (2018) estimated a northward shift of the feasible agriculture zone by up to

1,200 km by the end of the century. In sub-Saharan Africa, more than 20 percent of the mixed crop-livestock system in arid and semi-arid regions is projected to become unavailable for crop agriculture by mid-century (Jones and Thornton, 2009). Most water in the livestock value chain is used for feed production, accounting for more than 90 percent of water consumption in many systems (Legesse et al., 2017; Mekonnen and Hoekstra, 2012). The amount of water required for livestock consumption varies with local climate conditions with higher consumption under hot conditions (Ward and McKague, 2023). For example, once air temperatures exceed 30 °C, the expected poultry drinking water intake can increase by 50 percent above normal rates (Godde et al., 2021). In arid and semi-arid regions, the increased frequency, intensity and duration of droughts create a significant threat from water scarcity to livestock and feed production.

Water scarcity

Mekonnen and Hoekstra (2016) quantified that four billion people face severe water stress during at least one month per year, and 1.8 billion at least six months per year. Indeed, for providing the three main primary human needs of water, energy and food security, water is an essential resource for each (Vanham, 2016). The magnitude of water scarcity in a region depends on the supply relative to the demand. As human populations, incomes, and demand for livestock products increase, water scarcity will likely grow in importance as a constraint on future agricultural production (Cheng et al., 2022). Climate change is projected to change water availability (IPCC, 2014; 2021) and water usage in animal production (Rojas-Downing et al., 2017). Rising temperatures are likely to increase animal water consumption and irrigation water use per animal and per land area (Fader et al., 2016; Gerten et al., 2011). Competition for a limited water supply between livestock, crops, and nonagricultural uses will increase in the coming decades, resulting in the need for more efficient livestock production systems to address the water scarcity issue (Reynolds et al., 2010).

Consumptive water use in livestock production is generally divided into two categories: 1) drinking and processing water (direct blue water use); and 2) water use for production of feed, fodder and grazing (blue (i.e., irrigation) and green (i.e., rainfall) water use). A bit of definition is in order here. Blue water is considered fresh surface or groundwater (water in lakes, rivers and aquifers). Green water is rainfall or precipitation that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of rainfall evaporates or transpires through plants. Green water can be made productive for crop growth (although not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or all areas are suitable for crop growth). Grey water is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed upon water quality standards. The grey water footprint of a product is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain.

Increasing agricultural water security through irrigation (*blue water)* usage to complement soil moisture deficit has driven improved agricultural production in large regions of the world. The Green Revolution mentioned earlier greatly boosted food production, but turned out not to be sustainable (Falkenmark, 2013). The outcomes included unintended side effects such as depletion of river flows, river basin closures, groundwater depletion and severe water pollution. By the early 1990s, attention was drawn to green water in the soil as a fundamental component of the hydrological cycle (Falkenmark, 1995). This allowed a more accurate approach to the assessment of the total amount of water required for food production and human welfare. Today increasing attention is being paid to rain-fed (*green water*) food production, the dominant form of agriculture in regions where most rivers are small and carry water only during the rainy season (Falkenmark, 2013).

Water scarcity has both a physical and an economic aspect associated with it. Physical water scarcity occurs when physical access to water is limited (Vanham et al., 2018). It affects both blue water and green water (Falkenmark and Rockström, 2006; Rockström et al., 2009). Economic water scarcity occurs when water resources are physically available but a lack of institutional and/or economic capacity limits access to that water (Rosa et al., 2020a; Vallino et al., 2020). Because agriculture is the world's largest user of freshwater, it ties global food security to a dependence on reliable and resilient freshwater availability (D'Odorico et al., 2020). Therefore, these commitments necessitate increasing attention to global agricultural water scarcity in the context of humankind's ability to meet future food demand (He and Rosa, 2023).

Agricultural green water scarcity occurs when the amount of rainfall is unable to meet crop water requirements. In such cases, supplemental blue water is provided by irrigation to ensure adequate crop growth and prevent water stress (Pereira et al., 2002). Agricultural blue water scarcity occurs when blue water resources cannot meet irrigation water requirements (Rosa et al., 2020b). Agricultural blue water scarcity has been the focus of the water scarcity debate, and alarmingly, half of irrigated croplands are facing blue water scarcity or are under unsustainable irrigation practices (Rosa et al., 2019; Mekonnen and Hoekstra, 2020). As a result, rain-fed agriculture will continue to be a major component of global food systems (Rosa, 2022). Unfortunately, climate change is expected to reshape the extent of agricultural water scarcity worldwide (Rosa et al., 2020b; Fitton et al., 2019) to the point that, by the end of the century, agricultural blue water scarcity could require the transition of 60 million hectares of croplands from irrigated to rain-fed (Elliott et al., 2013). Compared with irrigated croplands, rain-fed croplands are expected to be more affected by climate change (Rojas et al., 2019). However, limited understanding of the impacts of climate change on green water availability and demand adds uncertainties to future water and food security and adaptation interventions in agriculture (He and Rosa, 2023).

Water scarcity increased food waste

Measures to reduce water scarcity have primarily focused on improving water productivity (Marston et al., 2021), especially in the agricultural sector, which is responsible for more than 90 percent of global consumptive freshwater use (Hoekstra and Mekonnen, 2012). The agriculture sector, both crop and livestock production, will need system level interventions, from farm to table, to address the water scarcity issue. Water scarcity is an ongoing challenge with no single remedy. Interventions such as shifting to more efficient irrigation technologies (Jägermeyr et al., 2015), growing crops best suited to a specific climatic environment (Davis et al., 2017) and cultivating less water intensive crops (Marston and Konar, 2017) can reduce the agriculture sector's water footprint and its contribution to water scarcity. However, one of the most promising means of reducing society's water footprint that goes largely ignored is by reducing global food waste and loss (Mekonnen and Fulton, 2018).

Food waste occurs at all points within the supply chain: on the farm, at processing facilities, during storage and transport/distribution and at retail outlets and households. At least one-third of all food produced is estimated to be lost or wasted globally (Gustavsson et al., 2011). Wasted food is also wasted water. One-fourth of freshwater consumed in global food production is effectively wasted since the food produced with this water is never consumed (Kummu et al., 2012). The blue water footprint of global crop production is 723 km^3/year, meaning uneaten plant-based food represents 174 km^3 of wasted blue water each year (Kummu et al., 2012). If wasted meat products are included, FAO (2013) estimates 250 km^3 of blue water was wasted due to food loss and waste in 2007.

Global food losses amount to 413 million metric tons at the agricultural production stage, 293 million metric tons in post-harvest handling and storage, 148 million metric tons in processing, 161 million metric tons in distribution, and 280 million metric tons is wasted in consumption for a total of 1.3 billion metric tons of annual food loss and waste (Gustavsson et al., 2011). In the United States alone, the total annual food loss and waste across all stages of the food supply chain is estimated to be 126 million tons, or about 10 percent of the world total (CEC, 2017). Global freshwater wasted due to food loss and waste per capita per year is ~21 m^3 (Chen et al., 2020). However, this amount varies greatly between high income (43 m^3 per capita) and lowincome (4 m^3 per capita) countries (Chen et al., 2020). As a result, more than three times as much surface water and groundwater are wasted each year due to food loss and waste than the average annual flow of the Nile River (Siam and Eltahir, 2017).

Losses throughout the food system not only increase the demands on food production but also induce the consequent production-related environmental impacts that could be avoided in the absence of food waste (Chen et al., 2020). Buzby et al. (2014) estimated that 31 percent of available food in the U.S. remains uneaten due to losses at the retail and consumer levels, equaling 1,249 calories/capita/day. All the world's 815 million hungry people (Blas et al., 2018) could be lifted out of energy or protein malnourishment on less than a quarter of the wasted food in the United States, United Kingdom and Europe (Stuart, 2009). Halving food loss and waste would also potentially increase food availability by 1,300 trillion kcal per year by 2050, corresponding to 22 percent of the estimated crop production increase required to meet demand in 2050 (Lipinski et al., 2013). Food loss and waste is responsible for 25 to 34 percent of the United States' consumptive freshwater used for food production (Hall et al., 2009; Birney et al., 2017; Mekonnen and Fulton, 2018). Cereals, fruits and vegetables are the three major food groups contributing the most to wasted nutrients followed by meat, poultry and eggs (Chen et al., 2020).

The last decade of research has established a clear link between wasted food and wasted water (Marston et al., 2021). Halving global food loss and waste could reduce the water footprint of global food production by 12 to 13 percent (Jalava et al., 2016; Springmann et al., 2018). In addition, reducing food loss and waste by 50 percent would improve water scarcity for over 720 million people globally, and totally eliminate local water scarcity for 131 million of those people (Jalava et al., 2016). However, food loss and waste result from a variety of causes (Thyberg and Tonjes, 2016), and it will take a diverse set of policies to combat it (Muth et al., 2019). Food waste is receiving growing interest from local and national policymakers, international organizations, non-governmental organizations and academics. Governments and international organizations have set policy targets to reduce food waste and its environmental impacts. Both the European Union (European Commission, 2019) and the United States (US EPA, 2019) have instituted goals to reduce food waste at the retail and consumer levels by 50 percent by 2030, following the United Nations' Sustainable Development Goal 12.3 (Rosa, 2017).

In addition to national and international interests, the private sector, particularly large transnational food corporations, plays a critical role in reducing food loss and waste all along the supply chain through their influence on both consumers and producers (Marston et al., 2021). Eight companies control 54 percent of the global soybean market, three companies control 42 percent of the global banana market, and three companies control 60 percent of the cocoa market (Folke et al, 2019). In the U.S., three companies control markets for three quarters of all cattle and over half of all pigs and chickens (Smith et al., 2017). This high concentration in the food sector means that implementing sustainability standards aimed at reducing food loss and waste by just a handful of companies would have substantial impacts throughout the supply chain. However, social pressure and government regulation may be needed to move food companies to reduce food loss and waste and implement sustainability practices throughout their supply chains, given the private sector's priority of profit over environmental or societal goals (Grizzetti et al., 2013; Folke et al., 2019). Even then, this may not be enough. More transformative climate interventions may be necessary. These could range from farm management adjustments, technological developments (precision agriculture, precision livestock farming, artificial intelligence), income-related responses to institutional changes and, in extreme cases, abandonment of crop and livestock farming in some areas due to water scarcity (Weindl et al., 2015; Herrero et al., 2016, 2018; Escarcha et al., 2018; Henry et al., 2018;).

Summary

Global warming and its associated changes on climate variables and climate variability affect feed and water resources as well as animal health and production. Global warming is expected to increase the intensity and frequency of extreme weather events, leading to unpredictable water availability and exacerbating water scarcity. Climate change also has implications for the processing, storage, transport, retailing and consumption of food products, which affects the amount of global food loss and waste. Food waste must be addressed if we expect to have a sustainable food security system in the future. Reducing food loss and waste has the potential to improve both food and water security. Water scarcity is one of the leading challenges of the twenty-first century, and it is expected to intensify because of climate change. Quantifying future impacts of climate change on crop and livestock systems is paramount to designing intervention strategies and adaptation solutions. Precision agriculture/precision livestock farming practices provide opportunities to demonstrate that wise use of agricultural technology and engineering have the potential to contribute to global food and water security as efforts are made to adapt to a changing global climate.

References

Baile, C.A., and J.M. Forbes. 1974. Control of feed intake and regulation of energy balance in ruminants. Physiological Reviews 54(1):160-214

Bett, B.K., J. Gachohi, C. Sindato, et al. 2017. Effects of climate change on the occurrence and distribution of livestock diseases. Preventive Veterinary Medicine 137(Part B):119-129.

Birney C.I., K.F. Franklin, F.T. Davidson, and M.E. Webber. 2017. An assessment of individual foodprints attributed to diets and food waste in the United States. Environmental Research Letters 12:105008.

Blas, A, A. Garrido, and B. Willaarts. 2018. Food consumption and waste in Spanish households: Water implications within and beyond national borders. Ecological Indicators 89:290-300.
Buzby, J.C., H.F. Wells, and J. Hyman. 2014. The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States. EIB-121. USDA-Economic Research Service.
CEC. 2017. Characterization and Management of Food Loss and Waste in North America – White Paper, North American Initiatives on Food and Organic Waste. Montreal, Canada.
Chen, C., A. Chaudhary, and A. Mathys. 2020. Nutritional and environmental losses embedded in global food waste. Resources, Conservation and Recycling 160:104912to
Cheng, M., B. McCarl, and C. Fie. 2022. Climate change and livestock production: A literature review. Atmosphere 13(1):140.
Collier, R.J., D.K. Beede, W.W. Thatcher, L.A. Israel, and C.J. Wilcox. 1982. Influences of environment and its modification on dairy animal health and production. Journal of Dairy Science 65:2213-2227.
Daramola, J.O., M.O. Abioja, and O.M. Onagbesan. 2012. Heat stress impact on livestock production. In V. Sejian, S.M.K. Naqvi, T. Ezeji, J. Lakritz, and R. Lal (Eds): Environmental Stress and Amelioration in Livestock Production. Springer, Berlin/Heidelberg, Germany. pp 53-73.
Davis, K.F., J.A. Gephart, K.A. Emery, A.M. Leach, J.N. Galloway, and P. D'Odorico. 2016. Meeting future food demand with current agricultural resources. Global Environmental Change 39:125-132.
Davis, K.F., M.C. Rulli, A. Seveso, and P. D'Odorico. 2017. Increased food production and reduced water use through optimized crop distribution. Nature Geoscience 10:919-924.
D'Odorico, P., D.D. Chiarelli, L. Rosa, and M.C. Rulli. 2020. The global value of water in agriculture. Proceedings of the National Academy of Sciences 117(36):21985-21993.
Elliott, J., D. Deryng, C. Müller, and D. Wisser. 2013. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences. 111(9):3239-3244.
Escarcha, J., J. Lassa, and K. Zander. 2018. Livestock under climate change: A systematic review of impacts and adaptation. Climate 6:54.
European Commission. 2019. EU Platform on Food Losses and Food Waste Terms of Reference. Available at: ec.europa.eu/food/sites/food/files/safety/docs/fw_eu-actions_flw_platform_tor.pdf. Accessed:18 September 2023.
Fader, M., S. Shi, W. von Bloh, A. Bondeau, and W. Cramer. 2016. Mediterranean irrigation under climate change: More efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrology and Earth System Sciences Discussions 12(8):8459-8504.
Falkenmark, M. 1995. Land-water linkages – a synopsis. Land and water integration and river basin management. FAO Land and Water Bulletin. Rome, Italy.
Falkenmark, M., and J. Rockström. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. Journal of Water Resources Planning and Management 132(3):129-132.
Falkenmark, M. 2013. Growing water scarcity in agriculture: Future challenge to global water security. Philosophical Transactions of the Royal Society A 371:20120410.
FAO. 2013. *Food Wastage Footprint: Impacts on Natural Resources*. Food and Agriculture Organization of the United Nations. Rome, Italy.

Fitton, N., P. Alexander, N. Arnell, B. Bajzelj, et al. 2019. The vulnerabilities of agricultural land and food production to future water scarcity. Global Environmental Change 58:101944.

Folke, C., H. Österblom, J.B. Jouffray, E.F. Lambin, et al. 2019. Transnational corporations and the challenge of biosphere stewardship. Nature Ecology and Evolution 3:1396-1403.

Gerber, P.J., H. Steinfeld, B. Henderson, A. Mottet, et al. 2013. *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

Gerten, D., J. heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha. 2011. Global water availability and requirements for future food production. Journal of Hydrometeorology 12:885-899.

Kandalam, G., and A. Samireddypalle. 2015. Impact of climate change on forage availability for livestock. In: *Climate Change Impact of Livestock: Adaptation and Mitigation*. Springer, Berlin, Germany. pp 97-112.

Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero. 2021. Impacts of climate change on the livestock food supply chain: A review of the evidence. Global Food Security 28:100488.

Grizzetti, B., U. Pretato, L. Lassaletta, G. Billen, and J. Garnier. 2013. The contribution of food waste to global and European nitrogen pollution. Environmental Science and Policy 33:186-195.

Gustavsson, J., C. Cederberg, U. Sonesson, R.V. Otterdijk, and A. Meybeck. 2011. *Global Food Losses and Food Waste: Extent, Causes and Prevention*. Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. 29.

Hall, K.D., J. Guo, M. Dore, and C.C. Chow. 2009. The progressive increase of food waste in America and its environmental impact. PLoS ONE 4:e7940.

He, L., and L. Rosa. 2023. Solutions to agricultural green water scarcity under climate change. PNAS Nexus 2(4):1-11.

Henry, B.K., R.J. Eckard, and K.A. Beauchemin. 2018. Review: Adaptation of ruminant livestock production systems to climate changes. Animal 12:S445-S456.

Herrero, M., J. Addison, C. Bedelian, E. Carabine, et al. 2016. Climate change and pastoralism: Impacts, consequences and adaptation. Revue Scientifique et Technique 35(2):417-433.

Herrero, M., D. Mason-D'Croz, C.M. Godde, J. Palmer, P.K. Thornton, and M. Gill. 2018. Livestock, land and the environmental limits of animal source-food consumption. Science Forum 2018 Background Papers. CGIAR Independent Science and Partnership Council. Rome, Italy.

Hoekstra, A.Y., and M.M. Mekonnen. 2012. The water footprint of humanity. Proceedings of the National Academy of Sciences 109:3232-3237.

Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press. New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 2021. *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., P. Zhai, A. Pirani, et al. (Eds.). Cambridge University Press. New York, NY, USA.

Jägermeyr, J., D. Gerten, J. Heinke, S. Schaphoff, M. Kummu, and W. Lucht. 2015. Water savings potentials of irrigation systems: Global simulation of processes and linkages. Hydrology and Earth System Sciences 19:3073-3091.

Jalava, M., J.H. Guillaume, M. Kummu, M. Porkka, S. Siebert, and O. Varis. 2016. Diet changes and food loss reduction: What is their combined impact on global water use and scarcity? Earth's Future 4:62-78.
John, D.A., and G.R. Babu. 2021. Lessons from the aftermaths of green revolution on food system and health. Frontiers in Sustainable Food Systems 5:644559. doi: 10.3389/fsufs.2021.644559.
Jones, P.G., and P.K. Thornton. 2009. Croppers to livestock keepers: Livelihood transitions to 2050 in Africa due to climate change. Environmental Science and Policy 12(4):427-437.
King, M., D. Altdorff, P. Li, L. Galagedara, J. Holden, and A. Unc. 2018. Northward shift of the agricultural climate zone under 21st-century global climate change. Scientific Reports 8:7904.
Kummu, M., H. De Moel, M. Porkka, S. Siebert, O. Varis, and P.J. Ward. 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertilizer use. Science of the Total Environment 438:477-489.
Legesse, G., K.H. Ominski, K.A. Beauchemin, S. Pfister, et al. 2017. Board-invited review: Quantifying water use in ruminant production. Journal of Animal Science 95:2001-2018.
Lipinski, B., C. Hanson, J. Lomax, L. Kitinoja, R. Waite, and T. Searchinger. 2013. Reducing food loss and waste, Installment 2 of creating a sustainable food future. World resources Institute. Washington, D.C.
Lopez, J., G.W. Jesse, B.A. Becker, and M.R. Ellersieck. 1991. Effects of temperature on the performance of finishing swine: I. Effects of a hot, diurnal temperature on average daily gain, feed intake, and feed efficiency. Journal of Animal Science 69:1843-1849.
Maribam, U., O.K. Hooda, P.S. Sharma, R.C. Upadhyay, and A.K. Mohanty. 2018. Differential level of oxidative stress markers in skin tissue of zebu and crossbred cattle during thermal stress. Livestock Science 207:45-50.
Marston, L., and M. Konar. 2017. Drought impacts to water footprints and virtual water transfers of the Central Valley of California. Water Resources Research 53:5756-5773.
Marston, L.T., Q.D. Read, S.P. Brown, and M.K. Muth. 2021. Reducing water scarcity by reducing food loss and waste. Frontiers in Sustainable Food Systems 5:651476. doi: 10.3389/fsufs.2021.651476.
Mekonnen, M.M., and J. Fulton. 2018. The effect of diet changes and food loss reduction in reducing the water footprint of an average American. Water International 43(6):860-870.
Mekonnen, M.M., and A.Y. Hoekstra. 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15:401-415.
Mekonnen, M.M, and A.Y. Hoekstra. 2016. Four billion people facing severe water scarcity. Science Advances 2(2):e1500323. doi: 10.1126/sciadv.1500323.
Mekonnen, M.M, and A.Y. Hoekstra. 2020. Blue water footprint linked to national consumption and international trade is unsustainable. Nature Food 1:792-800.
Morignat, E., J.B. Perrin, E. Gay, J.L. Vinard, D. Calavas, and V. Hénaux. 2014. Assessment of the impact of the 20003 and 2006 heat waves on cattle mortality in France. PLoS ONE 9:e93176.
Muth, M.K., C. Birney, A. Cuéllar, S.M. Finn, et al. 2019. A systems approach to accessing environmental and economics effects of food loss and waste interventions in the United States. Science of the Total Environment 685:1240-1254.
Pereira, L.S., T. Oweis, and A. Zairi. 2002. Irrigation management under water scarcity. Agricultural Water Management 57:175-206.

Rashamol, V.P., V. Sejian, M. Bagath, G. Krishnan, P.R. Archana, and R. Bhatta. 2018. Physiological adaptability of livestock to heat stress: An updated review. Journal of Animal Behaviour and Biometeorology 6(3):62-71.

Reynolds, C., L. Crompton, and J. Mills. 2010. Livestock and climate change impacts in the developing world. Outlook on Agriculture 39(4):245-248.

Rockström, J., M. Falkenmark, L. Karlberg, H. Hoff, S. Rost, and D. Gerten. 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. Water Resources Research 45(7).

Rojas, M., F. Lambert, J. Ramirez-Villegas, and A.J. Challinor. 2019. Emergence of robust precipitation changes across crop production areas in the 21st century. Proceedings of the National Academy of Sciences 116:6673-6678.

Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management 16:145-163.

Rosa, L. 2022. Adapting agriculture to climate change via sustainable irrigation: Biophysical potentials and feedbacks. Environmental Research Letters 17:063008.

Rosa, L., D.D. Chiarelli, C. Tu, M.C. Rulli, and P. D'Odorico. 2019. Global unsustainable virtual water flows in agricultural trade. Environmental Research Letters 14:114001.

Rosa, L., D.D. Chiarelli, M.C. Rulli, J. Dell'Angelo, and P. D'Odorico. 2020a. Global agricultural economic water scarcity. Science Advances 6:eaaz6031.

Rosa, L., D.D. Chiarelli, M. Sangiorgio, and I. Fung. 2020b. Potential for sustainable irrigation expansion in a 3 °C warmer climate. Proceedings of the National Academy of Sciences 117(47):29526-29534.

Rosa, W. (Ed,). 2017. *Transforming Our World: The 2030 Agenda for Sustainable Development: A New Era in Global Health.* Springer Publishing Company. New York, N.Y.

Siam M.S., and E.A. Eltahir. 2017. Climate change enhances interannual variability of the Nile River flow. Nature Climate Change 7:350-354.

Smith, T.M., A.L. Goodkind, T. Kim, R.E. Pelton, K. Suh, and J. Schmitt. 2017. Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains. Proceedings of the National Academy of Sciences 114:E7891-E7899.

Springmann, M., M. Clark, D. Mason-D'Croz, K. Wiebe, et al. 2018. Options for keeping the food system within environmental limits. Nature 562:519-525.

Steinfeld, H., C. Opio, J. Chara, K.F. Davis, P. Tomlin, and S. Gunter. 2019. Overview paper: Livestock, climate and natural resource use. Kansas State University. Available at: www.ksre.k-state.edu/news/stories/2019/09/Climate-and-Natural-Resource-Use.pdf. Accessed: 13 September 2023.

Stuart, T. 2009. *Waste: Uncovering the Global Food Scandal*. W.W. Norton and Company. New York, N.Y.

Syafwan, S, R.P. Kwakkel, and M.W.A. Verstegan. 2011. Heat stress and feeding strategies in meat-type chickens. World's Poultry Science Journal 67:653-674.

Thyberg, K.L., and D.J. Tonjes. 2016. Drivers of food waste and their implication for sustainable policy development. Resources, Conservation and Recycling 106:110-123.

US EPA. 2019. Winning on Reducing Food Waste. Available at: epa.gov/sustainable-management-food/federal-interagency-collaboration-reduce-food-loss-and-waste. Accessed: 18 September 2023.

Vallino, E., L. Ridolfi, and F. Laio. 2020. Measuring economic water scarcity in agriculture: A cross-country empirical investigation. Environmental Science and Policy 114:73-85.

Vanham, D. 2016. Does the water footprint concept provide relevant information to address the water-food-energy- ecosystem nexus? Ecosystem Services 17:298-307.

Vanham, D., A.Y. Hoekstra, Y. Wada, F. Bouraoui, et al. 2018. Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress." Science of the Total Environment 613-614: 218-232.

Ward, D., and K. McKague. 2023. Water requirements of livestock. Ontario Ministry of Agriculture, Food and Rural Affairs. Factsheet #23-023. February.

Weindl, I., L.C. Hermann, P. Alexander, et al. 2015. Livestock in a changing climate: Production system transitions as an adaptation strategy for agriculture. Environmental Research Letters 10:094021.

Yadav, B., G. Singh, A.K. Verma, N. Dutta, and V. Sejian. 2013. Impact of heat stress on rumen functions. Veterinary World 6(12):992-996.

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