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The big business of sustainable food production and consumption: Exploring the transition to alternative proteins

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A widespread sense of the unsustainability of the food system has taken hold in recent years, leading to calls for fundamental change. The role of animal agriculture is central to many of these debates, leading to interest in the possibility of a "protein transition," whereby the production and consumption of animal-derived foods is replaced with plant-based substitutes or "alternative proteins." Despite the potential sustainability implications of this transition, the developmental trajectories and transformative potential of the associated technologies remain underexplored. This article sheds light on these dynamics by addressing two questions: 1) how have alternative protein innovations developed over the past three decades, and 2) what explains their more recent acceleration? To answer these questions, the article makes an empirical analysis of four alternative protein innovations, and the partial destabilization of the animal agriculture system between 1990 and 2021, guided by the multi-level perspective. The analysis highlights an intensification in corporate engagement with alternative protein development and diffusion. This intensification is judged to be consistent with the beginnings of a wider corporate reorientation, occurring alongside a rise in pressures on the animal agriculture system, notably an increasing scientific consensus and societal awareness of the links between climate change and meat-intensive diets. The paper demonstrates how differences in technological maturity across the niche innovations have resulted in potentially transformative pressures, which are consistent with an emerging sustainability transition, manifesting differently in terms of the extent of diffusion of the alternative protein niches.

alternative proteins | animal agriculture | sustainability transition | food systems innovation

Significance

Animal agriculture is responsible for considerable environmental burden, and a key contributor to climate change. Meat alternatives are increasingly understood as potential solutions to decreasing this burden by enabling a shift away from conventional models of production and consumption of animal-derived foods. This paper explores the progress, drivers, and barriers of change by examining the development and diffusion of four key technologies used to produce "alternative protein" products. Recent developments are shown to be consistent with an emerging sustainability transition, particularly the increased engagement with alternative proteins by large food corporates. However, political, regulatory, and cultural barriers remain, and are more pronounced for some alternative protein technologies than others, affecting prospects for the progression of a transformational "protein transition."

The food system is heavily implicated in numerous sustainability challenges, including climate change, biodiversity loss, water pollution, public health issues, and animal welfare (1–3). A widespread sense of the unsustainability of the food system has taken hold in recent years, leading to calls for fundamental change (4, 5). The role of animal agriculture and the associated meat, dairy, egg, and fish industries are central to many of these debates, because of their contribution to many sustainability problems. Nevertheless, food consumption and production systems centred on animal-derived foods remain the dominant way of providing human beings with proteins in wealthy industrialised nations, and represent a growing share in many developing economies. The growth of the global middle class is further expected to increase demand for meat and dairy worldwide over the next several decades, which would intensify sustainability challenges.

Concerns about the unsustainability of animal-centric consumption and production systems has led to significant interest in alternative models of provision (6). One possibility that has generated much recent commentary is that of a "protein transition", envisaged as the replacement of animal-derived foods with plant-based substitutes and other novel sources of protein, commonly described using the umbrella term "alternative proteins"*. Below we identify four main kinds of alternative proteins, differentiated on the basis of production techniques:

- **Plant-based meat**: Using plant-based ingredients such as soy, yellow peas or wheat, which are processed with techniques such as extrusion, spinning, freeze structuring or "shear-cell" technology to produce meat-like textures. These techniques for producing meat substitutes can trace their origins to early 20th century chemurgical experimentation with soybeans in the USA. Products developed with some of these methods were commercialised in the 1950s, undergoing incremental refinement over the last 70 y.

*We use the term alternative proteins as shorthand for *novel high-protein foods*, namely processed plant-based meat substitutes and those derived from cellular agriculture.

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- **Single Cell Proteins (SCPs)**: Fermenting funghi, algae, yeast or other bacteria on a variety of nutrient media, sometimes derived from "waste", to create SCPs (such as the Quorn mycoprotein). SCP development can be traced to the activities of petrochemical firms in the 1950s, although Quorn remains one of very few successful commercialisations.
- **Precision (cellular) fermentation**: Combining fermentation with genetic engineering to enable bacteria to produce proteins typically found in animal-derived foods, such as casein or whey. These techniques originate in genetic engineering and pharmaceutical research of the 1970s. First applied to producing food ingredients (rennet) in the late 1980s, more concerted application to alternative proteins has emerged since the 2010s.
- **Cultured meat**: Using tissue engineering to produce "real" muscle tissue from cells taken from living animals, typically grown in bioreactors and combined to create products such as burgers or "nuggets". Tissue engineering techniques originated in regenerative medicine research carried out in the 1970s and 1980s, and were applied to food production from the late 1990s, with rapid intensification in the 2010s.

Although the literature has noted the sustainability promise of these alternative proteins (7, 8), their developmental trajectories have, with a few exceptions (e.g., refs. 9 and 10), remained underexplored. This is surprising because after long periods of relatively invisible development, various alternative protein products have burst onto the commercial scene in the last decade or so, although with variation across countries. The UK National Diet and Nutrition Survey (N = 15,655) indicates that UK consumption of plant-based meat and dairy substitute foods has increased significantly over the last two decades, doubling in terms of the number of people and the amount consumed, between 2008 to 2011 and 2017 to 2019. The analysis demonstrates a concomitant decline in meat consumption, from 99.0 g to 85.3 g per day per person, concluding that consumption of protein alternatives, "while still relatively small as a percentage of daily dietary energy intake, has increased significantly over the period 2008 to 2019 in the UK and appears to be accelerating" (11:5).

In addition to changing consumption, representation of protein alternatives in the UK media, taken here as proxy for wider societal awareness, has also increased markedly since the 1990s, gaining pace since the millennium, with a sharp upswing of attention in the mid-2010s (Fig. 1). Explanations for this rise include the release of influential documentaries relating to veganism or plant-based diets (12) and the growing influence of "celebrity vegans" (13, 14). Commercial interest in alternative protein technologies has also intensified in recent years, with rapid and significant increases in investment in alternative protein start-ups, reaching a reported $5 billion in 2021 globally (15). While projections of market growth vary considerably, estimates by business consultancies and financial services firms of up to a ten-fold increase in the market size over the next decade are common, demonstrating commercial expectations of future growth (see for example refs. 16 and 17).

These observed developments in alternative protein technologies and associated food consumption patterns demand closer scrutiny regarding their underlying dynamics and emerging outcomes. In this vein, this article addresses the following research questions: 1) how have the various alternative protein innovations developed over the past three decades, and 2) what explains their more recent acceleration? To answer these questions, the article makes an empirical analysis of the various alternative protein innovations, guided by the multi-level perspective (MLP) on socio-technical transitions—a framework increasingly recognised as providing valuable insights for sustainability science (18).

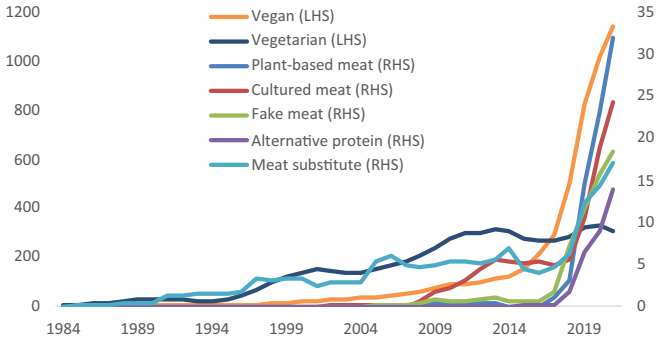

Fig. 1. Rising occurrence of references to plant-based foods in UK media 1984 to 2021. Note: Chart indicates five-year rolling average annual occurrence of AP terms and synonyms searched in Factiva database across 15 national UK broadsheet and tabloid newspapers.

The MLP suggests that transitions involve multi-dimensional interactions between emerging niche-innovations and deeply entrenched existing systems ("regimes") in the context of gradually changing "landscape" developments (19, 20). From this perspective, there are no inevitabilities because transitions require a confluence of technological, cultural, and political factors across these levels (19, 21).

Radical innovations, which substantially deviate in one or more dimensions from the existing system, tend to emerge in peripheral niches, where small networks of dedicated actors work on developing and improving innovations through research and development and other learning processes, in market, policy, or cultural dimensions (22). The diffusion of these innovations—the processes by which they become embedded within the broader societal environment beyond their original niche (23, 24)—is a precursor to more radical transformation of the system. Successful diffusion of novel technologies depends on the alignment of multiple developments, including increasing momentum of niche-innovations (e.g., through investment, performance improvement and cost reduction, consumer enthusiasm, or supportive cultural debates), as well as a destabilisation of the existing system. Regime destabilisation, "the process of weakening reproduction of core regime elements" (25: p. 35; see also ref. 26, this issue), is in turn a critical part of transition processes. Influential actors may otherwise remain committed to existing ways of operating, perpetuating the dominant system and limiting the scope for niche-innovations to expand or displace elements of the regime. Destabilisation may result from exogenous landscape pressures, weakening economic performance (e.g., shrinking markets and profitability), eroding socio-cultural legitimacy (e.g., from negative public debates), or weakening commitment of incumbent actors to existing technologies and business models (20, 25). Crucially, transitions research recognises that "actor's interests, identities, capabilities, and beliefs are not fixed, but are reconfigured during transitions" (27: p. 47), and as such the extent and manner in which powerful incumbent actors reorient from existing regimes towards niche-innovations can serve as an indicator of regime destabilisation. While recognising that transitions are multi-actor processes, this paper focuses on the domain of business, and in particular the role of corporate actors in identifying and creating commercial opportunities in the emergence and diffusion of alternative proteins.

The rest of the article is structured as follows. Section 1 outlines the research design. Section 2 presents the longitudinal case study, which describes the emergence and development of alternative protein niche-innovations and addresses partial destabilisation of the animal food production regime. We suggest that increased support for alternative protein niches is contributing to the

widening of "cracks" in the dominant animal agricultural regime, but that it remains too early to determine whether these cracks will develop into more transformative change. Section 3 draws conclusions, discusses the findings, and highlights key processes to which sustainability science scholars should remain attentive, as developments in this space unfold.

1. Research Design

In contrast to other sustainability transition domains, such as renewable electricity or electric vehicles, public agencies limitedly engage in statistical data-collection for alternative proteins, which means that few official datasets are available. The paper therefore employs a variety of other information sources by way of research design. Analysis of alternative protein niche-innovations draws on existing academic research, alongside primary research into start-up companies and multinational corporates, including from company websites, annual reports and press releases, as well as news media and third party market research. This includes analysis of corporate investment patterns at a global scale, using exemplar transactions by key companies, identified using an unpublished dataset of corporate venturing by food companies in alternative proteins (see ref. 28 for background). For the analysis of the existing animal food regime, we use company annual reports, statistics presented in third sector analysis, press releases, and press commentary. This combination and compilation of empirical material from a range of sources is consistent with much transitions research (29).

The research focuses largely on the business domain for several reasons. First, business firms are recognised within the MLP as significant actors that are central to existing systems and play important roles in transition processes (27, 30). Second, recent research on alternative proteins, the majority of which does not adopt a transitions lens, indicates significant interest in the emerging role of large food corporates (31, 32), feeding into longstanding debates around the power of corporates to shape food system outcomes. Reasons of scope and space prohibit extensive treatment of other actor types.

The developmental histories of alternative protein technologies have not been confined to any single geography, albeit that North America and Europe feature prominently, and there is a significant concentration of alternative protein companies located in those regions (33). The same has been true, with notable exceptions, of the large multinational food corporates which continue to develop interests in these technologies (Table 1). Many of these firms are active in numerous markets, including outside of their home regions, and have significant cross-border relationships, necessitating an analysis that does not focus on any single country or region. To capture this reality, observations are grounded mostly in the UK context—which on some measures has high consumption (34) and high rates of new product development (35) related to alternative proteins—while also drawing on developments across North America and wider Europe.

2. The Emerging Alternative Protein Transition

2.1. The Slow Emergence and Recent Acceleration of Niche-Innovations (1990 to 2021).

2.1.1. ***Technical and corporate consolidation in small market niches (1990 to 2000).*** The development of alternative protein products has a long history stretching back to the end of the 19th century (36). Our analysis begins in the 1990s, when the market was characterised by a range of small, relatively stable, market niches among vegetarians and health food advocates, with demand satisfied by a range of primarily plant-based protein products (and Quorn) produced and marketed primarily by SMEs. During this period start-ups periodically entered the market, including Vivera in the Netherlands, and Linda McCartney in the UK. The UK also saw (temporary) increases in the number of people identifying as vegetarians (37), corresponding to animal food-related health scares, including "mad cow" disease (bovine spongiform encephalopathy, or BSE), *E. coli* and salmonella. This led to suggestions that vegetarianism had "permeated the social mainstream" in the UK by the early 2000s (38). These movements were also developing an awareness of the possible links between meat and dairy production and climate change. Biotechnologies continued to advance, with the production of the enzyme 'chymosin' via precision fermentation approved by the United States' Food and Drug Administration (FDA) as a replacement for rennet in 1990 (39), a process which would later become important in the production of proteins commonly found in animal-based foods, such as casein and gelatine. The Dutch government began taking interest in the possibilities offered by alternative proteins, funding a research project into 'Novel Protein Foods', set up to explore issues including consumer acceptance, technological challenges, economics, and environmental issues.

An expanding market piqued the interest of larger food firms, prompting a wave of alternative protein company acquisitions by multinational corporates such as Kraft and Kellogg's. Corporate interest in the sector was further boosted in 1999 by the decision of the FDA to authorise health-related claims for soy products. By the mid-2000s, meat substitutes were the domain of large firms, either those with long-standing interests in the sector, or those that had acquired their way to leading positions in the market through takeovers of smaller firms, selling into the expanding ranks of vegetarians and health-conscious consumers.

2.1.2. ***Alternative proteins become a "solution" to climate change (2000 to 2013).*** In the 2000s, "serious modelling, thinking and scientific debate" began in relation to sustainable diets (40), including reduced or alternative meat and dairy consumption for environmental and health reasons. A turning point in public discourse around animal agriculture was the 2006 publication of the FAO's report *Livestock's Long Shadow* (41). While it was not the first document to indicate the environmental implications of animal agriculture, its major impact was in its framing of livestock as a major contributor to climate change. Although the size of that contribution has been a source of ongoing controversy, the report intensified discussions around the role of meat and dairy in contemporary diets, tying together established debates about the capacity of the food system to keep pace with population growth with modern analysis of the "nutrition transition" in which diets become more meat-intensive in line with rising incomes in emerging economies, along with newer and intensifying concerns about climate change. The report made no mention of alternative proteins as a potential solution, but operated as a key reference point for ensuing debates around the role of meat and dairy in diets (40), and is often cited by alternative protein company founders in discussions of their work (e.g., refs. 42–44).

The intensification of scientific and wider societal concerns around climate change in recent decades has served as a significant landscape pressure on the animal agricultural regime. Since 2006, the linkages between meat production and consumption and the climate debate have solidified, altering the technological selection environment through a new framing of alternative proteins as "solutions" to the climate challenge. Climate concerns have also frequently been tied to additional landscape discourses, particularly regarding population growth, fuelled in the 2000s and early

Table 1. Large food corporate involvement with alternative proteins

Firm	Involvement in alternative proteins
ADM: Major commodity processor with multiple business lines.	• Developed, patented, and trademarked Textured Vegetable Protein in late 1960s and early 1970s, and acquired portfolio of meat substitute firms throughout the 1980s. • Prolific investor in multiple alternative protein niches since 2018, with investments in Geltor (US fermentation-based ingredient producer), Perfect Day (US fermentation-based dairy start-up), Future Meat Technologies (Israeli cell-based meat start-up), Nature's Fynd (US fermentation-based meat and dairy start-up), MycoTechnology (US fermentation-based mycoprotein start-up), and PlantPlus Foods (US plant-based meat start-up).
Bunge: Major commodity processor with multiple business lines.	• Early investor in plant-based meat company Beyond Meat (exited 2019), with subsequent repeat investments in MycoTechnology (US fermentation-based mycoprotein start-up), Merit Functional Foods (Canadian plant-based ingredients company), and Australian Plant Proteins (Australian plant-based ingredient company).
Louis Dreyfus: Major commodity processor with multiple business lines.	• Investments in Motif FoodWorks (multitechnology ingredient start-up) and Gathered Foods (US plant-based seafood start-up).
Kellogg's: Major food processing conglomerate with portfolio of cereal and snack brands.	• Core actor in development of early modern meat substitutes in the late 19th century, with on-and-off involvement since mid-20th century, particularly via Morningstar Farm brand. • Multiple investments in several alternative protein niches since 2017, including repeat investments in MycoTechnology (US start-up producing mycoprotein through fermentation) and Plantible Foods (US plant-based ingredient manufacturer), and continued investment in own plant-based production capacity.
Unilever: Diversified consumer goods conglomerate with portfolio of food, supplement, and personal health-care products.	• Long-standing interests in plant-based meat substitutes, including as corporate sponsor of Dutch Novel Protein Foods project in the 1990s. • Contemporary involvement with plant-based meat substitutes via acquisition of The Vegetarian Butcher (Dutch plant-based meat company), and of fermentation via partnership with ENOUGH (UK start-up producing mycoprotein via fermentation), with additional investments in R&D partnership "The Hive" at Wageningen. Unilever targeting EUR1bn sales from plant-based meat and dairy products by 2025 to 2027.
General Mills: Major food processing conglomerate with portfolio of food brands.	• Developed and launched several pioneering plant-based meat substitute products in the 1960s, exiting the market in late 1970s. • Has invested in multiple alternative protein niches since 2016, including through Beyond Meat (US plant-based meat company), Kite Hill (US plant-based dairy start-up), and Gathered Foods (US plant-based seafood substitute start-up). Has also partnered with precision fermentation firm Perfect Day to develop dairy substitute product lines.
Nestle: Major food processing conglomerate with portfolio of brands across food, drink, and pet care, and one of the world's largest dairy processors.	• Has invested significantly in internal capacity, claiming to have "around 300 R&D scientists, engineers, and product developers" dedicated to plant-based foods across eight separate locations, while constructing plant-based manufacturing capacity in China and Malaysia. Has launched several plant-based product lines, including Garden Gourmet in Europe, Harvest Gourmet in Asia, and plant-based seafood brand Vuna. Has been reported to be undertaking exploratory work with cell-based meat company Future Meat Technologies.
JBS: World's largest meat processor with global interests across beef, chicken, and pork industries.	• Has gained exposure to multiple alternative protein niches through acquisitions, including Dutch plant-based meat company Vivera, plant-based product lines of Irish food processor Kerry, and Spanish cell-based meat company BioTech Foods. Launched own line of plant-based meat products and a plant-based innovation hub in Brazil, and is reported to be developing in-house R&D facility for cell-based meat.
Tyson: World's second largest meat processor, with interests across chicken, beef, and pork.	• Numerous investments across multiple alternative protein niches since 2017, including through Beyond Meat (US plant-based meat company, exited 2019), Upside Foods (US cell-based meat start-up), Future Meat Technologies (Israeli cell-based meat start-up), New Wave Foods (plant-based seafood start-up), and MycoTechnology (US fermentation-based mycoprotein start-up). Has also introduced plant-based meats into some of its own product ranges.
Cargill: World's largest food company by revenue, with interests in commodity trading and processing, meat processing, and more.	• Several investments across multiple alternative protein niches, including through Upside Foods (US cell-based meat start-up), Aleph Farms (Israeli cell-based meat start-up), PURIS (US pea protein producer), and Bflike (Belgian plant-based ingredients start-up). Launched its own plant-based meat substitute brand—PlantEver—for Chinese market. Company literature claims position as "largest private label supplier" of plant-based meat substitutes in the United States, with a "significant presence" in China.

2010s by claims that food production would need to increase by 70% by 2050 to satisfy a larger and more prosperous global population (45). These landscape pressures coincided with efforts to frame alternative proteins as "technology first and food second" (46), drawing new actors—particularly venture capitalists—into the fray. Concurrently, a new generation of researchers and entrepreneurs entered established plant-based niches, with the founding of the now high-profile firms such as Beyond Meat in 2009, The Vegetarian Butcher in 2010 and Impossible Foods in 2011.

The development of the fledgling industry of cellular agriculture also began to accelerate. The adaptation of tissue engineering techniques from medical science to the task of producing edible food products has been a work in progress since at least

the late 1990s, concentrated among a small number of scientists working in the Netherlands and United States. By the mid-2000s, the idea that tissue engineering could be a viable method for producing meat products was no longer science fiction, with academic commentary emphasising its technical (though at that stage not yet economic) feasibility (47). The Dutch government provided funding for a multi-year research project during this period (48), one of few instances of public sector support for the development of alternative proteins. Although this funding did not continue beyond 2009, scientific interest in the field endured, with activity subsequently becoming concentrated in the private sector (49). Some social movement actors also sought to promote development of the technology, with animal rights organisation People for the Ethical Treatment of Animals (PETA) offering an ultimately unclaimed $1mn prize to anyone who could develop a commercially viable production process during the early 2010s, while the non-profit New Harvest, founded in 2004, continued to channel funding to researchers and start-ups.

The cellular agriculture niche attracted mainstream attention with Mark Post's 2013 press conference, at which a 'lab-grown' burger was presented to the world's press. Post's company, Mosa Meat, and a growing number of other start-ups, have since attracted significant sums of venture capital in pursuit of improved products and economies of scale to enable commercialisation. Over a similar period, precision fermentation has also been adapted to the task of producing proteins usually derived from animal products such as casein, whey and collagen. In sum, the last two decades have seen not only an intensification of debates around sustainable diets, bolstered particularly by the rise to prominence of climate change as a landscape pressure on the existing regime, but also the parallel development of sophisticated biotechnologies that have attracted new researchers and entrepreneurs to the challenge of alternative protein production, opening multiple avenues for industry development.

2.1.3. ***Acceleration of some market niches (2013 to 2021).*** Interest in alternative proteins surged throughout the 2010s, driven by a confluence of technological, cultural, and commercial dynamics. Investment in alternative protein companies accelerated significantly, including by large mainstream food companies (see Table 1 for examples), and several companies experienced rapid growth, exemplified by the Initial Public Offering (IPO) of Beyond Meat in 2019. However, as evidenced below, the varying levels of maturity, and differences in the technological and regulatory challenges facing each alternative protein niche-innovation, has meant that progress has been uneven.

Diffusion of the plant-based meat niche accelerated rapidly, as technological refinements, including the development of more versatile processing techniques such as "shear cell" processing led to improvements in the taste and texture of products. Plant-based products became readily accessible to consumers during this period, appearing routinely on supermarket shelves, product advertising, popular media discussions and food service menus. All major retailers in the UK now stock their own "plant-based" alternative food ranges (in addition to other branded products), a trend repeated in the largest US and European retailers (e.g. Walmart, Carrefour and Tesco), reflecting market confidence in the mainstream appeal of these products. This trend continues in fast food service as major fast food companies (including Yum!, which owns KFC and Pizza Hut, and Restaurant International, which owns Burger King and Tim Hortons) established commercial relationships with plant-based firms, including The Vegetarian Butcher, Beyond Meat and Moving Mountains. Burger King opened an entirely plant-based outlet in London in 2022 and McDonalds has launched its 'McPlant' burger in collaboration with Beyond Meat. The inclusion of alternative protein products into traditionally meat-based consumer fast food offerings, alongside the building of alliances across these two sectors, is indicative of the food service sector's interpretation of significant commercial opportunities, consumer access and overall consumption of alternative proteins in place of traditionally meat-based offerings.

The acceleration of the cultured meat niche manifested differently than that of plant-based meat, reflecting its status as a less mature technology which has not yet reached a point of technological "closure". Acceleration is visible in the increased number of start-ups claiming to be developing products, currently reported to be in the region of 70 worldwide (50), and their support, primarily through venture capital, including investment by meat industry incumbents (discussed further in Section 2.2). Costs remain high, and although efforts to gain regulatory approvals are under way in several jurisdictions (with notable recent progress in the US), at the time of writing diffusion remains limited, with Singapore the only country to have approved a product for sale. Commercialisations are consequentially few in number, and questions remain about the possibility of delivering economically viable products. Nevertheless, these products have now moved beyond university laboratories, and are viewed by many to be on the brink of wider commercialisation.

The use of precision fermentation appears to have accelerated rapidly within a short space of time, with investments in start-ups growing from negligible levels in the mid-2010s to over a billion dollars in 2021 (15). The technology is geared towards the production of specific types of proteins and other molecules which can be developed into or incorporated into other products, including dairy products, plant-based and cultured meat. Commercialisations that have already gained regulatory approval in the USA include the heme iron used in Impossible Foods' plant-based burgers. However, regulation remains an issue in other jurisdictions, notably the European Union (EU), with the outcomes of ongoing applications for approval set to be a key determinant for their wider diffusion.

Quorn remains the only meat substitute on the market produced with single celled proteins (SCP). The brand was acquired in 2015 by Monde Nissin, a consumer goods producer based in the Philippines, for £550 million, and is continuing in its efforts to expand its international distribution and penetration within retail and food service. However, there is little evidence of single celled proteins being used to develop meat substitutes more widely, with interest in SCPs generally restricted to the production of animal feeds and supplements, for which regulatory barriers are lower than for the production of food for direct human consumption (51).

In the UK, alongside increasing availability of, and societal attention to, alternative proteins more generally (Fig. 1), alternative protein products are developing a degree of cultural legitimacy and "normality" unparalleled in earlier periods, indicating that a process of diffusion and societal embedding is under way. This increasing legitimacy is occurring alongside a rising interest in veganism by high end chefs as alternative proteins begin to attract attention in high end food culture more widely (52). They have also become viewed as social and economic opportunities for wealthy celebrities, including Formula 1 sports star Lewis Hamilton, whose UK-based plant-based burger chain Neat continues to expand (53).

Despite this clear rise in societal acceptance, these products remain discursively vulnerable, including to claims that products are highly processed, that they replicate undesirable features of the corporate food system, or that they are "unnatural" or "fake" foods (8). Rising demand for plant-based proteins has also highlighted

the limitations of existing infrastructure for processing and production, and the need for continued large-scale investment in supply chains to support further growth (see e.g., ref. 15). Such investments are now materialising, primarily enabled by engagement from food sector incumbents, including those traditionally associated with animal agricultural industries, such as global meat and dairy processing groups, which signify early signs of regime destabilisation, as discussed in the following section.

2.2. Partial Destabilisation of the Animal Food Regime and Tentative Reorientation (2000 to 2021). While the previous sub-section described developments in alternative protein niche-innovations, this sub-section describes developments in the existing animal agriculture regime, which has faced increasing landscape pressures in the last 20 y. This has led to some degree of destabilization, which, as set out above, can be seen to arise through a combination of increasing economic pressures, changes in legitimacy, and shifting commitments of incumbent actors, including the tentative diversification of business strategies to include support for niche-innovations (25, 20). These developments offer potential windows of opportunity for the further mainstreaming of alternative proteins and wider changes toward more sustainable food consumption-production systems.

In terms of the flow of economic resources, the meat industry does not appear to be experiencing a major crisis. Large meat and dairy corporates are generally profitable in recent years, although profits vary considerably at the level of individual farms and between sectors, each of which has a different structure, particularly in terms of the degree of vertical integration in lead firms and the shape of typical industry value chains. Sizeable agricultural subsidies—approximately $50 billion annually (54)—continue to support animal agricultural production worldwide, with no indications of major reductions in public sector financial support in the near future. The growth in per capita meat consumption has stagnated in many developed countries in the past decade, and even started to decline in some like the UK and Canada, but in global terms the industry remains on an expansionary trajectory, largely owing to increasing consumption in developing countries (55). Although population growth in most of these countries has increased markets in absolute terms, the per capita decline in demand in developed economy markets has increased the interest of incumbent firms in alternative proteins.

The second aspect of regime destabilisation refers to public legitimacy. This may involve changes in political and policy support, targeting by civil society or social movement activism, a shift in tone or content of media discourse, or changes in the cultural perceptions of an industry (25). On these dimensions there is some evidence of cracks emerging within the regime, at least partially due to climate-related landscape pressures. While direct political and policy support for animal agriculture in the form of subsidy remains intact, there is increasing acknowledgement of the link between livestock farming and climate change by political actors on global stages. The emerging scientific consensus on this issue has been accompanied by the strengthening of links between societal discourses of climate, sustainability and diet by environmental NGOs, in mainstream media, and in the attitudes of some consumer groups (56). Consequently, the suggestion that citizens of the developed world should reduce their meat consumption has moved from narrow circles (primarily academic and activist discussion) to mainstream debate. However, cultural-cognitive lock-ins to the idea that meat consumption is desirable, associated with health, luxury, and sociality continue to stabilise consumer habits, even among consumers that are motivated to eat less meat (57). In addition, animal agriculture retains its legitimacy within mainstream political discourse, as a source of employment, as a vital part of otherwise struggling rural communities, and by drawing attention to investments in production efficiency and "regenerative agriculture". Continuing policy support for animal agriculture has also manifested in efforts to place legal restrictions on labelling terminology for various alternative protein products. Although the ultimate outcome of these discursive struggles remains unknown, the degree of contemporary "mainstreaming" of meat reduction messaging nevertheless represents a departure from earlier periods.

The third aspect of regime destabilisation is decreasing commitment to the regime by incumbent actors. This can entail incumbents expanding their "search" processes into new territories, reprioritising R&D away from conventional to novel technologies, or significant strategic shifts by major industry players, any of which may signal that processes of firm or industry reorientation are in train, which may in time develop into more significant transformation of the regime. On this dimension, there are perhaps the most concrete signs of change as large food corporates have significantly increased their investment and product development activity in relation to alternative proteins over the last decade, with the last few years seeing major upticks in activity. Prolific investors have included global commodity processor Archer Daniels Midland, meat processor Tyson Foods, commodity and meat processor Cargill, and many more (Table 1). The entry of large incumbents into niches may generate additional legitimacy for those niches, prompting others to follow suit (30:59). Cases of such "followership", in which incumbent firms enter niches after the pioneering (and thereby riskier) efforts of other actors (27), are arguably now numerous with respect to alternative proteins. There is also considerable diversity in the approaches of large food companies towards alternative proteins, with some firms favouring in-house R&D and product development, while others have opted to invest in, acquire, or enter joint ventures with, third parties. Investments in start-up companies made through in-house corporate venture capital units are particularly prevalent. While deal sizes are not always made public, investments running into tens and hundreds of millions of dollars are increasingly common.

While several companies investing in alternative proteins in recent years have historic ties to alternative proteins (for instance, ADM and Kellogg in relation to plant-based meat), the last half decade saw a broadening of investment not only in plant-based products, but increasingly in the emerging technologies of cellular agriculture and precision fermentation. Particularly notable is the increase in the number and depth of relationships between meat companies and alternative protein firms. The largest meat processors in the world, including Brazil's JBS, and the US firms Tyson and Cargill, have all entered the market for alternative proteins in recent years (Table 1), in most cases for the first time. Evidence of reorientation is not limited to financial investments or product development, with both Tyson and Cargill having also recently made public decisions to re-brand themselves as "protein" rather than "meat" companies, suggesting a subtle shift in their corporate identities as they have moved to diversify their product offerings, which is potentially significant given that organizational identities play a substantive role in approaches to strategy and innovation (58).

While corporate investment in alternative proteins is certainly significant in size, it pales in comparison to the sums in which conventional animal agricultural industries trade, with annual revenues at the largest meat processors JBS and Tyson roughly 100 times those of the leading plant-based meat brands, while even a cursory glance at the scale of ongoing investment in conventional animal agricultural production makes clear that many firms with interests in alternative proteins remain committed to mainstream animal agricultural sectors.

2.3. Summary and Discussion of Transition Dynamics. The science and foundational technologies that underpin modern alternative proteins are notable for largely originating outside of the food industry, including petrochemical, genetics, biotechnology and medical fields. They have subsequently been adapted to the challenge of producing palatable, economically efficient alternatives to conventionally produced animal proteins. As such, the contemporary alternative protein industries are examples of the complex processes of niche innovation, in which multiple designs have emerged over time in line with an expanding scientific and technological frontier, with inherently uncertain prospects (see ref. 59). Each alternative protein niche has followed its own trajectory and remains at a different stage of maturity and diffusion. Technological progress has been particularly evident in the plant-based, precision fermentation, and cultivated meat niches within the last 15 y or so, accelerating as discourses of climate change and global population growth have intensified activity among multiple constellations of actors. This includes the university-based scientific research community, large and small corporate actors within and outside of the food industry, civil society groups and social movements. Shifting discourses have operated as landscape pressures on the animal agricultural regime, leading to increasingly mainstream recognition that meat and dairy consumption should be reduced in rich countries, creating a window of opportunity within which alternative proteins have gained a degree of legitimacy as potential solutions, albeit while remaining discursively vulnerable along several dimensions. These landscape pressures represent general drivers to explain accelerated change. However, there are also differences *between* alternative protein technologies. Variations in the technological maturity and regulatory issues across the various niches have resulted in landscape and regime pressures manifesting differently in terms of the extent of diffusion of the various alternative protein niches. The plant-based niche has diffused most widely due to its maturity relative to other alternative protein technologies, enabling the incorporation of increasingly sophisticated substitute products into the offerings of mainstream food service and retail companies, many of which have followed early movers into the plant-based niche in light of its perceived commercial successes and opportunities for growth. The SCP niche, meanwhile, remains occupied by a single firm, with wider expansion likely precluded by regulatory and cost considerations. Cultivated meat and precision fermentation have developed considerably since the 2000s, appearing now to stand on the brink of commercialisation, supported by significant venture capital and corporate increases in investment for R&D and production capacity, although lingering technical and regulatory challenges have meant that their diffusion remains limited. Moreover, despite recent acceleration, the market for alternative proteins in general remains small in comparison to conventional animal proteins.

The analysis of corporate "big business" activities demonstrates that new entrants and incumbents are exploiting opportunities arising from shifting public discourse, stimulating product and market development through acquisitions, investments, and joint ventures. The combination of niche technical advances and landscape pressures has driven an intensification of engagement with alternative proteins on the part of incumbent food system actors, including some large meat and dairy firms. This corporate engagement with alternative proteins is indicative of regime destabilisation, being consistent with tentative weakening of some incumbent actors' commitment to the regime. In turn, it potentially enhances the legitimacy of these technologies within the mainstream, paving the way for other firms to follow, thereby further reinforcing the industry trend. This intensifying involvement of large food corporates signifies more than "defensive hedging", with continued technological development, expanding markets, and strong discursive pressures, prima facie consistent with processes of industry reorientation, and therefore of a potentially emerging sustainability transition. However, it remains to be seen whether wider technological, economic, political, and cultural factors will align sufficiently to favour the continued progression or further acceleration of a systemic protein transition.

To date the development of alternative proteins has been largely a private sector affair, with public policy support largely (albeit not entirely) absent from the narrative. At the time of writing, there are tentative signs of public sector interest in alternative proteins in some jurisdictions (illustrated by recent public sector investments in several European countries, as well as the development of initial "roadmaps" for engagement such as that of the UK's innovation agency (60)). However, it remains the case that most investment in alternative proteins remains within the private sector, notwithstanding ongoing efforts by advocacy groups to generate further public sector interest. The absence of public sector support stands in contrast to other resource intensive production-consumption systems such as energy or mobility. Taken together with the continued support for the existing regime in the form of both substantial financial subsidies for animal agriculture, and political support for the desirability of widespread availability of meat products, this may serve as a significant hurdle for a transition to alternative proteins.

3. Conclusions

Applying a socio-technical lens to the question of how alternative proteins could contribute to a sustainability transition in food production and consumption draws attention to the question of if and how multiple pressures may align to destabilise the dominant animal agricultural regime and enable diffusion of alternative protein products, stimulating change in industry and consumer practices. The potential alignment of such factors is particularly challenging to forecast at the present juncture, characterised as it is for large parts of the world by macroeconomic and geopolitical uncertainty.

Nevertheless, the analysis indicates that development of alternative protein niches has accelerated in recent decades, and particularly within the last 15 y, following an intensification of engagement with existing scientific and technological foundations by a variety of actors which have sought to develop and commercialise novel solutions to food system challenges. In connection with the first research question that frames this paper, the analysis has emphasised that a generalised acceleration in the development of alternative protein technologies has also been marked by considerable differences in the extent of their diffusion, at least partly related to the varying technical and regulatory conditions pertaining to each niche. In connection with the second research question, the analysis reinforces a general finding associated with the MLP, namely that while the novelty which arises in niches may put pressure on the established regime, wider transformation requires regime shift to be precipitated by regime-internal and/or wider landscape pressures. In this case, strong discursive pressures surrounding meat and dairy consumption have led to increased levels of corporate engagement, which may in turn have provided boosts to the legitimacy of alternative protein technologies, encouraging further engagement from additional firms. In this way, the analysis has also highlighted processes of regime destabilisation and industry reorientation.

These findings reinforce the strengths of MLP-based transition analyses, including an inherent attentiveness to the multitude of factors that influence change, and as a means of integrating micro-, meso- and macro-level developments. Transitions research in

general enables researchers to recognise the complex, non-linear and long-term nature of the role of innovation in changing production and consumption systems, giving attention not only to the characteristics of technological artefacts, but to the interaction of technologies with human agency in social, institutional, and organisational contexts over time (21), epitomised in our case by the differences between alternative protein niches. Transition frameworks also help to structure analysis of the open but constrained and contingent possibilities for future change, emphasising that there are no foregone conclusions, and that we should be mindful of the ambiguous roles that powerful incumbent actors can play.

While our analysis has investigated the roles of several kinds of companies, one limitation is that it has not paid significant attention to upstream agricultural producers. Future research could further investigate the disruption of animal agriculture, and the potential reshaping of arable supply chains involved in providing proteins and other inputs required for alternative protein production as well as the implications for rural communities and landscapes. Burton (2019) (61) already provided some useful initial insights in this regard, analyzing biosynthetic proteins as disruptors to conventional agriculture that affect the value of animal by-products. Framing alternative proteins as advanced technologies, scholars have also started exploring the significance of new actors such as venture capitalists and other investors, which influenced the political, cultural, and economic dynamics of change (7, 46). Further unravelling the implications of post-animal bioeconomy transition pathways for food systems will require researchers to engage with a range of perspectives, further deepening insights set out here. As such we welcome recent efforts to develop research agendas across issues such as the transformation of rural space, eating practices and identities (6), as part of broader efforts to understand the significance of these ongoing processes of change.

Data, Materials, and Software Availability. All study data are included in the main text.

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