Agriculture and Human Values (2023) 40:373–394
https://doi.org/10.1007/s10460-022-10338-x

A review of megatrends in the global dairy sector: what are the socioecological implications?

Milena Bojovic[1] · **Andrew McGregor**[1]

Accepted: 16 June 2022 / Published online: 14 July 2022

Abstract

The global dairy industry is undergoing a period of expansion and consolidation, alongside heightened critique and competition from non-dairy alternatives. This review identifies four key megatrends within the global dairy sector, focusing in on the socioecological challenges associated with each. The megatrends were identified through a literature review of recent publications within the dairy science and social science fields, as well as a review of grey literature from intergovernmental and institutional reports. Key findings include geographical range shifts in production and consumption of dairy milk from the Global North to the Global South; intensification of production agendas that strive for mechanisation, standardisation, and corporatisation of the sector; increasing awareness of the ecological impacts of intensive dairying; and finally, disruptions to the sector driven by plant-based milks and, potentially, synthetic milks. We identify under-researched socioecological challenges associated with each of these trends. Although dairy milk may be homogenous in its final form, the sector remains heterogenous in its impacts across spaces, places, and scales, as increasingly intensive dairying systems fundamentally reshape human–cattle relations. The combined impacts of these trends bring into question the mythologies of milk and the assumed desirability of ever-expanding dairy industries. Our review finds that the future of dairy is not clear nor uncontroversial and that more attention needs to be directed to maximising and broadening the social benefits of the dairy and dairy alternatives, minimising the human and non-human costs, and limiting contributions to global climate change.

Keywords Dairy · Milk · Agriculture · Megatrends · Socioecological impacts

Introduction

Dairy[1] milk exists as a fresh product (as milk or by-products of milk), in powdered forms, and as a synthesized set of proteins and fats in industrial foodstuffs. The United Nations Food and Agriculture Organisation (FAO 2019) estimates that over 80% of the world's population consume dairy products on a regular basis. Innumerable human and non-human lives and associated ecologies are entangled in milk production and consumption, creating social and ecological (socioecological) vulnerabilities that are casting clouds over the future of the sector. Based on the analysis below, we believe the global dairy sector is likely to undergo a period of significant transition over the next few decades.

There have been increasing calls to move beyond animal-based food systems to more sustainable forms of food production in a bid to address the true costs of animal agriculture and build more resilient food systems (for example, see Poore and Nemecek 2018; Springmann et al. 2018; Willet et al. 2018; Pieper et al. 2020). Morris et al. (2021, p. 2) characterise this shift as a "societal grand challenge". In this paper we engage with this challenge by synthesising current trends in dairy and identifying emerging challenges and opportunities. The aim is to generate knowledge that can contribute to research agendas and policy dialogues about how to live (and eat) sustainably in the current epoch of global environmental change.

Our approach differs from other reviews of the sector conducted via institutional sustainability reports, dairy sciences,

✉ Milena Bojovic
Milena.bojovic@hdr.mq.edu.au

Andrew McGregor
Andrew.McGregor@mq.edu.au

1 Discipline of Geography and Planning, Macquarie University, Balaclava Rd, Macquarie Park, Sydney, NSW 2109, Australia

[1] For this paper, the term 'dairy' refers to bovine milk in its whole form, as well as milk powder, butter, cheese, yoghurt, ice-cream, cream and any other industrially processed foods that may contain milk by-products (often in the form of milk powder).

or agricultural economics that tend to focus upon expansion and growth within the sector. Instead, we analyse the socioecological dimensions of change. In doing so we are interested in how people, places and environments are being affected by trends within the dairy sector in order to highlight unintentional or hidden impacts of change.

The first section of the paper explains the methodological framing for this review. Following this, we identify four megatrends, where megatrends are approached as trajectories of social, economic, environmental, or technological change occurring over the coming decades that "continually reshape the world around us" (Hajkowicz 2015, p. 3). The four trends we identify are:

(1) Shifting geographies and scales of production and consumption,
(2) Intensification of capital, land and animals,
(3) Growing awareness of the ecological impacts of dairy,
(4) Alternative milk distruptions.

The discussion section of the paper synthesises the four trends to reveal how they come together to inform the scale and diversity of challenges facing the sector and their associated socioecological implications. Our analysis raises questions about the mythologies of milk, particularly the often-unspoken assumption that an ever-expanding industry is good for people, cattle or the planet.

Methodology

In this section, we explain our methodological approach. We outline our data collection process, how we are approaching socioecological impacts, and how we define and identify megatrends. We also briefly reflect on the limitations of our review through what was included and excluded through this process. Before continuing, it is important to note our focus is on planetary trends, however we are also interested in differences between the countries commonly grouped as the Global North and Global South. Countries in the Global North include European, North American, Australian and New Zealand dairy industries, whereas the Global South incorporates predominantly Asian, African and Latin American markets. We draw on these imagined geographies to discuss trends, though we acknowledge that the reality of these categories is much more nuanced and a detailed synthesis of each region's dairy industry is likely to reveal much greater diversity and difference.

Data selection process

To begin the process for this review, we read through recent grey literature produced by influential multilateral institutions that reported on the current state and future modelling of the global dairy sector. This included reports from the United Nations FAO (see FAO 2019, 2020; FAO et al. 2020), the OECD–FAO coalition (see OECD–FAO 2010, 2020, 2021), as well as information from the Intergovernmental Panel on Climate Change (IPCC) special report on land and climate change (see Mbow et al. 2019). We also analysed high profile papers that have examined the role of livestock within future food systems in the context of climate change (see Springmann et al. 2019; Willet et al. 2018). After reading these reports, key search terms were chosen based upon reoccurring themes in the literature. These were used in Scopus and Google Scholar database searches and included terms like "dairy trends", "dairy review", "dairy" AND "sustainability", "climate change", "plant-based milks", "synthetic dairy", "synthetic milks" and similar searches.

In this scoping study, we prioritised articles from the period 2017 to 2021.[2] We followed a similar review process to Aschemann-Witzel et al. (2020) work on plant-based trends to inform our selection of academic literature, focussing on peer-reviewed journal articles published in the past 5 years that highlighted the most current trends and issues in the sector. Our search highlighted academic literature that came predominantly from the fields of dairy science, food innovation and social science scholarship. We initially identified academic reviews of the dairy sector, such as those published within the Journal of Dairy Science (see Beaver et al. 2020; Schuster et al. 2020; Britt et al. 2018; Pulina et al. 2018; McCarthy et al. 2017) and other key review papers across different environmental, social and nutritional journals about dairy production and consumption (see Gauly et al. 2013; Aschemann-Witzel et al. 2020; Fiel et al. 2020; Roy et al. 2020; Stephens 2020; Hjalsted et al. 2020; Lonkila and Kaljonen 2021; Cogato et al. 2021; Wankar et al. 2021). We narrowed in on the reviews that we felt had particular relevance to our socioecological framing. We also purposively selected 40 case study papers referred to in the reviews that concentrated upon a socioecological dimension of a megatrend we were interested in, such as plant-based milks or intensification. Our data selection process is shown in Fig. 1. A list of all reviewed articles is available in "Appendix".

Socioecological analysis

Our review centres upon the megatrends that are contributing to socioecological change within dairy industries. Rather than see ecological or social impacts bracketed off from one another as may be the case in an economic or environment

[2] There are articles referred to throughout this review that have been published outside of this timeframe but nonetheless contribute to the understanding of how the global dairy sector has evolved over time.

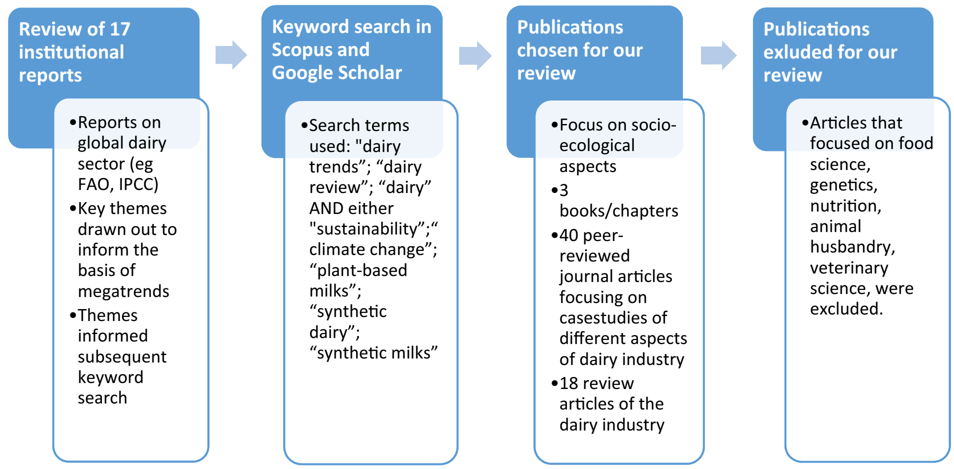

Fig. 1 Flow chart of data selection process for our review

review, we attempt to bring the multiple human and non-human actors that comprise dairying, including the economies, environments and bodies that enable and are shaped by dairying, into view and consideration. Our approach has been influenced by political ecology, more-than-human geography and the broader environmental humanities, which highlight that the relations *between* things as an important factor in shaping the world (see Whatmore 2002; Latour 1999; Haraway 2003). Concepts like "co-becoming" recognise how humans, cattle and environments never evolve on their own but are caught up in complex relations that change over time. Here we are interested in identifying the megatrends that are reshaping these relations within dairy industries and the ramifications for the human and non-human actors within it. This requires recognising cattle as "lively" more-than-human actors (Collard and Dempsey 2013; Holloway and Bear 2017; Bear and Holloway 2019; Gillespie and Collard 2015; Gillespie 2021) who shape and are shaped by these trends and highlighting the intended and unintended outcomes of dairy industries at different scales (for example, see McGregor et al. 2021). It also requires a level of abstraction, as we cannot do justice to the in-depth ethnographic work on dairying, and instead draw upon selected case study research to help think through some of the impacts of megatrends for socioecological communities.

In doing so, we build upon and extend the work of Clay and Yurco (2020) on the political ecology of milk, Clay et al.'s (2020b) examination of the drivers of dairy intensification and possibilities of dairy alternatives, Mylan et al.'s (2019) exploration of the possibilities of plant-based milk and Zafrilla et al.'s (2020) review of the sustainability challenges to dairy livestock systems. These researchers have begun challenging the implicit assumption in much of the literature that dairy should be encouraged to grow and expand. Instead, our socioecological analysis problematises this thinking by tracing how megatrends in dairy are related to changing relations and socioecological wellbeing of humans, non-humans, and environments. In doing so we follow Sexton et al. (2019, p. 48) who argue that such approaches can create more openings for narratives that evoke and invent "more compassionate human–animal relationships".

Data analysis: identifying megatrends

The idea of megatrends was first introduced by Naisbitt (1982) as a means identifying new ideas, interpretative communities, ways of knowing and worldviews for subsequent analysis (Slaughter 1993). The mega refers to the macro-scale of the processes and the likely impacts of the trend, with Mittelstaedt et al. (2014, p. 254) arguing that megatrends are complex "social science constructs" which are "seismic in their effect, both in time and space". They are "seismic" because as Visconti et al. (2014, p. 363) assert, a megatrend "is the beginning of a new trajectory that interrogates the established direction a system has followed before". As such megatrends destabilise the status quo creating new opportunities and challenges for those reliant upon existing structures. They are social because, as Rohner (2018, p. 30) contends, megatrends "impacts the lens with which society views the world, thus influencing values and thinking". We approach megatrends within dairy as sector-wide processes that are transforming how and where the dairy sector operates and how socioecologies are affected by and interact with dairying. Megatrends shape and are shaped by existing socioecological structures including institutional systems, organisations, operations, environments and human and non-human actors (Turner 2005).

We identified megatrends in the global dairy sector through an iterative process. We first identified a broad range of reoccurring themes that appeared in the grey and academic literature that related to socioecological challenges and opportunities. Each of these themes are relevant to the dairy sector, are discussed in dairy industry reviews, and tend to attract case study research. We then sought to group

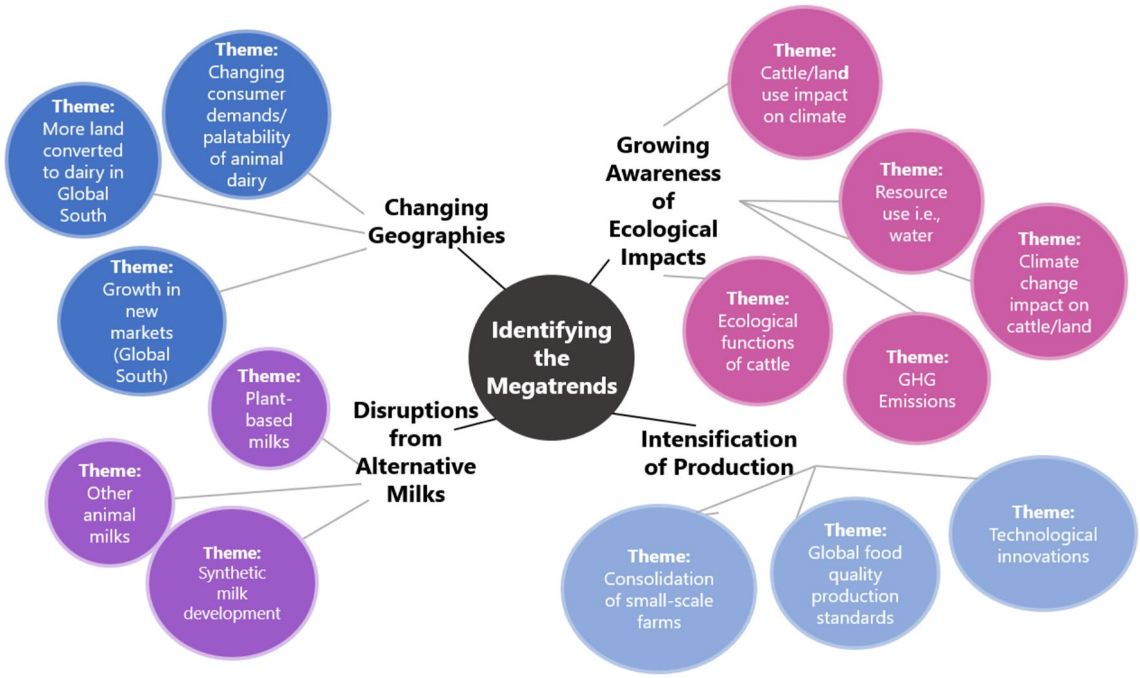

Fig. 2 Mind map used to identify themes and megatrends process

these themes to identify the broader megatrend of which they were a part. For example, robotics and automated milking is an important theme that is transforming elements of the sector however the disruptive influence of automation is much more significant when considered alongside the related themes of corporatisation and standardisation, both of which are aligned with automation, collectively contributing to a megatrend around dairy intensification. Similarly, while dairy emissions are a source of much analysis, when combined with various other issues in the literature, such as the climate change induced heat stress or resource depletion, they combine to form a sector wide megatrend about the growing concern of various aspects of dairying's relationship with the environment. Themes shifted to megatrends when they could be grouped in a way that suggested macro-scale, sector-wide changes. The themes and megatrends are evident in Fig. 2.

In focusing on socioecological dimensions of megatrends and identifying them in this iterative way we do not attempt to identify all the trends happening across the dairy sector. There are two main gaps in our analysis. First, we do not focus in on trends within dairying subfields such as food science, genetics, nutrition, or veterinary science. While important advancements are occurring in each of these fields it is only at the point in which trends in these fields impact the broader socioecological relations of the dairy industry that they would become incorporated into this analysis. Second, and relatedly, our focus is upon large scale trends that are occurring now in the dairy sector rather than a focus on emerging research priorities or small-scale changes. As such we acknowledge, for example, that there is a great deal of promising discussion about climate smart and regenerative agriculture amongst key multilateral bodies (for example, see FAO 2021), however, based on our review of the literature, this has yet to have widespread impacts that are causing a seismic shift within the sector. Instead, we see these sorts of initiatives as themes that emerging as part of a broader megatrend concerned about the environmental impacts of dairying. Indeed, if such initiatives are to gain widespread uptake, they will need to engage with other more established megatrends, such as intensification, that seems to push in counter directions. We now discuss each megatrend in turn.

Megatrends

Shifting geographies and scales of production and consumption: from North to South

Consumption of dairy milk[3] was historically contingent on regional availabilities of resources, arable land, population growth and access to cattle. Cattle originated in the Middle East but became domesticated in many parts of the world and

[3] This point does not include other types of animal milks such as camel, mare, sheep or goat, which continue to be a vital food source for many rural and nomadic cultures.

embedded in local dairy systems. Cattle ranges expanded considerably through colonialism when these "creatures of empire" played a key role in territorial expansion (Anderson 2004). By the twentieth century, narratives about milk had become mythologised, associated with generalised goodness and story lines of "modernisation, progress and nation building" within European and North American markets (Clay and Yurco 2020, p. 3). High intake of dairy products has been widely promoted in Northern countries, often for bone health due to its high calcium content (Willet et al. 2019). The dairy industry is now well established in the Global North with consumption of fresh dairy projected to reach 25.2 kg per capita of milk solids by 2030, compared with 12.6 kg per capita[4] (OECD–FAO 2021, p. 179) in the South. However, as we discuss below, demand for dairy milk has flattened out or is declining in some countries in the North where plant-based milks are capturing part of the market.

Dairy milk has since proven globally attractive with demands for animal-based proteins (meat and dairy) increasing in poorer countries as incomes rise (Stephens 2020). Increasing dairy consumption is part of the so-called "nutrition transition" (Popkin 2003) that necessitates an accompanying "livestock revolution" (Delgado 2003) to produce more meat and dairy. Advertising campaigns supporting the consumption of milk (see Zafrilla et al. 2018) are increasing demands for fresh dairy products in growing markets across the Global South, particularly in India, Pakistan and parts of Africa (OECD–FAO 2020, p. 175). For example, OECD–FAO (2020) find that more "away-from-home" eating in Southeast Asian countries is driving up demand for dairy consumption, such as cheese, as consumers eat more processed fast-foods.

Part of the success of dairy expansion has come from the adaptability of milk products, which can be transported in powdered forms. At present, fresh dairy products tend to be more expensive in the Global South (such as Sub-Saharan Africa, Eastern and South-eastern Asia) than in the Global North as fresh milk is more expensive to trade due to its highly perishable nature (FAO et al. 2020). To ensure a constant and cheaper supply of longer-life milk, fresh milk is converted to powdered forms, for which an integrated network of export markets have been developed. Most dairy imports and exports are in the form of whole milk powder (WMP) or skim milk powder (SMP) (OECD–FAO 2020). The major dairy exporters are New Zealand, the European Union and the United States (OECD–FAO 2020).

The OECD–FAO Agricultural Outlook (2021) projections for 2021–2030 have modelled increased production across developed and developing countries, according to kilo tonnes per week (kt pw) shown in Table 1. This is in line with OECD–FAO (2010) findings from a decade earlier, which projected more milk will be produced outside of the OECD and that growth is expected for all dairy products with WMP, butter and cheese having the strongest growth. Production in the Global South now outstrips that of the North, much of it associated with rapid growth in India and China. However given approximately 80% of the world's population is in the South, it is still lower on a per capita basis. Nevertheless, the present outlook clearly identifies a period of rapid growth for the dairy sector in the Global South as it is predicted to expand by approximately a third in the next 10 years as shown in Table 1.

Table 1 Global milk production trends 2021–2030

Year	Developed Countries (kt pw)	Developing Countries (kt pw)
2021	409,765	447,115
2030	435,996	583,695

Global milk production trends based on kilo of tonnes per week (OECD–FAO 2021)

According to *Rabobank's* annual listing of top global dairy companies by turnover for 2020 (see Table 2), most large dairy organisations are from the Global North (Ledman and van Buttum 2020). Each of these multibillion-dollar companies owns multiple brands of both dairy products (milks, yoghurts, cheeses) as well as by-products that contain milk (confectionary, pet food, cereals) (Nestle 2021). However, dairy companies from China have moved up in ranking in recent years due to expanding total net worth and production capacity (through more mechanised forms of milk production). The Yili Group, which is known as Asia's largest dairy firm (Dairy Industries International 2020), has expanded its global reach, with partnerships involving Thailand, New Zealand, Italy, the Netherlands and Uruguay (Oceania Dairy 2020).

The recent and accelerating growth in dairy production in the South is occurring when the sector looks very different to what it did when it originally expanded in the North. As will be discussed, dairy is more corporatised, mechanised and mobile, and must compete in national and international markets, not just local ones. Current conditions favour capital-intensive rather than labour-intensive operations, favouring larger businesses over more traditional smaller family run farms. Dairy has become a key site of investment and capital accumulation, influencing the form and shape of the industry as it expands in the Global South. This presents land use and livelihoods challenges for small scale farms and farming communities and raises questions about who benefits from the expansion of dairy in the Global South across spaces and scales. The rapid growth of dairy production and

[4] It is important to note that figures about global dairy consumption may mask the vast differences across regions.

Table 2 Global dairy company rankings based on turnover in USD billion (RaboResearch 2020)

Global dairy rankings 2019/2020 2020 Rank	2019 Rank	Change	Company name and headquarter location	Dairy turnover for 2019 in USD billion
1	1	*No change*	Nestle (Switzerland)	22.1
2	2	*No change*	Lactalis (France)	21.0
3	6	↑	Dairy Farmers of America (USA)	20.1
4	3	↓	Danone (France)	18.2
5	8	↑	Yili (China)	13.4
6	4	↓	Fonterra (New Zealand)	13.2
7	5	↓	FrieslandCampina (Netherlands)	12.6
8	10	↑	Mengniu (China)	11.9
9	7	↓	Aria Foods (Denmark/Sweden)	11.8
10	9	↓	Saputo (Canada)	11.3

consumption in the Global South means that the socioecological challenges of dairy expansion will be concentrated there, as we discuss below.

Intensification of capital, land, and animals

Multiple and inter-related processes of dairy intensification represent a second megatrend in the dairy sector. The growth of large dairy companies (see Table 2) has resulted in an intensification of capital amongst a smaller group of influential actors, who have, in turn, sought to maximise profits by intensifying production, making the most out of dairying land and dairying bodies, both human and non-human. While milk production has historically been undertaken by pasture-based smallholder farms, economies of scale favour larger corporate entities over these smaller traditional businesses. This can result in smaller farms being bought out or replaced through a variety of means and consolidated into large dairy production systems who can invest in mechanisation and meet industry standards for greater profitability. Improved national and international transportation and processing systems enables this transition as more distant players can compete in what used to be mainly local markets. Further consolidation of dairy farms through processes of mergers, acquisitions and strategic alliances in the dairy industry are expected to continue (Knips 2005) as less competitive smaller dairy farms exit the market (for example, see Sewell 2021).

One of the drivers of capital intensification are the sanitation and quality standards demanded in contemporary food systems. Quality assurance for food is now an essential element within the global food industry and it is widely acknowledged that as standards become stricter, food manufacturers are required to invest in infrastructure and quality controls to remain competitive (Kotsanopoulos and Arvanitoyannis 2017). Agri-food chains are governed by strong interdependencies among retailers and controlling bodies that impose a variety of regulations (Gianni et al. 2017). The dairy sector is no exception to this, with increased public awareness regarding food safety pushing the dairy sector to improve the safety and image of dairy products (Ding et al. 2019). Britt et al. (2018) argue that structural consolidation of dairy farming will continue as the sector becomes more vertically integrated and that this requires more inputs to ensure milk products are meeting product quality demands, resulting in more resource and energy intensive production lines. From the collection of milk to the process of pasteurisation, homogenisation, storage, packaging, and distribution, each of these components comes with its own social, political, economic and environmental costs and expectations. Dairy processing, for example, is recognised as one of the most energy intensive sectors within the food industry (Briam et al. 2015; Challis et al. 2017; Ladha-Sabur et al. 2019), having particular safety requirements due to the perishable nature and limited shelf life of milk (Douphrate et al. 2013).

Meeting these standards can be difficult for small dairy producers and "traditional" household producers due to a lack of access to modern processing technologies and the time and expense meeting such standards may incur (Britt et al. 2018). Cattle bodies and outputs like milk vary dramatically across space and environments. While the push for quality standards advantages larger players as a form of risk management, it is having significant impacts upon those who cannot meet those standards (Lonkila and Kaljonen 2021). In a case study on family farms in the Global South, Bosc et al. (2018, p. 313) found that the functioning of family farms is often far removed from the "standards of agricultural specialisation" required by public policies. Regional differences in terms of development, regulations and exporting opportunities (Kotsanopoulos and Arvanitoyannis 2017) risks further marginalising smaller and poorer farmers who may not be able to meet and adapt to changing expectations. For example, Minten et al. (2020) found that although dairy milk production, quality and supply is increasing due to the prevalence of larger scale farms and their capacity to adopt new technologies and resources, smaller farms are increasingly excluded "because of relatively higher coordination costs that downstream firms in the value chain incur in their commercial engagements with these small farms" (Minten et al. 2020, p. 2). Reardon et al. (2009), similarly found that there was a trend of shifting from local sourcing in countries in the Global South to national, regional, and global networks to reduce cost and increase efficiencies within a competitive market context. China estimates that at least 100,000 small-scale dairy farmers have stopped farming altogether since 2010, not helped by a ban on the collection of milk from many small-scale family farms due to concerns about milk quality (Bai et al. 2018).

A second driver and outcome of a more consolidated and intensive dairy sector has been investment in new technologies such as robotics to reduce labour costs. Automatic milking systems (AMS) represent the most advanced shift towards mechanisation in the sector. Introduced in the 1990s (Jacobs and Siegford 2012), AMS essentially involves robots automatically milking cows, minimising the need for conventional human intervention/labour. The world's largest "milking carousel" was recently acquired by one of China's leading producers of raw milk, Lvyuan Animal Husbandry (GEA Group 2020). This machine is capable of milking 10,000 cows, 3 times per day. While technical apparatuses such as milking machines facilitate a more efficient production process, thereby reducing costs and providing a competitive advantage over smaller non-automated producers, it also generates a disembodied and increased moral distance between humans and the cattle as both become progressively alienated from one another (Clarke and Knights 2021; Holloway and Bear 2017). AMS encourages a shift away from animal husbandry and multispecies relations to a much more mechanical relationship where the metrics for animal health and wellbeing are quantified in artificial intelligence systems.

Mechanisation in milking, along with the increased prominence of feedlot rather than pasture-based production systems, are intensifying dairy production in increasingly corporatized environments (Clay et al. 2020b). Increased intensification of dairy agriculture reinforces objectifying constructions of cows as commodities whose primary value comes from their ability to produce milk that can be sold for profit. Alternative ways of engaging with them as feeling complex beings (Schuster et al. 2020) becomes more and more difficult as human–cow encounters become rarer, routinised and limited. Farmers are now producing more for less, however there are also less farmers and farm workers needed to produce this milk, and cows have less opportunity to build more felt and caring relationships with humans. These intensive systems of production face the accusations of animal cruelty, a lack of transparency, and "placelessness", that have long been levelled at intensive animal agricultural systems (Sexton et al. 2019, p. 64; Gillespie 2018). The effort to make milk quicker, cheaper and more homogenous is central to efforts to expand dairy industries, favouring consumers and large dairying companies at the expense of small farms and farm animals. Much more work is needed to track the socioecological impacts of the transition in the Global North and South from distributed small scale farming systems to larger intensified production systems where the livelihoods and wellbeing of farmers, farm workers and farm animals are given appropriate consideration (Steenveld et al. 2012).

Growing awareness of the ecological impacts of dairy

It is increasingly recognised that the global dairy sector has an important role to play in the reduction of global emissions, being a significant contributor of greenhouse gasses, mostly through methane released through eructation, but also through land use change, refrigeration, transport and various other sources (Bar-On et al. 2018). The ecological impacts of animal agriculture are well documented with livestock industries also associated with land degradation due to overgrazing, soil erosion and salinisation, deforestation, biodiversity loss, and the contamination of surface and groundwater (Saari et al. 2020). The findings of the UN Food and Agriculture Organisation's (2006) controversial and ground breaking report *Livestock's Long Shadow* first raised the alarm at a global scale and have been bolstered by studies ever since (e.g. Willet et al. 2019). Poore and Nemeck (2018, p. 4), for example, found that even the lowest-impact animal products exceed the environmental impacts of vegetable-based proteins, to the extent that meat, aquaculture, eggs, and dairy use ~ 83% of the world's farmland, contribute 56–58% of food-related emissions, but provide only 37% of protein intake. These and similar findings are placing pressure on dairy industries to lower emissions and develop more sustainable systems. The most recent Sixth Assessment Report by the IPCC (MassonDelmotte et al. 2021) notes substantive increases in methane emissions, with animal agricultural being one of the largest sources.

Research into enteric fermentation, the metabolic process that creates methane in cattle rumen, has targeted the digestive system of cattle to limit the production of methane. Despite thirty years of experiments however, improvements have been minimal and inconsequential when compared with the increasing size of the global herd (McGregor et al. 2021). Lively cattle bodies have resisted technological control. Even if much touted but somehow eternally immanent methane mitigating "breakthroughs" are achievable at scale, the ever-increasing demand, production and wastage of food that is part and parcel of the industrial food system (Ormond 2020) means that the raft of other environmental problems associated with dairy would remain. The ongoing expansion of the dairy industry will exasperate pollution issues from acidification to eutrophication on land and freshwater systems (Poore and Nemecek 2019; Rotz 2018; Fiel et al. 2020), as well as the displacement of natural carbon sinks (Harwatt et al. 2019) if current production and consumption trajectories persist. While there are efforts to price the environmental and social externalities of dairy to provide a fairer price and contribute to climate change mitigation (Pieper et al. 2020) there are also clear limits to this approach (see McAfee 1999).

Zafrilla et al. (2020) reflected on recent reports by the IPCC to argue that livestock production is being positioned as the subject of new forms of climate governance, or as Ormond (2020, p. 163) suggests "corporate carbon commitments" are being redirected to farm level. For example, climate friendly(er) dairy will rely on improvements in cattle breeds and feed (Wankar et al. 2021) and improvements in animal health to minimise "wastage" (Mylan et al. 2019). However, each of these changes come with their own costs and challenges. For example, some forms of seaweed have been identified as potential feed additives that can reduce methane emissions (Kinley et al. 2020). In addition to reducing biogenic methane, the cultivation of seaweed could have net benefits for local labour forces and supporting regional economies (Kinley et al. 2020). However, like any intensive production system, this raises questions about the sustainability of large-scale aquaculture, as the cultivation of seaweed for the global meat and dairy cattle herd of over a billion animals will invariably have negative impacts on marine ecosystems (Hasselström et al. 2018). The logistics appear challenging at the very least.

Further case studies and empirical research that examines the impacts of that climate mitigation strategies may have upon human and non-human stakeholders is needed to envision what climate friendly cattle may look like in the future (see Ormond 2020). For example, if feed additives are a requirement for low emissions dairy production this is likely to increase the costs of production, favouring larger players over smaller ones and further threaten the viability of small farms. In contrast there is some promising work on agro-ecology and regenerative farming being promoted by institutions like the FAO that recasts well managed cattle as assets in the fight against climate change and ecological degradation (for example, see Teague and Kreuter 2020). Agroecology principles as defined by the FAO aim to include social values in conjunction with environmental practices that reflect "dignity, equity, inclusion and justice, associated with gender and intergenerational equality and access to decent jobs" (Barrios et al. 2020, p. 236) and tend to favour the more traditional small scale family farms still prevalent in the Global South. While interest in this area is growing to counter the "monocultures of industrial agriculture" and help small scale farms to prosper (Altieri et al. 2015, p. 874), it has yet to attract the mass investment required at sufficient scale to counter opposing processes favouring intensification of production.

For some, promissory narratives (Sexton et al. 2019) of low emissions cattle through technological or agricultural fixes are a bridge too far, heightening the need for systemic shifts towards plant-based proteins as a replacement for animal-based protein. Rather than being a radical idea the "societal grand challenge" of moving away from or limiting animal-based food systems (see Mylan et al. 2021) is being echoed in major intergovernmental reports, including the IPCC Special Report on Climate Change and Land (Mbow et al. 2019) and the EAT-LANCET Commission (Willett et al. 2019), as well as the earlier UN Environment Programme report (Hertwich et al. 2010, p. 82) which argued for a substantial reduction of animal products in human diets in order to lessen the negative environmental impacts from agriculture more broadly. Dairy industries need to develop much more sustainable production processes if they are to mitigate growing consumer concerns about the environmental impacts of the industry.

Alternative milk disruptions

Alternative proteins, in the form of plant-based milks and the gradual development of synthetic milks (grown from fermentation techniques and/or animal cells) are emerging as a fundamental disruption to conventional animal milk production and consumption. Although milks such as soy and nut-milks have had a role throughout human history (Valenze 2011), the popularity of these products has increased in volume and expanded in range in recent times driven by consumers who are motivated by both ecological and health concerns (Lonnie et al. 2018). This change in consumer preferences is particularly evident in the Global North (see Stokel-Walker 2018; Franklin-Wallis 2019; Mintel 2019). Lonkila and Kaljonen (2021) argue that the future viability of the global dairy industry is contingent on the attention paid to the "entangled changes" of food production, technological development and consumer demands. Demographics play a role in driving these changes with Stewart et al. (2020) finding that the consumption of dairy milk in the US drops off steadily with age (Moshfegh et al. 2019). Stokel-Walker (2018) refers to this process as older consumers "aging out of the market", while younger consumers are also shifting towards dairy alternatives. McCarthy et al.'s (2017) US based study found that animal welfare and environmental concerns tend to be primary drivers as to why people might purchase alternative milk over cow's milk. In their research, they found that the main reasons consumers drink milk is out of habit or "for the flavour" rather than its nutritional quality. Debates around the nutritional properties of milk are out of scope for this review but are more questioned than at any time in the past (for example, see Michaëlsson et al. 2014; Aune 2015; Jakobsen et. al 2021). We discuss each form of alternative milk below.

Plant-based milk

Plant-based foods and proteins have become a focal point in the pursuit of sustainability goals (Aschemann-Witzel et al. 2020). Sales of plant-based milks are on the rise in the Global North, contributing to a decline in per capita consumption of dairy milk in some countries, including the US (Stewart et al. 2020) where dairy milk sales in the US fell to $12 billion in 2019 from $15 billion in 2015, resulting in some large American dairy producers filing for bankruptcy (Garabito 2020). Neo and Lim (2021) found that interest in alternative protein production and consumption were creating opportunities for more localised production in Asia, driven in part by a push for more nutritious "immunity-boosting" products in countries such as China. The OECD–FAO (2020) report on global dairy and agriculture argues that plant-based dairy substitutes are growing in popularity due to consumer awareness around lactose intolerance, and the health and environmental impact of dairy products (see also Mylan et al. 2019). Business opportunities for plant-based products are viewed as positive (Acschmann-Witzel et al. 2020) and are now also being pursued by some existing dairy companies around the world. For example, *Danone* acquired the plant-based foods company WhiteWave in 2017, which they note was a "strategic move towards meeting consumer expectations for healthier and sustainable choices… enriching our portfolio and complimenting dairy fermented products" (Danone 2021). Early adopters of this trend are set to increase sales and production outputs as the increase in demand for plant-based alternatives continues to reconfigure the market.

The interest in plant-based milks derives from a number of negative associations with dairy relating to health (Clay et al. 2020a), environmental impacts (see Willet et al. 2018; Springmann et al. 2018) and animal welfare, particularly in intensive systems where there is a "perceived disconnect from naturalness" (Beaver et al. 2020, p. 5749). Land use change from pasture to crops to produce plant-based milks is a growing possibility on the horizon (Philippidis et al. 2021) if novel dietary patterns such as veganism within Western food culture becomes more mainstream (Chiorando 2018). However, a widespread transition to plant-based milk production remains distant and faces many socio-cultural, economic and political hurdles which beckons research from both the physical and social sciences in order to fully understand the socioecological ramifications of such a shift (Philippidis et al. 2021). For example, dairy industries across North America, Europe and Australia are engaging in contests over labelling animal-free alternatives such as milk, butter and cheese (Sexton et al. 2019). In the US, calls for the reintroduction of the "Dairy Pride Act" have been made to protect dairy industries from plant-based alternatives by claiming milk can only be made by animals (Keller and Heckman LLP 2019). Alternative milk brands in the European Union face a ban on using terms or imagery on packaging which refer to or evoke dairy products (Bonadio and Borghini 2021). This is positioned as a move to avoid confusion for consumers at the supermarket, however such strategies clearly reflect the interests of dairy industries keen to protect their markets. More research is needed on the potential growth of plant-based alternatives and what contribution they may make to food transitions (Mylan et al. 2019; Lonkila and Kaljonen 2021).

Synthetic milk

Synthetic milks grown through cellular agriculture (milk that shares the same biochemical make up on animal milk but produced without animal bodies) are emerging as an additional competitor to animal-based milks. Cellular agriculture is an emergent field in which agricultural products—most typically animal-derived agricultural products—are produced through processes operating at the cellular level, as opposed to (typically farm-based) processes operating at the whole organism level (Stephens 2020). Cellular agriculture can be defined as "attempts to sustainably supplant animal products with biomass cultured from cells" in-turn creating openings for new food production and novel economic geographies (Jönsson 2020, p. 922). This new form of food has attracted significant investment from venture-capitalists, particularly concentrated in the Silicon Valley region of San Francisco (Sexton 2020) but is also being developed in many richer parts of the world including Israel, Australia and Europe. The US-based company *Perfect Day* has recently partnered with the company *Brave Robot* to create the world's first animal-free dairy ice creams (Starostinetskaya 2021). They market their product by claiming cow's milk ice cream to be "tasty, but unsustainable", plant-based ice cream as "more sustainable, but not tasty" and their product as "both sustainable AND tasty" (Brave Robot 2021). Unlike synthetic meat which faces difficulties in matching the complexity and textures of different meat products, synthetic milk is likely to be indistinguishable from dairy milk due to its liquid form. If it can be produced more cheaply than dairy milk the potential for a relatively rapid change in the dairy industry brought on by cellular agriculture is high. However, at present, the technology is still evolving and the scalability of cellular milk is a challenge (Pandya 2016). Reality has not matched the promises envisioned by innovators in the alternative protein sector thus far.

If synthetic milk can replace dairy as an ingredient in the industrial food processing sector (von Massow and Gingerich 2019) this could present significant challenges for large-scale producers who depend on the exportability of powdered milk products. In their analysis of the possibilities offered by synthetic milks, Jönsson et al. (2019) characterise these novelties as “post-animal products” which “carry new realities, new ontologies with them” (Mol as cited in Jönsson et al. 2019, p. 72). These new forms of food appear better for animal welfare on the basis that there are no livestock animals harmed in the making (synthetic milk can be produced from yeast). Thus, the creation of cellular agriculture and synthetic milks offer the possibility of unfettered production of animal products without conventional spatial constraints and welfare concerns (Jönsson 2020), as no animal bodies are concealed or abstracted in the production of milk (Leroy et al. 2020). These disruptions in the dairy sector may steer humanity towards radically different food systems (Leroy et al. 2020) where synthetic milks compete with traditional dairy. A recent report into the future of dairy by think tank Rethinkx (Tubb and Seba 2019) argued that by 2030, new fermentation industries could create up to 700,000 jobs in the US alone. However, Lonkila and Kaljonen (2021, p. 10) warn that synthetic meat and milk alternatives are entangled in capital-intensive agriculture and may further the unequal distribution of protein-rich diets across spaces. As such, alternative proteins do not necessarily challenge corporatisation, homogenisation or consider questions of justice within global food production and consumption (for humans, non-humans and environments), instead they may represent a new stage of consolidation that further marginalises low tech dairy systems. Capital intensive synthetic milk production could eventually further displace many people from the global dairy sector, albeit with potential environmental and animal welfare gains. However, with these new technologies, it may become a possibility that small scale, independently owned breweries could be rolled out in ways that fracture current consolidation processes and empower animal-less local producers in new and interesting ways.

Other animal milks

In addition to plant-based and synthetic milks, other animal milks are, in some contexts, being developed to compete with dairy milk production. On smaller scales, Numpaque et al. (2020) find that for different regions of the world, other animal species such as mare, donkey, yak, reindeer, camel and llama have an important share in milk consumption. At present, world milk production is estimated as 81% cow milk, 15% buffalo milk, and 4% total for other animal milks (OECD–FAO 2020). In their review of trends in the dairy sector, Pulina et al. (2020) found that within the last 50 years, sheep and goat milk production has more than doubled and is expected to increase up to 26% for sheep milk and 53% for goat milk by 2030. Miller and Lu (2019) find that rising consumer demand, strong prices, and climate change are influential factors for the uptake in new goat milk industries in countries such as New Zealand, China and the US. Goat milk has been found to be less allergenic, contain more nutritional benefits than plant-based alternatives (Park 2021) and softer gastric digestion than other non-cattle milks (Roy et al. 2020). Additionally, the production of small ruminant milks has been suggested as more environmentally friendly and socially appropriate for some rural communities (Pulina et al. 2020). At present, the upscaling of these industries faces barriers as Vouraki et al. (2020) find that sector lacks the professionalisation, management training and supply chain integration that cow dairy milk has, which results in varied levels of productivity. It is also questionable if the intensification such scaling up would require is desirable for people, animals or the planet.

Discussion

In this section we look across the four megatrends to reflect on emerging socioecological challenges for dairy industries. One of the most striking trends is the shift in the volume of global dairy production and consumption from North to South. While Northern markets are saturated with milk, there is room for immense growth in parts of the Global South. This creates opportunities for new jobs in the dairy sector and promises nutritional benefits for under-nourished human communities, as long as they can access affordable milk products. The geographic expansion of dairy is being driven by large multinational companies who are investing in more intensive forms of farming. This includes automated milking systems and more confined animal production systems that make milk faster and cheaper, by slashing labour costs and maximising bodily production. Dairying is becoming more homogenous and placeless as it adapts to increasingly stringent industry standards oriented around consumer safety and risk management. Hence the form of dairy expansion that is likely to take place in new areas of the Global South, is more mechanised, corporate and standardised than what has occurred in the past.

While the global growth of dairy is often positioned as a positive outcome for food security and economies, replicating older mythologies about progress and modernisation, our analysis suggests such narratives should be viewed with caution. The literature tends to emphasise the productivity and economic gains for economies and consumers but there is a dearth of work analysing the social costs of dairy farming that focuses on the welfare of humans and non-humans. It is evident, for example, that the corporatisation and intensification of dairy production favours larger companies over small dairy producers. Further mechanisation of dairy production raises questions about the size and longevity of the dairy labour force and is likely to exacerbate the already established trend of pushing smaller dairy milk producers out of competitive markets. In addition, if dairy production is predicted to grow significantly in the Global South over the next decade (OECD–FAO 2021), this raises concerns about where the land and resources to enable such an increase is to come from. It is likely that land use pressures will increase the risk of land use conflicts and deforestation, as even intensive dairy farming still requires extensive feed production systems. Dairy cattle require a significant amount of land and resources for the volume of food produced. For example, 1 l of cow's milk can use up to 1020 l of water throughout the whole process (Rotz 2018). It is likely many of the environmental pressures associated with dairy in the Global North will be replicated or intensified. particularly where environmental regulations are lax, in the South, including river and groundwater pollution, greenhouse gas emissions and soil degradation.

As the environmental costs of dairy production become more well known the pressure on smallholders is likely to increase as societies seek to minimise impacts. Expectations for low emissions food products are increasing and may eventually result in regulations requiring feed additives or vaccinations to reduce methane emissions. While larger businesses are likely to be able to absorb these costs, environmental regulations may add to the challenges faced by smallholder farmers. There is also the possibility for bespoke markets to evolve that support small holder farms employing regenerative or agro-ecological principles. However, the general trend is towards intensification or production and more research is needed to fully understand the implications of intensification, standardisation and regulations on human and non-human lives (Holloway and Bear 2017). Currently, it seems that many of the benefits of expansion are likely to be captured by large multinational companies, but the immediate social and environmental costs are to be felt locally. As such, many rural communities risk being disadvantaged by such a transition without sufficient government protections. Alternatively, as Weis (2013) reminds us, there is nothing inevitable or even necessarily desirable about ever-expanding animal-based diets and production systems, particularly for regions such as Asia, where a large proportion of the population are historically lactose intolerant (Valenze 2011). At a global scale the climate impacts of dairy production are significant and any increase in dairy cattle in the Global South should be at least matched by decreases of dairy cattle in the Global North. Efforts to expand dairy as the world struggles with global heating is irresponsible and goes against calls for richer countries to "declare a timeframe for peak livestock" after which countries steadily decrease livestock numbers in order to pursue global climate goals (Harwatt et al. 2019, p. 9).

The world seems a long way from this sort of governmental intervention and so, in the absence of industry-led limits on the global herd, consumers and food tech investors are taking their own action through alternative milk products. Plant and synthetic milks mimic dairy milk in terms of colour, texture, consistency, and taste while at the same time, distancing the product from the unfavourable aspects of dairy, from animal welfare through to health and environmental concerns. Plant-based milks have successfully captured parts of the market and synthetic milks show as yet unrealised promise to make a large impact. However, by mimicking milk, both approaches subtly reinforce dairy milk (and animal products in general) as the norm for modern diets (Lonkila and Kaljonen 2021). A critical question for alternative milks is whether replacing one form of industrial production (animal-based dairy) with another (plant and cellular-based dairy) will be socially and environmentally beneficial. Mylan et al. (2019) argue that alternative milks and their functioning within the food system in relation to the organisation of markets and consumption remains largely unchanged. Additionally, Sexton et al. (2019) suggest that upscaling alternative proteins (and other animal protein analogues) takes society further away from cultivating more localised food systems based on care and trust. Addressing issues of sustainability through alternative dairy may have some environmental and animal welfare benefits but may accelerate trends of corporatisation and centralised control of food systems, with potentially devastating impacts for small farmers. Such innovations risk merely changing the components of dairy systems (inputs from plants rather than animals) while extending corporate control over land and labour. The social costs of transitioning from dairy milk to plant-based or synthetic milks would be immense for rural communities and as such requires much more research to explore the socioecological dimensions of transitions away from animal-based dairy systems and how, and if, such transitions can be done in just and fair ways.

Conclusion

We have identified four megatrends affecting the global dairy sector and highlighted key challenges for the future. The impacts of shifting geographies, intensification, ecological pressures and the possibilities offered by milk alternatives are creating openings for interdisciplinary scholarship to engage with the under-researched impacts of these trends. Such research should recognise the vitality and agency of cattle and other actors within dairy systems, and that the expansion of dairy industries is not just an economic process, but one that is embedded with more-than-human relations (Collard and Dempsey 2013). Cattle not only require food, water, land and labour to produce milk, but they increasingly require robots, quality standards, methane mitigation technologies, intensive farming, investment and international markets if they are to survive. It is the liveliness of cattle that has shaped these relations, a liveliness that dairy industries will never fully control or contain and is resulting in the megatrends we have identified here. While some megatrends reflect an enthusiastic embrace and expansion of these increasingly corporatized assemblages, others reflect concerns about their destructive socioecological impacts, resulting in a growing market for dairy alternatives. There is a need for more critical case study research that focuses on the complex impacts dairying, and dairy alternatives, are having on place, people and cattle.

Our review suggests that the future of dairy is not clear nor uncontroversial. The mythology that milk is unquestionably good and universally beneficial is not borne out by this review and the almost teleological assumption that dairy will simply roll out across the planet to benefit all deserves careful scrutiny to assess its true costs. If dairy is to live up to its promises, much more attention needs to be directed to maximising and broadening the socioecological benefits of the industry, minimising the human and non-human costs, including those inflicted on cattle, and limiting its contributions to global environmental change. With some trends working against these goals, the social license of dairy is likely to erode in mature markets, creating further openings for milk alternatives, each of which comes with its own set of challenges. While dairy is likely to continue expanding in the immediate future, the megatrends and socioecological challenges we have identified here are substantial and suggest its medium-term future trajectories are much less certain.

Appendix

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
B	Creatures of Empire: how domestic animals transformed early America	*N/A*	2004	Anderson, VD	N/A
G	Developing countries and the global dairy sector part I global	*Pro-Poor Livestock Policy Initiative*	2005	Knips	N/A
G	Livestock's long shadow: environmental issues and options,	*United Nations Food and Agriculture Organisation*	2006	FAO	N/A
J	Agrifood industry transformation and small farmers in developing countries	*World Development*	2009	Reardon et al	C
G	Agricultural Outlook 2010	*Organization for Economic Cooperation and Development*	2010	OECD–FAO	N/A
G	Accessing the environmental impacts of consumption and pro	*United Nations Environment Program*	2010	Hertwich et al	N/A
J	Invited review: The impact of automatic milking systems on dairy cow management, behavior, health, and welfare	*Journal of Dairy Science*	2012	Jacobs and Siegford	R

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
J	Comparing technical efficiency of farms with an automatic milking system and a conventional milking system	*Journal of Dairy Science*	2012	Steeneveld et al	C
J	Future consequences and challenges for dairy cow production systems arising from climate change in Central Europe—a review	*Animal (Cambridge, England)*	2013	Gauly et al	R
J	The dairy industry: a brief description of production practices, trends, and farm characteristics around the world	*Journal of Agromedicine*	2013	Douphrate et al	R
J	Milk intake and risk of mortality and fractures in women and men: cohort studies	*British Medical Journal*	2014	Michaëlsson et al	C
J	A comparison of product-based energy intensity metrics for cheese and whey processing	*Journal of Food Engineering*	2015	Briam et al	C
J	Dairy products, calcium, and prostate cancer risk: a systematic review and meta-analysis of cohort studies	*The American Journal of Clinical Nutrition*	2015	Aune et al	R
G	Beverage choices among children: what we eat in America	*U.S. Department of Agriculture, Agricultural Research Service*	2016	Moshfegh et al	N/A
J	Bovine and human becomings in histories of dairy technologies: robotic milking systems and remaking animal and human subjectivity	*BJHS Themes*	2017	Holloway and Bear	C
J	The Role of Auditing, Food Safety, and Food Quality Standards in the Food Industry: A Review	*Comprehensive Reviews in Food Science and Food Safety*	2017	Kotsanopoulos	R
J	Human factors in dairy industry process control for energy reduction	*Journal of Cleaner Production*	2017	Challis et al	C

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
J	Drivers of choice for fluid milk versus plant-based alternatives: What are consumer perceptions of fluid milk?	*Journal of Dairy Science*	2017	McCarthy et al	C
J	Food integrated management systems: dairy industry insights	*The International Journal of Quality and Reliability Management*	2017	Gianni et al	C
J	Global environmental costs of China's thirst for milk	*Global Change Biology*	2018	Bai et al	C
J	Invited review: Learning from the future—A vision for dairy farms and cows in 2067	*Journal of Dairy Science*	2018	Britt et al	R
J	Invited review: Current production trends, farm structures, and economics of the dairy sheep and goat sectors	*Journal of Dairy Science*	2018	Pulina	R
J	Modeling greenhouse gas emissions from dairy farms	*Journal of Dairy Science*	2018	Rotz	C
J	The impact of seaweed cultivation on ecosystem services—a case study from the west coast of Sweden	*Marine Pollution Bulletin*	2018	Hasselström et al	C
J	Options for keeping the food system within environmental limits	*Nature*	2018	Springmann et al	C
J	Protein for Life: Review of Optimal Protein Intake, Sustainable Dietary Sources and the Effect on Appetite in Ageing Adults	*Nutrients*	2018	Lonnie et al	R
J	The biomass distribution on Earth	*Proceedings of the National Academy of Sciences—PNAS*	2018	Bar-On et al	C
J	Reducing food's environmental impacts through producers and consumers	*Science (American Association for the Advancement of Science)*	2018	Poore and Nemecek	C
B	*Diversity of Family Farming Around the World Existence, Tra*	*N/A*	2018	Bosc et al	N/A
G	Food Security. In: Climate Change and Land: an IPCC special report	*Intergovernmental Panel on Climate Change*	2019	Mbow et al	N/A
J	Current status of global dairy goat production	*Asian–Australasian Journal of Animal Science*	2019	Miller and Lu	R

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
J	Framing the future of food: The contested promises of alternative proteins	*Environment and Planning. E, Nature and Space*	2019	Sexton et al	C
J	Rage against the regime: Niche-regime interactions in the societal embedding of plant-based milk	*Environmental Innovation and Societal Transitions*	2019	Mylan et al	C
J	Determinants of the competitive advantage of dairy supply chains: Evidence from the Chinese dairy industry	*International Journal of Production Economics*	2019	Ding et al	C
J	Food in the Anthropocene: the EAT–Lancet Commission on Healthy Diets from Sustainable Food Systems	*The Lancet (British Edition)*	2019	Willet et al	C
J	Mapping energy consumption in food manufacturing	*Trends in Food Science and Technology*	2019	Ladha-Sabur	C
J	Diversity of milks other than cow, sheep, goat and buffalo: in terms of nutrition and technological use	*Turkish Journal of Agriculture: Food Science and Technology*	2019	Numpaque et al	C
G	Milking the vegan trend: a quarter (23%) of brits use plant-based milk	*Mintel*	2019	Mintel	N/A
G	Rethinking Food and Agriculture 2020–2030	*RethinkX*	2019	Tubb and Seba	N/A
G	Scientists call for renewed Paris pledges to transform agriculture	*The Lancet*	2019	Harwatt et al	N/A
G	Climate change and the global dairy cattle sector	*United Nations Food and Agriculture Organisation*	2019	FAO	N/A
J	Palatable disruption: the politics of plant milk	*Agriculture and Human Values*	2020	Clat et al	C
J	Dairy intensification: Drivers, impacts and alternatives	*Ambio*	2020	Clat et al	R
J	A decision support system for economically sustainable sheep and goat farming	*Animals (Basel)*	2020	Vouraki et al	C
J	Geoengineering super low carbon cows: food and the corporate carbon economy in a low carbon world	*Climatic Change*	2020	Ormond	C

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
J	Plant-based food and protein trend from a business perspective: markets, consumers, and the challenges and opportunities in the future	*Critical Reviews in Food Science and Nutrition*	2020	Aschemann-Witzel et al	R
J	Food as software: Place, protein, and feeding the world Silicon Valley-style	*Economic Geography*	2020	Sexton	C
J	Sustainability in the dairy industry: a systematic literature review	*Environmental Science and Pollution Research International*	2020	Fiel et al	R
J	Composition, structure, and digestive dynamics of milk from different species—a review	*Frontiers in Nutrition (Lausanne*	2020	Roy et al	R
J	Livestock in evolving foodscapes and thoughtscapes	*Frontiers in Sustainable Food Systems*	2020	Leroy et al	C
J	Political ecology of milk: Contested futures of a lively	*Geography Compass*	2020	Clay and Yurco	C
J	Are plant-based analogues replacing cow's milk in the American diet?	*Journal of Agricultural and Applied Economics*	2020	Stewart et al	C
J	Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed	*Journal of Cleaner Production*	2020	Kinley et al	C
J	Symposium review: Considerations for the future of dairy cattle housing: An animal welfare perspective	*Journal of Dairy Science*	2020	Beaver et al	C
G	Dairy and dairy products' 2020	*OECD–FAO Agricultural Outlook 2020–2029*	2020	OECD–FAO	N/A
J	Invited review: Academic and applied approach to evaluating longevity in dairy cows	*Journal of Dairy Science*	2020	Schuster	R
J	Sharing the safe operating space: Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels	*Journal of Industrial Ecology*	2020	Hjalsted	C
G	Global Dairy Top 20,	*RaboBank*	2020	Ledman and van Battum	N/A
G	Global dairy top 20	*Raboresearch*	2020	Rabobank	N/A

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
J	Calculation of external climate costs for food highlights inadequate pricing of animal products	*Nature Communications*	2020	Pieper	C
J	The transforming dairy sector in Ethiopia	*PLoS ONE*	2020	Minten et al	C
J	Many meats and many milks? The ontological politics of a proposed post-animal revolution	*Science as Culture*	2020	Jönsson et al	C
J	On breweries and bioreactors: Probing the "present futures" of cellular agriculture	*Transactions Institute of British Geographers*	2020	Jönsson	C
B	The sustainability challenge of dairy livestock systems'	*Sustainable and Environmentally Friendly Dairy Farms*	2020	Zafrilla et al	N/A
J	Cellular agriculture in the UK: a review [version 2; peer review: 2 approved, 2 approved with reservations]	*Welcome Open Research*	2020	Stephens et al	R
G	Diary Market Review	*United Nations Food and Agriculture Organisation*	2020	FAO	N/A
G	The state of food security and nutrition in the world 2020,	*United Nations Food and Agriculture Organisation*	2020	FAO et al	N/A
G	IPCC 2021: Summary for policymakers. in: climate change 20	*Intergovernmental Panel on Climate Change*	2021	Masson-Delm	
otte et al	N/A				
G	*Table C.5—World dairy projections: Milk, butter and cheese*	*OECD–FAO Agricultural Outlook 2020–2029*	2021	OECD–FAO	N/A
J	Promises of meat and milk alternatives: an integrative literature review on emergent research themes	*Agriculture and Human Values*	2021	Lonkila and Kaljonen	R
J	Challenges and tendencies of automatic milking systems (AMS): a 20-years systematic review of literature and patents	*Animals*	2021	Cogato et al	R
J	The impact of plant-based non-dairy alternative milk on the dairy industry	*Food Science of Animal Resources*	2021	Park	C

Publication type (J: journal, B: book, G: grey lit, M: media article)	Title	Journal	Date	Author	Article type (R: review, C: case study)
J	Priorities for social science and humanities research on the challenges of moving beyond animal-based food systems	*Humanities and Social Sciences Communications*	2021	Morris et al	C
J	Milking It for All It's Worth: Unpalatable Practices, Dairy Cows and Veterinary Work	*Journal of Business Ethics*	2021	Clarke et al	C
J	Eating your greens: a global sustainability assessment	*Resources, Conservation and Recycling*	2021	Philippidis	C
J	Intake of dairy products and associations with major atherosclerotic cardiovascular diseases: a systematic review and meta-analysis of cohort studies	*Scientific Reports*	2021	Jakobsen et al	R
J	The vegan trend and the microfoundations of institutional change: A commentary on food producers' sustainable innovation journeys in Europe	*Trends in Food Science and Technology*	2021	Saari et al	C
J	Heat stress in dairy animals and current milk production trends, economics, and future perspectives: the global scenario	*Tropical Animal Health and Production*	2021	Wankar et al	C

Acknowledgements The authors would like to thank Professor Lesley Hughes and Dr. Greg Walkerden for their valuable comments at the various stages of writing for this paper.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

References

Anderson, V.D. 2004. *Creatures of Empire: How domestic animals transformed early America*. Oxford: Oxford University Press.

Altieri, M.A., C.I. Nicholls, A. Henao, and M.A. Lana. 2015. Agroecology and the design of climate change resilient farming systems. *Agronomy for Sustainable Development* 35 (3): 869–890. https://doi.org/10.1007/s13593-015-0285-2.

Aune, D., D.A. Navarro Rosenblatt, D.S. Chan, A.R. Vieira, R. Vieira, D.C. Greenwood, L.J. Vatten, and T. Norat. 2015. Dairy products, calcium, and prostate cancer risk: A systematic review and meta-analysis of cohort studies. *The American Journal of Clinical Nutrition* 101 (1): 87–117. https://doi.org/10.3945/ajcn.113.067157.

Aschemann-Witzel, J., R.F. Gantriis, P. Fraga, and F.J.A. Perez-Cueto. 2020. Plant-based food and protein trend from a business perspective: Markets, consumers, and the challenges and opportunities in the future. *Critical Reviews in Food Science and Nutrition*. https://doi.org/10.1080/10408398.2020.1793730.

Bai, Z., M.R. Lee, L. Ma, S. Ledgard, G.L. Velthof, W. Ma, M. Guo, M. Zhao, Z. Wei, S. Li, S. Liu, X. Havlík, P. Luo, J. Hu, and F. Zhang. 2018. Global environmental costs of China's thirst for milk. *Global Change Biology* 24 (5): 2198–2211. https://doi.org/10.1111/gcb.14047.

Barua, M. 2014. Volatile ecologies: Towards a material politics of human–animal relations. *Environment and Planning A* 46 (6): 1462–1478. https://doi.org/10.1068/a46138.

Bar-On, Y.M., R. Phillips, and R. Milo. 2018. The biomass distribution on Earth. *Proceedings of the National Academy of Sciences of USA* 115 (25): 6506–6511. https://doi.org/10.1073/pnas.1711842115.

Barrios, E., B. Gemmill-Herren, A. Bicksler, E. Siliprandi, R. Brathwaite, S. Moller, C. Batello, and P. Tittonell. 2020. The 10 elements of agroecology: Enabling transitions towards sustainable agriculture and food systems through visual narratives. *Ecosystems and People (abingdon, England)* 16 (1): 230–247. https://doi.org/10.1080/26395916.2020.1808705.

Bear, C., and L. Holloway. 2019. Beyond resistance: Geographies of divergent more-than-human conduct in robotic milking. *Geoforum* 104: 212–221. https://doi.org/10.1016/j.geoforum.2019.04.030.

Beaver, A., K.L. Proudfoot, and M.A. von Keyserlingk. 2020. Symposium review: Considerations for the future of dairy cattle housing: An animal welfare perspective. *Journal of Dairy Science* 103 (6): 5746–5758. https://doi.org/10.3168/jds.2019-17804.

Bonadio, E., and A. Borghini. 2021. Vegan 'dairy' products face EU ban from using milk cartons and yoghurt pots—And UK could be next. In *Brave New Europe*, 24 January. https://braveneweurope.com/enrico-bonadio-andrea-borghini-vegan-dairy-products-face-eu-ban-from-using-milk-cartons-and-yoghurt-pots-and-uk-could-be-next. Accessed 20 March 2021.

Bosc, P.M., J.M. Sourisseau, P. Bonnal, P. Gasselin, É. Valette, and J.F. Bélières. 2018. *Diversity of family farming around the world existence, transformations and possible futures of family farms*. Dordrecht: Springer.

Brave Robot. 2021. Brave Robot. https://braverobot.co/. Accessed 8 Feb 2021.

Briam, R., M.E. Walker, and E. Masanet. 2015. A comparison of product-based energy intensity metrics for cheese and whey processing. *Journal of Food Engineering* 151: 25–33. https://doi.org/10.1016/j.jfoodeng.2014.11.011.

Britt, J., R. Cushman, C. Dechow, H. Dobson, P. Humblot, M. Hutjens, G. Jones, P. Ruegg, I. Sheldon, and J. Stevenson. 2018. Invited review: Learning from the future—A vision for dairy farms and cows in 2067. *Journal of Dairy Science* 101 (5): 3722–3741. https://doi.org/10.3168/jds.2017-14025.

Challis, C., M. Tierney, A. Todd, and E. Wilson. 2017. Human factors in dairy industry process control for energy reduction. *Journal of Cleaner Production* 168: 1319–1334. https://doi.org/10.1016/j.jclepro.2017.09.121.

Chiorando, M. 2018. 2019 will be year of the vegan' according to the economist. *Plant Based News*, 26 December. https://plantbasednews.org/culture/2019-year-vegan-the-economist. Accessed 2 July 2021.

Clarke, C., and D. Knights. 2021. Milking it for all it's worth: Unpalatable practices, dairy cows and veterinary work? *Journal of Business Ethics*. https://doi.org/10.1007/s10551-020-04666-3.

Clay, N., and K. Yurco. 2020. Political ecology of milk: Contested futures of a lively food. *Geography Compass* 14 (8): 12497. https://doi.org/10.1111/gec3.12497.

Clay, N., A.E. Sexton, T. Garnett, and J. Lorimer. 2020a. Palatable disruption: The politics of plant milk. *Agriculture and Human Values* 37 (4): 945–962. https://doi.org/10.1007/s10460-020-10022-y.

Clay, N., T. Garnett, and J. Lorimer. 2020b. Dairy intensification: Drivers, impacts and alternatives. *Ambio* 49 (1): 35–48. https://doi.org/10.1007/s13280-019-01177-y.

Cogato, A., M. Brščić, H. Guo, F. Marinello, and A. Pezzuolo. 2021. Challenges and tendencies of automatic milking systems (AMS): A 20-years systematic review of literature and patents. *Animals (basel).* 11 (2): 356. https://doi.org/10.3390/ani11020356.

Collard, R.C., and J. Dempsey. 2013. Life for sale? The politics of lively commodities. *Environment and Planning A* 45 (11): 2682–2699. https://doi.org/10.1068/a45692.

Dairy Industries International. 2020. *Yili rises to top five in 2020 global dairy top 20*. Dairy Industries International, 7 September. https://www.dairyindustries.com/news/35223/yili-rises-to-top-five-in-2020-global-dairy-top-20. Accessed 4 Feb 2021.

Danone. 2021. *Essential Dairy and Plant-based products*. Danone. https://www.danone.com/brands/dairy-plant-based-products.html. Accessed 4 Feb 2021

Douphrate, D.I., R.G. Hagevoort, M.W. Nonnenmann, P. Kolstrup, C.L. Reynolds, M. Jakob, M. Kinsel, and M. 2013. The dairy industry: A brief description of production practices, trends, and farm characteristics around the world. *Journal of Agromedicine* 18 (3): 187–197. https://doi.org/10.1080/1059924X.2013.796901.

Delgado, C.L. 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. *The Journal of Nutrition* 133 (11): 3907S-3910S. https://doi.org/10.1093/jn/133.11.3907S.

Ding, H., Y. Fu, L. Zheng, and Z. Yan. 2019. Determinants of the competitive advantage of dairy supply chains: Evidence from the Chinese dairy industry. *International Journal of Production Economics* 209: 360–373. https://doi.org/10.1016/j.ijpe.2018.02.013.

FAO. 2006. *Livestock's long shadow: Environmental issues and options.* United Nations Food and Agriculture Organisation of the United Nations. https://www.fao.org/3/a0701e/a0701e00.html. Accessed 20 Dec 2020.

FAO. 2019. *Climate change and the global dairy cattle sector*. United Nations Food and Agriculture Organisation. https://www.fao.org/3/CA2929EN/ca2929en.pdf. Accessed 20 May 2021.

FAO. 2020. *Diary market review*. United Nations Food and Agriculture Organisation. http://www.fao.org/3/ca8341en/CA8341EN.pdf. Accessed 18 Dec 2020.

FAO, IFAD, UNICEF, WFP and WHO. 2020. *The state of food security and nutrition in the world 2020*. Food and Agriculture Organisation of the United Nations. https://www.fao.org/documents/card/en/c/ca9692en. Accessed 21 Jan 2021.

Fiel, A.A., D. Schreiber, C. Haetinger, A.M. Haberkamp, J.I. Kist, C. Rempel, A.E. Maehler, M.C. Gomes, and G.R. da Silva. 2020. Sustainability in the dairy industry: A systematic literature review. *Environmental Science and Pollution Research International* 27 (27): 33527–33542. https://doi.org/10.1007/s11356-020-09316-9.

Franklin-Wallis, O. 2019. White gold; the unstoppable rise of alternative milks. *The Guardian*, 29 January. https://www.theguardian.com/news/2019/jan/29/white-gold-the-unstoppable-rise-of-alternative-milks-oat-soy-rice-coconut-plant. Accessed 1 July 2020.

Garabito, D. 2020. "Cash Cows": The growth of plant-based alternatives. *McGill Business Review*, 11 May 2020. https://mcgillbusinessreview.com/articles/cash-cow-the-growth-of-plant-based-alternatives. Accessed 31 Jan 2021.

Gauly, M., H. Bollwein, G. Breves, K. Brügemann, S. Dänicke, G. Daş, J. Demeler, H. Hansen, J. Isselstein, S. König, M. Lohölter, M. Martinsohn, U. Meyer, M. Potthoff, C. Sanker, B. Schröder,

N. Wrage, B. Meibaum, G. von Samson-Himmelstjerna, H. Stinshoff, and C. Wrenzycki. 2013. Future consequences and challenges for dairy cow production systems arising from climate change in Central Europe—A review. *Animal (cambridge, England)* 7 (5): 843–859. https://doi.org/10.1017/S1751731112002352.

GEA Group. 2020. *GEA installs largest milking rotary parlor in China for 10,000 cows.* Gesellschaft für Entstaubungsanlagen, 13 November, https://www.gea.com/en/news/trade-press/2020/t8900-gea-milking-rotary-parlor-in-china.jsp. Accessed 1 March 2022.

Gianni, M., K. Gotzamani, and F. Vouzas. 2017. Food integrated management systems: Dairy industry insights. *The International Journal of Quality and Reliability Management* 34 (2): 194–215. https://doi.org/10.1108/IJQRM-05-2015-0076.

Gillespie, K., and R.C., Collard. 2015. *Critical Animal Geographies: Politics, intersections, and hierarchies in a multispecies world*, 1st ed. London: Routledge.

Gillespie, K. 2018. *The cow with ear tag #1389*. Chicago: The University of Chicago Press.

Gillespie, K. 2021. The afterlives of the lively commodity: Life-worlds, death-worlds, rotting-worlds. *Environment and Planning. A* 53 (2): 280–295. https://doi.org/10.1177/0308518X20944417.

Hajkowicz, S. 2015. *Global megatrends: Seven patterns of change shaping our future*. Clayton South: CSIRO Publishing.

Haraway, D.J. 2003. *The companion species manifesto: Dogs, people, and significant otherness*. Chicago: Prickly Paradigm.

Harwatt, H., W.J. Ripple, A. Chaudhary, M.G. Betts, and M. Hayek. 2019. Scientists call for renewed Paris pledges to transform agriculture. *The Lancet*. https://www.thelancet.com/pdfs/journals/lanplh/PIIS2542-5196(19)30245-1.pdf/. Accessed 27 April 2021.

Hasselström, L., W. Visch, and F., Gröndahl, G.M. Nylund, and H. Pavia. 2018. The impact of seaweed cultivation on ecosystem services—A case study from the west coast of Sweden. *Marine Pollution Bulletin* 133: 53–64. https://doi.org/10.1016/j.marpolbul.2018.05.005.

Hertwich, E., E. van der Voet, S. Suh, A. Tukker, M. Huijbregts, P. Kazmierczyk, M. Lenzen, J. McNeely, and Y. Moriguchi. 2010. *Accessing the environmental impacts of consumption and production*. United Nations Environment Program. https://www.resourcepanel.org/reports/assessing-environmental-impacts-consumption-and-production. Accessed 10 June 2021.

Hjalsted, L., A. Laurent, M.M. Anderson, K.H. Olsen, M. Ryberg, and M. Hauschild. 2020. Sharing the safe operating space: Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13050.

Holloway, I., and C. Bear. 2017. Bovine and human becomings in histories of dairy technologies: Robotic milking systems and remaking animal and human subjectivity. *BJHS Themes* 2: 215–234. https://doi.org/10.1017/bjt.2017.2.

Jacobs, J., and J. Siegford. 2012. Invited review: The impact of automatic milking systems on dairy cow management, behavior, health, and welfare. *Journal of Dairy Science* 95 (5): 2227–2247. https://doi.org/10.3168/jds.2011-4943.

Jakobsen, M.U., E. Trolle, M. Outzen, H. Mejborn, M.G. Grønberg, C.B. Lyndgaard, A. Stockmarr, S.K. Venø, and A. Bysted. 2021. Intake of dairy products and associations with major atherosclerotic cardiovascular diseases: A systematic review and meta-analysis of cohort studies. *Scientific Reports* 11 (1): 1303–1328. https://doi.org/10.1038/s41598-020-79708-x.

Jönsson, E., T. Linné, and A. McCrow-Young. 2019. Many meats and many milks? The ontological politics of a proposed post-animal revolution. *Science as Culture* 28 (1): 70–97. https://doi.org/10.1080/09505431.2018.1544232.

Jönsson, E. 2020. On breweries and bioreactors: Probing the "present futures" of cellular agriculture'. *Transactions of the Institute of British Geographers* 45 (4): 921–936. https://doi.org/10.1111/tran.12392.

Keller and Heckman LLP. 2019. Dairy Pride Act' Introduced Again. *The National Law Review*, 19 March. https://www.natlawreview.com/article/dairy-pride-act-introduced-again. Accessed 10 March 2021.

Kinley, R.D., G. Martinez-Fernandez, M.K. Matthews, R. de Nys, M. Magnusson, and N.W. Tomkins. 2020. Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. *Journal of Cleaner Production* 259: 120836. https://doi.org/10.1016/j.jclepro.2020.120836.

Knips, V. 2005. *Developing countries and the global dairy sector part I global overview*. Pro-Poor Livestock Policy Initiative. https://www.fao.org/3/bp204e/bp204e.pdf. Accessed 10 Feb 2021.

Kotsanopoulos, K.V., and I.S. Arvanitoyannis. 2017. The role of auditing, food safety, and food quality standards in the food industry: A review. *Comprehensive Reviews in Food Science and Food Safety* 16 (5): 760–775. https://doi.org/10.1111/1541-4337.12293.

Ladha-Sabur, A., S. Bakalis, P.J. Fryer, and E. Lopez-Quiroga. 2019. Mapping energy consumption in food manufacturing. *Trends in Food Science and Technology* 86: 270–280. https://doi.org/10.1016/j.tifs.2019.02.034.

Latour, B. 1999. *Politics of nature*. Cambridge: Harvard University Press.

Ledman, M., and S. van Battum. 2020. *Global Dairy Top 20*. RaboBank. https://research.rabobank.com/far/en/sectors/dairy/dairy_top_20_2020.html. Accessed 4 Feb 2021.

Leroy, F., A.H. Hite, and P. Gregorini. 2020. Livestock in evolving foodscapes and thoughtscapes. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2020.00105.

Lonkila, A., and M. Kaljonen. 2021. Promises of meat and milk alternatives: An integrative literature review on emergent research themes. *Agriculture and Human Values* 38 (3): 625–638. https://doi.org/10.1007/s10460-020-10184-9.

Lonnie, M., E. Hooker, J.M. Brunstrom, B.M. Corfe, M.A. Green, A.W. Watson, E.A. Williams, E.J. Stevenson, S. Penson, and A.M. Johnstone. 2018. Protein for life: Review of optimal protein intake, sustainable dietary sources and the effect on appetite in ageing adults. *Nutrients* 10 (3): 360. https://doi.org/10.3390/nu10030360.

MassonDelmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou. 2021. IPCC 2021: 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*. Cambridge: Cambridge University Press.

Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.A. Tubiello, and Y. Xu. 2019. Food security. In *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/srccl/. Accessed 10 March 2021.

McAfee, K. 1999. Selling nature to save it? Biodiversity and green developmentalism. *Environment and Planning d, Society and Space* 17 (2): 133–154. https://doi.org/10.1068/d170133.

McCarthy, K., M. Parker, A. Ameerally, S. Drake, and M. Drake. 2017. Drivers of choice for fluid milk versus plant-based alternatives: What are consumer perceptions of fluid milk? *Journal* *of Dairy Science* 100 (8): 6125–6138. https://doi.org/10.3168/jds.2016-12519.

McGregor, A., L. Rickards, D. Houston, M.K. Goodman, and M. Bojovic. 2021. The biopolitics of cattle methane emissions reduction: Governing life in a time of climate change. *Antipode* 53 (4): 1161–1186. https://doi.org/10.1111/anti.12714/.

Michaëlsson, K., A. Wolk, S. Langenskiöld, S. Basu, E. Warensjö Lemming, H. Melhus, and L. Byberg. 2014. Milk intake and risk of mortality and fractures in women and men: Cohort studies. *British Medical Journal* 349 (1): 6015–6015. https://doi.org/10.1136/bmj.g6015.

Mittelstaedt, J.D., C.J. Shultz, W.E. Kilbourne, and M. Peterson. 2014. Sustainability as megatrend: Two schools of macromarketing thought. *Journal of Macromarketing* 34 (3): 253–264. https://doi.org/10.1177/0276146713520551.

Miller, B.A., and C.D. Lu. 2019. Current status of global dairy goat production: An overview. *Asian-Australasian Journal of Animal Science.* 32 (8): 1219–1232. https://doi.org/10.5713/ajas.19.025.

Mintel. 2019. *Milking the vegan trend: A quarter (23%) of brits use plant-based milk*. Mintel, 19 July. https://www.mintel.com/press-centre/food-and-drink/milking-the-vegan-trend-a-quarter-23-of-brits-use-plant-based-milk. Accessed 1 July 2021.

Minten, B., Y. Habte, S. Tamru, and A. Tesfaye. 2020. The transforming dairy sector in Ethiopia. *PLoS ONE* 15 (8): e0237456. https://doi.org/10.1371/journal.pone.0237456.

Morris, C., M. Kaljonen, L. Aavik, B. Balázs, M. Cole, B. Coles, S. Efstathiu, T. Fallon, M. Foden, E.H. Giraud, M. Goodman, E.H. Kershaw, R. Helliwell, P. Hobson-West, M. Häyry, P. Jallinoja, M. Jones, T. Kaarlenkaski, M. Laihonen, A. Lähteenmäki-Uutela, S. Kupsala, A. Lonkila, L. Martens, R. McGlacken, J. Mylan, M. Niva, E. Roe, R. Twine, M. Vinnari, and R. White. 2021. Priorities for social science and humanities research on the challenges of moving beyond animal-based food systems. *Humanities and Social Sciences Communications* 8 (1): 1–12. https://doi.org/10.1057/s41599-021-00714-z.

Moshfegh, A.J., A.O. Garceau, E.A. Parker, and J.C. Clemens. *Beverage choices among children: What we eat in America, NHANES 2015–2016*. U.S. Department of Agriculture, Agricultural Research Service. https://www.ars.usda.gov/ARSUserFiles/80400530/pdf/DBrief/22_Beverage_choices_children_1516.pdf. Accessed 10 June 2021.

Mylan, J., C. Morris, E. Beech, and F.W. Geels. 2019. Rage against the regime: Niche–regime interactions in the societal embedding of plant-based milk. *Environmental Innovation and Societal Transitions* 31: 233–247. https://doi.org/10.1016/j.eist.2018.11.001.

Naisbitt, J. 1984. *Megatrends: Ten new directions transforming our lives*. London: MacDonald.

Neo, P. and F.Y. Lim. 2021. *Six top trends set to impact APAC's F&B development in 2021—Featuring Mondelez, Chobani, Kirin, Nestle and more.* Food Navigator Asia, 4 January. https://www.foodnavigator-asia.com/Article/2021/01/04/Six-top-trends-set-to-impact-APAC-s-F-B-development-in-2021-featuring-Mondelez-Chobani-Kirin-Nestle-and-more. Accessed 19 Feb 2021.

Nestle. 2021. *Brands.* Nestle. https://www.nestle.com/brands. Accessed 4 Feb 2021.

Oceania Dairy. 2020. Yili Group. Oceania Dairy. https://oceaniadairy.co.nz/yili-group/. Accessed 4 Feb 2021.

Numpaque, M., T. Şanlı, and E.A. Anli. 2019. Diversity of milks other than cow, sheep, goat and buffalo: In terms of nutrition and technological use. *Turkish Journal of Agriculture: Food Science and Technology* 7 (12): 2047–2053. https://doi.org/10.24925/turjaf.v7i12.2047-2053.2623.

OECD–FAO. 2010. *Agricultural Outlook 2010*. Paris: OECD Publishing.

OECD–FAO. 2020. *OECD–FAO Agricultural Outlook 2020–2029*. Paris: OECD Publishing. https://doi.org/10.1787/aa3fa6a0-en.

OECD–FAO. 2021. *Table C.5—World dairy projections: Milk, butter and cheese*. OECD–FAO. https://www.oecd-ilibrary.org/agriculture-and-food/world-dairy-projections-milk-butter-and-cheese_0ca74b06-en. Accessed 28 Aug 2021.

Ormond, J. 2020. Geoengineering super low carbon cows: Food and the corporate carbon economy in a low carbon world. *Climatic Change* 163 (1): 135–215. https://doi.org/10.1007/s10584-020-02766-7.

Pandya, R. 2016. Developing the animal-free future of dairy. *YouTube*. https://www.youtube.com/watch?v=wv7gjWg5wTY&t=607s. Accessed 7 Feb 2021.

Park, Y.W. 2021. The impact of plant-based non-dairy alternative milk on the dairy industry. *Food Science of Animal Resources* 41 (1): 8–15. https://doi.org/10.5851/kosfa.2020.e82.

Pieper, M., A. Michalke, and T. Gaigler. 2020. Calculation of external climate costs for food highlights inadequate pricing of animal products. *Nature Communications* 11 (1): 6117–6117. https://doi.org/10.1038/s41467-020-19474-6.

Philippidis, G., H. Ferrer-Pérez, P. Gracia-de-Rentería, R. M'barek, and A.I. Sanjuán López. 2021. Eating your greens: A global sustainability assessment. *Resources, Conservation and Recycling*. 168: 105460. https://doi.org/10.1016/j.resconrec.2021.105460.

Poore, J., and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science (american Association for the Advancement of Science)* 360 (6392): 987–992. https://doi.org/10.1126/science.aaq0216.

Popkin, B.M. 2003. The nutrition transition in the developing world. *Development Policy Review* 21 (5–6): 581–597. https://doi.org/10.1111/j.1467-8659.2003.00225.x.

Pulina, G., M. Milán, M. Lavín, A. Theodoridis, E. Morin, J. Capote, D. Thomas, A.H. Francesconi, and G. Caja. 2018. Invited review: Current production trends, farm structures, and economics of the dairy sheep and goat sectors. *Journal of Dairy Science* 101 (8): 6715–6729. https://doi.org/10.3168/jds.2017-14015.

Raboresearch. 2020. *Global dairy top 20*. Rabobank. https://research.rabobank.com/publicationservice/download/publication/token/H5laAEfE5bCRp5mv9cP. Accessed 20 Aug 2021.

Reardon, T., C.B. Barrett, J.A. Berdegué, and J.F. Swinnen. 2009. Agrifood industry transformation and small farmers in developing countries. *World Development* 37 (11): 1717–1727. https://doi.org/10.1016/j.worlddev.2008.08.023.

Rohner, P. 2018. Water: A megatrends perspective. In *Assessing global water megatrends*, 1st ed, eds. A.K. Biswas., C. Tortajada, and P. Rohner, Singapore: Springer.

Rotz, C.A. 2018. Modeling greenhouse gas emissions from dairy farms. *Journal of Dairy Science* 101 (7): 6675–6690. https://doi.org/10.3168/jds.2017-13272.

Roy, D., A. Ye, H. Singh, and P.J. Moughan. 2020. Composition, structure, and digestive dynamics of milk from different species-a review. *Frontiers in Nutrition (lausanne)* 7: 577759. https://doi.org/10.3389/fnut.2020.577759.

Saari, U.A., C. Herstatt, R. Tiwari, O. Dedehayir, and S.J. Mäkinen. 2021. The vegan trend and the microfoundations of institutional change: A commentary on food producers' sustainable innovation journeys in Europe. *Trends in Food Science and Technology* 107: 161–167. https://doi.org/10.1016/j.tifs.2020.10.003.

Schuster, J.C., H.W. Barkema, A. De Vries, D.F. Kelton, and K. Orsel. 2020. Invited review: Academic and applied approach to evaluating longevity in dairy cows. *Journal of Dairy Science* 103 (12): 11008–11024. https://doi.org/10.3168/jds.2020-19043.

Sewell, S. 2021. Small farms vanish every day in America's dairy land: 'There ain't no future in dairy'. *The Guardian*, 21 July. https://www.theguardian.com/environment/2021/jul/21/

small-farms-vanish-every-day-in-americas-dairyland-there-aint-no-future-in-dairy. Accessed 6 Aug 2021.
Sexton, A.E., T. Garnett, and J. Lorimer. 2019. Framing the future of food: The contested promises of alternative proteins. *Environment and Planning E, Nature and Space* 2 (1): 47–72. https://doi.org/10.1177/2514848619827009.
Sexton, A.E. 2020. Food as software: Place, protein, and feeding the world Silicon Valley-style. *Economic Geography* 96 (5): 449–469. https://doi.org/10.1080/00130095.2020.1834382.
Slaughter, R. 1993. Looking for the real "megatrends." *Futures: the Journal of Policy, Planning and Futures Studies* 25 (8): 827–849. https://doi.org/10.1016/0016-3287(93)90033-P.
Springmann, M., M. Clark, D. Mason-D'Croz, K. Wiebe, B.L. Bodirsky, L. Lassaletta, S.J. de Vries, S.J. Vermeulen, M. Herrero, K.M. Carlson, M. Jonell, M. Troell, F. DeClerck, L.J. Gordon, R. Zurayk, P. Scarborough, M. Rayner, B. Loken, J. Fanzo, H.C. Godfray, D. Tilman, J. Rockström, and W. Willett. 2018. Options for keeping the food system within environmental limits. *Nature* 562 (7728): 519–525. https://doi.org/10.1038/s41586-018-0594-0.
Starostinetskaya, A. 2021. Worlds first dairy-identical vegan ice cream launches at 5000 stores. *VegNews*, 5 February. https://vegnews.com/2021/2/dairy-identical-vegan-ice-cream-at-5-000-stores. Accessed 8 Feb 2021.
Steeneveld, W., L. Taue, H. Hogeveen, and A.G.J. Oude Lansink. 2012. Comparing technical efficiency of farms with an automatic milking system and a conventional milking system. *Journal of Dairy Science* 95 (12): 7391–7398. https://doi.org/10.3168/jds.2012-5482.
Stephens, E. 2020. Cellular agriculture in the UK: A review. *Open Research* 5: 12. https://doi.org/10.12688/wellcomeopenres.15685.2.
Stewart, H., F. Kuchler, J. Cessna, and W. Hahn. 2020. Are plant-based analogues replacing cow's milk in the American diet? *Journal of Agricultural and Applied Economics* 52 (4): 1–18. https://doi.org/10.1017/aae.2020.16.
Stokel-Walker, C. 2018. The irresistible rise of alternative milks like Oatly has dairy farmers freaked. *Wired*, 22 August.https://www.wired.co.uk/article/non-dairy-milk-alternatives-oatly-soy-oat-rice-vegan. Accessed 12 Feb 2021.
Teague, R., and U. Kreuter. 2020. Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2020.534187.
Tubb, C., and T. Seba. 2019. *Rethinking food and agriculture 2020–2030.* RethinkX. https://static1.squarespace.com/static/585c3439be65942f022bbf9b/t/5d7fe0e83d119516bfc0017e/1568661791363/RethinkX+Food+and+Agriculture+Report.pdf. Accessed 2 July 2021.
Turner, J. 2005. A new approach for theoretically integrating micro and macro analysis. In *The SAGE handbook of sociology*, ed. C. Calhoun, C. Rojek, and B. Turner, 405–422. London: SAGE Publications.
Valenze, D. 2011. *Milk: A local and global history*. London: Yale University Press.
Visconti, L.M., Y. Minowa, and P. Maclaran. 2014. Public markets: An ecological perspective on sustainability as a megatrend. *Journal of Macromarketing* 34 (3): 349–368. https://doi.org/10.1177/0276146714525201.
von Massow, M., and M. Gingerich. 2019. Lab-grown dairy: The next food frontier. *The Conversation*, 12 June. https://theconversation.com/lab-grown-dairy-the-next-food-frontier-117963. Accessed 12 March 2021.
Vouraki, S., I. Skourtis, K. Psichos, W. Jones, C. Davis, M. Johnson, L.R. Rupérez, A. Theodoridis, and G. Arsenos. 2020. A decision support system for economically sustainable sheep and goat farming. *Animals (basel)* 10 (12): 2421. https://doi.org/10.3390/ani10122421.
Wankar, A.K., S.N. Rindhe, and N.S. Doijad. 2021. Heat stress in dairy animals and current milk production trends, economics, and future perspectives: The global scenario. *Tropical Animal Health and Production* 53 (1): 70. https://doi.org/10.1007/s11250-020-02541-x.
Weis, A.J. 2013. *The ecological hoof print: The global burden of industrial livestock*. London: Zed Books.
Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L.J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J.A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S.E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, and C.J.L. Murray. 2019. Food in the Anthropocene: The EAT–Lancet Commission on Healthy Diets from Sustainable Food Systems. *The Lancet (british Edition)* 393 (10170): 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
Whatmore, S. 2002. *Hybrid geographies: Natures, cultures, spaces*. London: Sage.
Zafrilla, J., A. García-Alaminos, and F. Monsalv. 2020. The sustainability challenge of dairy livestock systems. In *Sustainable and environmentally friendly dairy farms*, ed. S. García-Yuste, 1–17. Cham: Springer.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Milena Bojovic is a PhD Candidate in the Discipline of Geography and Planning, in the School of Social Sciences at Macquarie University, Sydney. Her research examines the intersections of climate change and animal agriculture, looking at the environmental and social sustainability issues within these food systems. Her current work explores the potential upscaling of non-animal-based foods and just transitions for humans, non-humans and environments within food systems.

Andrew McGregor is an Associate Professor in the in the Discipline of Geography and Planning, in the School of Social Sciences at Macquarie University, Sydney. He is a human geographer who studies human-environment interactions in Australia and Southeast Asia. He has research expertise in the social justice dimensions of climate mitigation initiatives related to food, forests and agriculture. His current work explores just transitions in the food sector, with a particular focus on low emissions plant-based foods.