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Perspective

A governance framework to manage the food-environment-livelihood trilemma of alternative proteins

Niels Søndergaard,[1,*] João Francisco Adrien Fernandes,[2] Jeffrey Potent,[2] Kevin Karl,[3] Marcelo Furtado,[4] and Walter Baethgen[5]
[1]Institute for International Relations, University of Brasília, Brasilia, Brazil
[2]School of International and Public Affairs, Columbia University, New York, NY, USA
[3]Center for Climate Systems Research, Columbia University, New York, NY, USA
[4]Institute of Latin American Studies, Columbia University, New York, NY, USA
[5]International Research Institute for Climate and Society, Columbia University, New York, NY, USA
*Correspondence: niels.soendergaard@unb.br
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SUMMARY

Global food systems are closely interconnected with contemporary challenges such as food security, environmental crises, and inclusive development. Protein production, in particular, is strongly associated with these issues, as the resource-intensive predominant production models can lead to environmental pressures and food inequity. Alternative proteins (APs) have been proposed as part of the solution to meeting future global protein demand while keeping modes of production and consumption within planetary boundaries. Here, we stress that the potential of APs to address this crucial food-environment-livelihoods trilemma hinges on collective social choices made early in the sociotechnical transition. We therefore call for a managed and socially embedded transition in which public agents together with civil society and private actors work to ensure balanced outcomes, with global and domestic food inequities in mind. Our emphasis on AP adoption as an open-ended process highlights the underlying political economy of food systems transitions and technological development.

INTRODUCTION

Accelerating ecological crises have placed issues related to food production and consumption at the center of the global sustainability agenda. Proteins are key in this respect, as they provide essential macronutrients but are also commonly characterized by resource-intensive modes of production. Debates about how to guarantee sustainable future proteins have frequently highlighted the need to limit the consumption of animal-source (AS) protein.[1–5] The contributions of AS protein to climate change have often been stressed, either in the form of emissions directly produced as part of the production process[6–8] or through land-use change due to pasture expansion or feed production.[9–14] Beyond climate-related emissions, large-scale AS protein production systems have also been found to negatively affect biodiversity[15,16] and phosphorus and nitrogen cycles,[6,17] as well as bacterial and zoonotic virus risks.[18,19]

In response to contemporary and, notably, future sustainability challenges related to AS production, alternative proteins (APs) have been highlighted as a potential solution.[20–24] The notion of APs refers to a broad category of foodstuffs rich in amino acids, frequently proposed as a substitution for AS proteins, to mitigate negative environmental externalities from meat production. Some AP products are already available for consumers, such as plant-based meat substitutes and precision-fermented products (e.g., mycoproteins and algae). Others, such as cultured meat and insect-based products are still at a more incipient stage of development. In recent years, both public and scientific interest in APs has grown substantially.[21] Beyond the food-environment nexus, much research has thus far tended to focus on issues such as technological maturity[25–30] and consumer acceptance.[31–37] While this approach may be relevant to understanding the challenges in the development and dissemination of AP products, much less attention has been directed at the wider socioeconomic reverberations of this process. A move toward increased AP consumption invariably entails a range of trade-offs and dilemmas related to the technological trajectories and potential societal disruptions that characterize sociotechnical transitions. Outcomes within critical areas such as food security, social development, and environmental sustainability often follow a path-dependent logic, being defined by collective social choices early in the process. A failure to properly address this challenge could not only compromise the purported sustainability goals of AP adoption but maybe even lead to adverse outcomes in terms of nutrition, livelihoods, and resource use. We, therefore, heed calls to take a step backwards and examine the role of APs within future global food systems from a socioeconomic perspective[38] to understand the wider reverberations of a potential socioinstitutional change toward meat alternatives.[39,40] This requires critical scrutiny of existing knowledge about APs, not only regarding their product-specific features (e.g., cost, climate impact, nutrition, technological profile), but also concerning issues such as global accessibility, potential impacts on AS producers, and the development of AP food chains (e.g., their institutions, market structure and power relations), as well as the cultural significance and social embeddedness of APs.

Irrespective of their composition, future protein production systems will have to address primordial concerns related to (1) nutrition and global food security, (2) environmental integrity and planetary boundaries, and (3) livelihoods and social needs.[24,41–44] As these three dimensions are closely interconnected, changes within one are bound to affect the others. We refer to this as the food-environment-livelihoods trilemma. Ensuring a balanced transition toward APs requires attention to the synergies between these dimensions. For example, a risk exists that a myopic focus on greenhouse gas (GHG) emissions could compromise nutritional properties or livelihoods dependent on existing AS production systems, and vice versa. Conversely, positive experiences with APs have also resulted in new sources of income for farmers, while providing health benefits for consumers and positive environmental results. Ultimately, the long-term sustainability outcomes of the growth of APs will therefore depend on a holistic governance approach that contemplates socioeconomic impacts, technological inclusiveness, and global inequalities through a managed and socially embedded[45] transition. Crucially, rather than a purely market-enabling approach, a mission-oriented engagement[46] by public agents is needed to steer this process through their regulatory capacity and in partnerships with civil society and private actors.

In this paper, we seek to inform scholars and policymakers about important questions and considerations that will need to be addressed in any transition toward APs, irrespective of the magnitude of the shift. We initially provide an overview of the current and future global protein landscape. Thereafter, we discuss the broader societal implications of a sociotechnical transition toward APs, with a view to nutritional and domestic and global socioeconomic outcomes. In the final section, we present important policy perspectives in the form of a framework for managing the food-environment-livelihoods trilemma to ensure a holistic and socially robust introduction of APs within global food systems. The conclusion summarizes our key points and future perspectives.

AN OVERVIEW OF THE GLOBAL PROTEIN LANDSCAPE

In recent decades, global protein demand has risen dramatically, which has led to great pressure on food systems worldwide. Meat consumption has grown rapidly, driven mainly by rising demand in Asia, in particular, China (p. 8 of WEF – World Economic Forum[47]). From 2000 to 2019, protein consumption worldwide increased by 45%, from 166 million to 245 million tons. Among global regions, North America accounts for 6% of this increase; Latin America and the Caribbean for 7%; Europe, 8%; Africa, 15%; and Asia, 63%.[48] AS protein consumption nonetheless remains most elevated in high-income countries relative to middle- and low-income countries, both in total volume and as a share of total protein intake.[49]

With a look to the future, a major challenge for global food systems is to feed a global population of close to 10 billion people by 2050.[5] Following current consumption trends, the demand acceleration spurred by population growth will be further exacerbated by growing income in many parts of the world.[49,50] Different projections exist for the caloric and protein demand by 2050. The total global food demand has been projected to increase by 35%–56% between 2010 and 2050.[51] Animal protein, specifically, has been expected to grow from 303 million tons in 2013 to 450 million tons by 2050,[52] while the size of the global animal herd is estimated to grow from 27.3 billion to 41.8 billion heads in a business-as-usual scenario.[53] Such expansion would prompt a range of environmental pressures on the food system, projected to spur an 87% increase in GHG emissions, a 67% growth in demand for cropland, a 65% spike in blue-water use, and a rise of 54% for phosphorus and 51% for nitrogen fertilizers.[6] In sum, current trajectories of global food consumption would likely result in serious harm to global ecosystems and risks of exceeding crucial planetary boundaries.[17,54]

Closing the "food gap" is likely unfeasible only through yield increases, meaning that measures on the consumption side also will become necessary.[2] Dietary changes toward less resource-intensive food sources, such as legumes, nuts, fruits, and vegetables, may provide an important step.[5,55] This is not least because of the loss of human-edible protein in the conversion of plant-based protein to AS protein. Globally, the equivalent of 89 g of edible protein/person/day is fed to animals for the production of 38 g/person/day of AS protein. This leads to a conversion loss of 51 g/person/day, exceeding the required intake of 44 g/person/day.[56] On average, the production of 1 kg of AS meat requires 2.8 kg of human-edible feedstuffs in ruminant systems and 3.2 kg within monogastric systems.[57] Confronted with the double imperative of increasing global food and protein availability, while ensuring that this occurs within planetary limits, APs have been presented as part of the solution.[20,21,23] By circumventing the stage of conversion of human-edible plant proteins into AS protein, APs may provide a less resource-intensive alternative to meeting future global food needs. Studies of AP products thus point to noticeable reductions in terms of direct emissions, as well as land and energy use relative to AS protein.[22,24,58] Assessing the broader environmental impacts of APs compared with AS protein is a complex task, but different estimates have been made. Comparing chicken with plant-based AP analogs, Detzel et al.[20] found that, beyond a favorable GHG emissions performance, the latter also have smaller impacts in terms of aquatic and terrestrial eutrophication, acidification, and ozone depletion, while the former is associated with less water and energy use. With specific regard to nitrogen use, a key advantage of plant-based APs in relation to AS protein is the fact that legume crops require much less nitrogen fertilizer compared with most feed crops (p. 5107 of Detzel et al.[20]). Broad-scoped "cradle-to-plate" analyses, encompassing diverse environmental impacts associated with the production of different APs, also highlight the favorable performance of plant-based meat and insects compared with cultivated meat and mycoprotein.[59] However, as most AP products are in an incipient stage of development, their environmental performance may change substantially as technologies improve.

The global AP market could see a rapid acceleration in the years to come. Plant-based meat alternatives, for example, provide a readily available product choice, which could reach 10% of the global meat market by 2030.[60] Other estimates point to a compound annual growth rate (CAGR) of the plant-based protein market of 7.2% from 2022 to 2032.[61] The market for all meat substitutes (plant-based, fermentation, mycoprotein, etc.) reached US$36 billion, compared with US$844 billion for conventional animal protein, but the former outpaced the latter at a CAGR of 6% compared with 3%.[62] APs thereby still represent a very modest share of global protein consumption, although important trends appear to fuel their steady growth. Given that APs could become an important part of future global food systems, it becomes imperative to scrutinize their potential to provide for improved sustainability outcomes through the lens of food security, environmental conservation, and livelihoods.

ALTERNATIVE PROTEINS' CHARACTERISTICS

Modern techniques for meat replacement products have been known since the 1960s, while more rudimentary forms of processing of plant-based meat-like products date back to the 10th century in Asia.[28,34] Different forms of APs have nonetheless gained momentum in recent years, spurred mainly by their supposed potential to reconcile nutritional and environmental benefits. Diets with desirable health outcomes have frequently been associated with positive environmental outcomes.[5,63] A brief overview of the different AP product categories does indeed highlight some important nutritional and environmental co-benefits but also paints a rather complex picture of this relationship.

Plant-based meat alternatives (PBMAs), which in a practical definition may be viewed as "meat-like plant-based foods,"[64] today encompass a wide array of products that span from "simple" meat substitutes based on leguminous products to meat substitutes created with sophisticated technologies. These products often contain soy, pea, and gluten protein. Recent product innovations have sought to make PBMAs more appealing to meat eaters by mimicking animal-based conventional protein.[21,34] PBMAs can also present a range of health advantages in terms of low levels of cholesterol and saturated fats, as well as a fiber-rich constitution. These nutrition benefits are often coupled with a positive environmental profile, due to less resource-intensive modes of production.[65,66] Yet, large amounts of sodium often used in plant-based products raise questions about their health benefits. Doubts also remain regarding whether PBMAs' high degree of processing compromises their nutritional profile and micronutrient content[21,67] and degrades digestibility.[28,68,69] Moreover, plant-based alternatives may also fall short on a range of nutrients found in AS protein essential to children, nursing mothers, and the elderly.[70–72]

Mycoprotein is another significant AP product category that is already marketed to consumers. Mycoprotein is based on the *Fusarium venenatum* fungus cultivated in a controlled environment. Initially invented in the aftermath of the Second World War as an affordable protein source, today, products known under the "Quorn" label are sold in many different countries. Mycoprotein has a meat-like texture and the sensory property of animal protein.[29] Vegetarian variants use egg albumen as a binder, while vegan product variations use potato protein. Mycoprotein contains a high protein content and a favorable amino acid balance while possessing less fat and more fiber than animal-based meat. Although it requires extensive processing, its carbon footprint is around 4–10 times lower than that of conventional meat alternatives.[21] One issue that remains questionable in mycoproteins is the source of the nitrogen needed for their production. Thus, the production process requires ammonium, which is currently mainly being produced with the Haber-Bosch process, a very high-energy-consuming procedure.

Estimating the number of people worldwide who regularly consume insects is difficult, but it is likely to be in the hundreds of millions.[73] Beyond specific products, such as carminic acid (E12), attempts to incorporate insects into industrial food systems are relatively novel. Large sums have recently been invested in innovations to make insects commercially competitive for both human and animal nutrition.[27] Insects have been highlighted as a sustainable meat alternative due to their short life cycle and low resource footprint.[74] They have also been exalted for their high content of protein, omega-3 acids, and important micronutrients.[68] The digestible indispensable amino acid score (DIAAS) varies for different species of insects. For example, house crickets and banded crickets have been found to provide a high-quality protein source for both children and adults, while the protein in lesser mealworms mainly is adequate for older children and adults.[75] The black soldier fly can also serve as an alternative for animal feed.[76] As insects can absorb nutrients from organic waste, they utilize resources that otherwise would have been discarded.[47] Insect life-cycle assessments (LCAs) conducted by Salomone et al.[77] show that 10 tonnes of food waste can produce a yield of up to 300 kg of dried larvae and 3,346 kg of compost. Insects can thereby be part of waste management systems with multiple sustainability benefits. However, given that insect production depends on large amounts of waste inputs, their total potential yield is ultimately limited by the availability of biological waste resources. The very recent commercial use of insects as food or animal feed means that proper legislation to guarantee that products are free of contaminants and toxins has not yet been implemented.[27] The degree of consumer acceptance of insects is likely to hinge strongly on the cultural context. Studies of Western consumers suggest that unfamiliarity and reluctance pose substantial obstacles to widespread insect consumption in the short and intermediate term.[78] Global regions with a history of insect consumption also present a large internal sub-regional variation.[27] A potentially important question relates to whether regions traditionally known for consuming insects will be more inclined to embrace novel industrialized product versions.

Finally, cultured—or "lab-grown"—meat has also raised significant expectations that it could become an important AP source with a light resource footprint compared with AS protein.[50] In 2013, the Dutch Mark Post produced the first lab-grown burger, at a cost of US$300,000. Since then, unit costs have fallen significantly. By 2020, a restaurant in Singapore served cultured chicken at the price of US$23 per meal. As lab-grown meat cultivation requires far fewer physical and natural resources compared with AS meat, it has been defended as an attractive alternative in terms of its sustainability performance.[79] However, the production of cultured meat requires substantial amounts of energy (including the energy to produce the nitrogen needed in the process), meaning that a fossil-dominated electricity matrix compromises its sustainability performance.[80] Just like AS protein, cultured meat presents a favorable amino acid balance and high digestibility. However, in their current state, these products are similarly associated with high levels of cholesterol and saturated fats. Cultured meat also appears to face significant consumer skepticism, and studies have found it to be among the least preferred AP options.[81] Consumer-based surveys from the United States conclude that, even when prices are held constant, 72% of respondents prefer conventional beef, while only 5% prefer cultured meat, lower than for any other AP beef-like products surveyed.[82] This highlights the challenges related to the introduction of cultivated meats. Yet, this situation could change in the future, especially given the trend for young people to be more open to this product category.[82]

While certain nutritional and environmental benefits are associated with AP products, this brief review still paints a somewhat muddy picture, which makes it difficult to definitively proclaim their superiority to AS with regard to sustainability. Their relative sustainability performance also depends on the specific AS product with which they are compared, given the substantial variation in environmental impacts of different conventional meat products.[83] Moreover, nutrition outcomes should not be viewed exclusively with consideration to specific products, but rather on a broader dietary basis, given the importance of protein complementarity.[84] Finally, critical voices have also highlighted an ''overemphasis on protein,'' stressing how this constitutes one of many sources of macro- and micronutrients with importance regarding food security.[85]

With these insights in mind, we stress the need to adopt a more holistic and contextually sensitive approach in discussing the future of APs. Moreover, APs ought to be viewed in relation to the wider sociotechnical landscape in which they are introduced as one among many elements that together may bring about sustainable transformations. Rather than assuming beneficial outcomes from AP dissemination alone, we must consider them as only one among many different components within complex, culturally particular food systems to ensure positive synergies with existing food sources and needs.

A SOCIOECONOMIC PERSPECTIVE ON ALTERNATIVE PROTEINS

Considering how APs are embedded within society regarding both consumption and production becomes imperative for the sector as it develops. The consumption of APs relates to food culture and social appreciation, as well as their potential to satisfy a population's food needs. In addition to their environmental and nutritional properties, new protein sources have thus also been examined from a point of departure toward their socioeconomic performance and ability to contribute to a socially inclusive food supply.[39] It is worth noting that many AP products are currently priced on the higher end of the market, above US$2 per 200 kcal.[86] However, as production reaches scale and unit costs drop, APs could become an affordable alternative for low-income groups, thereby displacing AS products to premium markets.[87] There is some risk that cost-lowering directives steer AP producers toward increasingly industrial hyperprocessing methods that could jeopardize nutritional composition. Despite the benefit of associated emissions reductions from AP-AS substitution, this trade-off could nonetheless exacerbate nutritional inequities. Meanwhile, without action to mitigate AS demand, resource-intensive food habits will continue to drive disproportionate GHG emissions by wealthy populations.

The AP product market structure also warrants further scrutiny in terms of its socioeconomic inclusiveness. Currently, the AP market is relatively limited in size, but projections suggest that plant-based and cultivated meat could reach a 10% market share of the global meat market—or US$140 billion—by 2030.[88] Estimates ranging farther into the future suggest a gross value added for this sector of US$177 billion by 2035 and US$218 billion by 2050.[58] The AP market has become highly competitive, with a strong presence of established traders and food processing companies.[47,61] These entities have been largely motivated to be on the right side of potential disruptions to the food sector; many have also sought to advance a narrative of *transforming* the food sector (rather than disrupting it).[38] Most market players operate along a business-to-consumer model, but increasingly, business-to-business models have emerged.[89] This points to a process of consolidation of capital-intensive AP production chains afforded only by resource-endowed first-movers. While the concentration of AP production among existing market leaders could help accelerate dissemination, it raises a series of questions regarding the consequences of dominant players assuming control of the protein transition from an incipient stage of technological introduction. Notably, it becomes crucial to examine whether certain favorable options for APs' technological trajectories are foreclosed by prematurely picking the market winners. When dominant market players define path dependencies of production models, the evolution of more radical experimentation is often severely limited. Sensitivity to such risks is crucial, as an early lock-in of AP trajectories is likely to affect the degree of technological inclusiveness within the market and determine whether a more diverse set of market actors can also contribute to shaping the food system.

A GLOBAL VIEW OF ALTERNATIVE PROTEINS

Cultural norms and differences are key factors in defining the degree and modality of AP incorporation into regional diets.[36,81,90,91] While a transition toward increased AP consumption has an impact on food systems at the global level, research has thus far been largely limited to Northern countries.[31] Analysis of future AP market growth nonetheless points to Asia as the most important center of consumption.[32,47,90,92] Within certain product lines, Asian consumption already far outpaces that of Europe and North America.[93] This transition ought still to be viewed as an open-ended process subject to a variety of concerns regarding not only custom and tradition but also societal aspirations and visions of modernity, as well as more concrete considerations such as relative availability and affordability.

Despite the estimated future worldwide growth of APs, research and development efforts are predominantly centered in the Global North. Companies involved in the development of cultured meat, for example, are concentrated in Europe and North America, with a few exceptions in China, India, and several other high-income Asian countries.[89] While important research institutions are based mainly in Europe, investors and patent holders in the AP sector are predominantly North American.[94] This may be a natural consequence of the elevated per-capita protein consumption of high-income countries.[14] The average per-capita yearly meat consumption (ruminant and monogastrics) in North America (95 kg) and Europe (63 kg) is substantially higher than intake in Asia (26 kg) and Africa (12 kg).[95] Berners-Lee et al.[56] found the average global excess consumption of protein to be around 36 g/person/day, or 84%. Considering the global disparities in protein intake, this could suggest a need for reducing the average per capita protein consumption in some high-income countries and for a possible shift from AS protein toward increased consumption of vegetable protein. In addition to this, APs could substitute a share of the remaining meat intake in countries characterized by an elevated AS consumption to alleviate environmental pressures and negative health effects of overconsumption.

The global inequality of AS protein consumption also draws attention to the geographical context in relation to which AP technologies are developed and the kinds of problems they are intended to solve. Nutritional challenges vary dramatically between countries according to their level of income and depend heavily on geography, requiring tailored solutions. For example, many low- and lower-middle-income countries have limited cold-chain and storage capacity compared with upper-middle- and high-income countries.[96] Asia, Africa, and Latin America thereby account for the largest losses of foodstuffs because of precarious or absent refrigeration capacity.[97] Dissemination of certain AP production systems that necessitate cold-chain logistics and facilities could thereby face challenges in some countries. Moreover, while radically innovative food production technologies could support important food security outcomes in low-income countries, their lack of capital and technological know-how constitutes a significant obstacle.[98] Meaningful adaptation of AP technologies and production structures to the low- and lower-middle-income countries may thus require strong efforts of co-creation and contextual sensitivity to the socioeconomic and environmental realities in these regions.[43,47]

Assuming that APs are adopted at scale in the Global South, it becomes crucial to understand how they interact with other food sources and modes of production in local food systems. A key concern relates to whether displacement of livestock should be viewed as an intrinsically desirable outcome from a sustainability perspective. Livestock production in the Global South has in many cases been found to promote landscape and biodiversity preservation, provide high-quality nutrition, and support livelihoods. This situation may also apply in areas of high-income countries where large-scale livestock production has not taken hold, either because of an inherent lack of suitability or as the result of concerted policy decisions to advance or preserve small-scale, possibly regenerative production systems.[4,43,99,100] This converges with studies suggesting positive interaction effects between crops and livestock production, as marginal lands and co-products from cultivated crops can sustain a limited amount of livestock and thereby provide an important source of nutrition for local communities in the form of dairy and meat products.[101] In other cases where extensive livestock production is associated with large-scale pasture degradation, as is the case, for example, in the Brazilian Cerrado, integration of semi-intensive livestock systems alongside managed pastures, crop, and forestry may result in sustainable intensification that can provide significant environmental and social gains.[102,103] In this regard, silvopastoral systems are a particularly pertinent case in point.

These examples highlight the importance of a holistic evaluation of the sustainability of future protein production systems in the Global South. The pronounced differences in terms of both climatic and societal circumstances between countries worldwide thus mean that interventions successfully made in some are unlikely to have the same effect in others. A significant risk, in this respect, concerns the danger of adopting a "carbon myopic" perspective, insensitive to other crucial sustainability parameters.[104] This should by no means be interpreted as an outright rejection of the significant mitigation potential of APs also in the Global South. Increased AP consumption may indeed serve a very important purpose in limiting resource pressures from industrialized and high-intensive meat production systems in both the Global North and the Global South. Moreover, positive synergies and contextually contingent complementarities may also exist between APs and AS, in relation to both production and consumption.[70,101,105,106] We, therefore, argue that sustainability interventions within protein systems are more likely to be successful when applying a holistic systems approach, accounting for the complex and regionally defined interactions between different food production systems.

THE POLICY PERSPECTIVE

The dissemination of APs within agri-food markets may be viewed as part of a broader sociotechnical transition bound to produce diverse societal impacts.[107,108] Disruptions within parts of the agricultural and livestock sector could result in significant socioeconomic implications for a broad range of actors along agri-food chains.[109] Moreover, there is no guarantee that the current market-enabling approach to AP development will necessarily be sensitive to social and environmental concerns beyond a few climate-related key performance indicators (p. 164 of Stephens et al.[38]). The view of APs as a technological fix for addressing profound sustainability challenges within modern livestock production has thereby been met with criticism.[38,40] In terms of policy implications, this calls for a managed and socially embedded transition and for the need to ensure balanced outcomes on a wide range of socioenvironmental parameters.

The public sector can play a key role regarding many of the issues arising in relation to APs. An initial task would be to guarantee transparent information about the nutritional, environmental, sanitary, and phytosanitary characteristics of these products. Public regulatory authorities will have to assume an important market-shaping function by establishing the necessary regulatory and institutional framework to ensure transparency about the nutritional profile and other important sustainability features of APs. Beyond the provision of the basic regulatory infrastructure, discussions have also revolved around the need for a more direct public engagement in market structuration and creation. Fiscal incentives and differentiated taxes provide potentially effective instruments to increase the attractiveness of APs among consumers and to reward certifiable sustainability features. Official labels could also be part of a multicomponent approach to AP development and sustainable agriculture to accelerate the initial market entry of these products.

Recent policy debates concerned both with pathways to confront overarching global sustainability challenges[46] and with APs more specifically[58,110] have highlighted the need for public actors, not only to play a supportive role but even to "take the driver's seat" in bringing about food system change.[47] Public investment could be key, especially with regard to confronting initial barriers and sources of risk, to create confidence and attract increased private resources. Science and technological development is a particular case in point; existing studies suggest that global public spending on R&D and commercialization needs to increase to US$4.4 billion and US$5.7 billion annually to permit the full benefits of APs to be reaped.[58] Public investment in emerging sectors and technologies can also become important when market actors hesitate to commit their resources. In the field of APs, this type of investment can be particularly important regarding technologies that have not yet reached the stage of maturity. In this regard, public engagement can help shape technological platforms of future food systems to support inclusiveness and solutions yielding the largest social gains. Spreading investments across many incipient AP technologies can also help to ensure that projects and products reach the stage of commercial maturity, thus avoiding "picking industry winners" from early on. Public efforts can also help connect the different network participants and align their efforts around solving joint coordination problems. Such network governors[111] can become particularly important when success depends on transdisciplinary cooperation across professional and thematic areas.[110] Crucially, fruitful public-private partnerships can also support the construction of shared infrastructure and critical overhead capital to facilitate the early stages of market development.[112]

Finally, the adoption of fiscal regimes aligned with key sustainability targets presents a promising option to stimulate the growth of AP products with the best social performance.[6,113] Taxation instruments with positive and negative incentive structures for AP and AS products, respectively, have been found to provide a potentially useful tool to spur positive environmental and nutritional outcomes.[55,114] The downside to this type of regulation is that it could mean that meat consumption becomes a privilege reserved for wealthy consumers, thereby nurturing social discontent. Whatever the specific policy instruments chosen to incentivize robust AP solutions, they will need to combine climate, nutritional, and social targets in a multifaceted regulatory approach.[113] In this regard, higher-order principles for holistic sustainability concepts, such as those embodied in the notion of planetary health,[44,115–117] may provide important stepping stones for policymakers.

A GOVERNANCE FRAMEWORK FOR ALTERNATIVE PROTEINS

Based on the many complex issues that mark the prospects of the introduction of APs into modern food systems that we have identified in this paper, we present a governance framework meant to inform scholars and practitioners about key challenges and opportunities. We suggest that this framework will have applicability at regional, national, and sub-national scales and that the factors contributing to findings from applying the framework likely would vary significantly based upon the scale and context in which the framework is applied. The framework is structured into two axes, with the first relating to the three dimensions of the food-environment-livelihoods trilemma. The second axis concerns crucial thematic areas, which we believe are essential to consider in relation to this trilemma, to ensure constructive and sustainable outcomes of any sociotechnical transition toward APs.

As can be read from Table 1, the food-environment-livelihoods trilemma encompasses these three dimensions that are key to assessing the sustainability of APs from a holistic perspective. The nutritional dimension encompasses both food access and macro- and micronutrients as well as the broader dietary consequences of the introduction of APs. The environmental dimension considers GHG emissions, biodiversity, resource use, and other planetary boundaries that become important to examine in relation to the ecological impacts of global food production. The livelihoods dimension concerns income, modes of production, and subsistence, as well as other relevant socioeconomic issues. The thematic categories related to the food-environment-livelihoods trilemma are assessed regarding global equity, the scope of sustainability conceptions, and market concentration. Global equity refers to a perspective that accounts for the differentiated impacts of APs in countries depending on their relative level of income, entailing the importance of paying specific attention to the needs of low-income countries. Given the noticeable difference in global food systems, the path to supporting positive nutritional, environmental, and livelihood outcomes through AP introduction is likely to be contextually contingent. Targeted efforts may need to be directed to ensure that low-income countries reap the potential benefits and avoid key risks. The scope of sustainability conceptions refers to the comprehensiveness with which this notion is assessed when examining the multifaceted consequences of sociotechnical transitions toward APs. This notion can be viewed on a scale spanning from myopic to holistic conceptions of sustainability. While the former would focus on single sustainability parameters, such as GHG emissions or specific product features, the latter implies the need to analyze planetary boundaries and (food) systemic effects of protein transitions. Finally, market concentration refers to the degree to which AP production and commercialization are centered around a few dominant players that define prices, standards, and technological trajectories. This is likely to define the degree to which AP markets are inclusive concerning small- and medium-sized players and localized production systems and technologies. While some degree of concentration of cutting-edge AP technological development around capital-intensive industries may be unavoidable, participation of a broader scope of societal stakeholders in defining the evolution of APs appears crucial to ensure socially sustainable outcomes.

Global equity, the scope of sustainability conceptions, and market concentration may not account for all of the potentially important challenges related to a future process of protein transition. However, we believe that the framework provides an important point of departure for assessing the food-environment-livelihoods trilemma in relation to concrete policy issues,

Table 1. A governance framework for practitioners and scholars to engage with the opportunities and challenges of APs within modern food systems

	Food/nutrition dimension	Environment dimension	Livelihood dimension
Global equity	ensure that AP products address food needs in low- and lower-middle-income countries, regarding their nutritional composition, but also with regard to accessibility in terms of price and logistics	assess how APs may alleviate pressures from resource-intensive industrialized AS protein production:	explore how low- and lower-middle-income countries and, especially, local communities can benefit from value-added activities in AP production chains
	avoid attempts to substitute important sources of quality AS nutrition for vulnerable populations with inferior AP products	(1) in high-income countries, this can contribute to diminishing current overconsumption of AS protein (2) regarding low- and lower-middle-income countries, this may help some populations leapfrog beyond the stage of AS protein overconsumption	prioritize sustainable AS production models, such as extensive pastures or integrated crop-livestock-forestry systems, that are important to the livelihoods of large populations in developing countries
Scope of sustainability conceptions (narrow vs. broad	support the development of APs with a healthy nutritional profile in terms of both macro- and micronutrients, while discouraging features of hyperprocessed food associated with negative health outcomes; new research may be required to identify the existence and bioavailability of various micronutrients in newly developed APs	adopt comprehensive life-cycle assessments of the emissions of APs relative to AS protein products, and support the development of APs with the greatest sustainability outcomes	steer the development of the AP sector toward desirable socioeconomic and socioenvironmental outcomes; a crucial point in this regard is to ensure positive synergies between: (1) nutrition, food security, and food safety
	evaluate health outcomes of APs on a dietary basis, in terms of how they complement and affect consumption of other foodstuffs, rather than on a restricted product basis	avoid a “carbon myopic” approach to APs; evaluate their environmental gains relative to AS alternatives with focus on planetary boundaries, including biodiversity, land and water use, biochemical flows, etc.	(2) an ecologically safe and healthy environment for human existence and for biodiversity that could be negatively affected by wide-ranging cultivation of new AP crops
		advance regulation that ensures that environmental claims of APs are rooted in robust labeling and certification procedures	(3) livelihoods, incomes, and economic aspirations of low-income population segments ensure that fiscal incentives, such as differentiated sales taxes directed at unhealthy and emissions-intensive products, do not disproportionately affect low-income population segments; negative backlashes in this respect could be partially offset by making healthy and low-emission products more economically attractive

(*Continued on next page*)

Table 1. *Continued*

	Food/nutrition dimension	Environment dimension	Livelihood dimension
Degree of market concentration	direct R&D funding and other support measures toward the goal of spurring a diverse set of AP products and market players that, in different ways, address the food and nutrition needs of global populations; R&D funding should include a focus on the development of new AP technologies that require low capital, operation, and maintenance costs	support the development of a diverse set of AP products and innovations with differentiated sustainability features to ensure many options reach the stage of technological maturity	incentivize the development of dynamic AP markets, characterized by a wide set of players and product alternatives, to avoid premature consolidation
	steer competition within the emerging AP market toward healthy and affordable foodstuffs, if necessary, through regulations discouraging nutritionally poor products	involve a diverse set of stakeholders, such as public actors, private companies, civil society organizations, academia, etc., to work to support solutions for a diverse future AP landscape, driven not only by market-oriented motives but equally by societal concerns about improved sustainability	support the dissemination and local adaption of AP production technologies to ensure inclusion of local economies, labor, and consumer demands within the sector

Source: authors' elaboration.

which may be expanded in future research. With this framework, we, therefore, hope to guide scholars and decision-makers toward considering issues and approaches that can help shape the dissemination of APs in a socially desirable direction, which in the long run also is likely to provide robust sustainability outcomes.

Conclusions

In this paper, we have sought to draw attention to the socioeconomic implications of the introduction of APs within global food systems. We have highlighted the need for critical scrutiny of existing knowledge about APs, with regard to their product- and process-specific features (cost, climate impact, nutrition, technological profile, etc.), but also concerning their role within global food systems more broadly, which relates to issues such as global accessibility and uptake, animal protein displacement potential and impacts, market structure, and power relations in AP food chains. We argue that analyses of APs within global food systems (independent of their relative future importance) should adopt a holistic perspective in relation to the trilemma (1) food, (2) environment, and (3) livelihoods, to grasp the wider societal reverberations of this sociotechnical transition. In terms of policy implications, this calls for a managed and socially embedded transition, in which public agents, through their regulatory capacity and in partnership with civil society and private actors, steer this process to ensure balanced outcomes on a wide range of socioenvironmental parameters. Finally, we have presented our governance framework for analysis of the opportunities and challenges concerning the introduction of APs within modern food systems, through which we seek to provide a point of departure for assessing the food-environment-livelihoods trilemma with consideration of contemporary policy issues.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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