Alternative proteins are likely essential for biodiversity conservation

Authors: Nitin Sekar,[1] Alex Dehgan,[1,2] Paul Bunje,[1] Cleo Verkuijl,[3] Shayna Fertig,[4] Kavya Jain,[1] Jeremy Radachowsky,[5] Glenn Hurowitz,[6] Christopher A. Jordan,[7] Wes Sechrest, [7] David Goodman,[8] Eric Dinerstein.[1,9]

[1] Conservation X Labs, 1050 30th St NW, Washington, DC, USA 20007.
[2] Rob Walton School of Conservation Futures, Arizona State University.
[3] Stockholm Environment Institute US, Somerville, MA, USA.
[4] Good Food Institute, PO Box 96503, PMB 42019, Washington, DC 20090-6503, USA
[5] Wildlife Conservation Society, Mesoamerica & Western Caribbean Regional Program, Avenida 15 de Marzo, Casa No. 3, Flores, Petén 17001, Guatemala
[6] Mighty Earth, 1701 Rhode Island Ave NW, Suite 3-123, Washington, DC 20036, USA
[7] Re:wild, PO Box 129, Austin, TX, USA, 78767
[8] School of Geography and the Environment, University of Oxford, Oxford, UK.
[9] Landseed.earth, Cabin John, MD, USA, 20818

Summary: Alternative proteins offer a sustainable and especially scalable opportunity to address the threats that animal-sourced foods pose to biodiversity

Abstract:

Animal-sourced foods play a major role in four of the five greatest drivers of biodiversity loss, and the conservation community must do more to address the threats that animal-sourced foods pose. While a variety of tools can help address the problems posed by animal-sourced foods, conservation must prioritize strategies that enable sustainability gains at scale to achieve global consensus goals relating to ecosystem, climate, and species protection in the coming decades. We compare three major strategies—conventional diet change away from animal-sourced foods, reform of existing animal production systems (e.g., feed additives, regenerative grazing), and alternative proteins as a disruptive technology—on their potential for reducing the impacts of our food system at scale. Building on life cycle analyses and studies of other low-carbon technologies, we conclude alternative proteins likely offer a singular opportunity to achieve the level of disruption and transformation in food that solar panels and electric vehicles are achieving in energy and transportation. We also outline the role that the conservation community can play in generating government financing for and public acceptance of alternative proteins, ensuring alternative proteins continue to be sustainable, and fostering a socially just transition for communities who currently produce animal-sourced foods for their livelihoods.

Keywords: animal-sourced foods, food system transformation, land sparing, sustainable proteins, disruptive technology, Kunming-Montreal Global Biodiversity Framework.

Animal-sourced foods and biodiversity

The conservation community must do more to address the threats that animal-sourced foods (ASFs) pose to biodiversity. ASFs remain an important source of nutrition in parts of the world,[1] and hunting, fishing, and animal agriculture are among the oldest human livelihoods. However, current global levels of ASF consumption are inefficient, polluting, and unsustainable.[2,3] Animal agriculture leaves limited resources for wildlife: humans and farmed animals make up 98% of the world's mammal biomass, with just 2% remaining for the 6,700 wild mammal species.[4] ASFs are a major factor behind four of the five greatest drivers of biodiversity loss: habitat loss, climate change, pollution, and direct overexploitation of wild species.[5–7] Destruction of habitat contributes to the decline of 88.3% of threatened species and is the dominant threat facing 71.3% of threatened species (see SOM).[8] Agricultural lands occupy 49% of the planet's ice-free terrestrial surfaces, [9] and meat, aquaculture, eggs, and dairy use up about 83% of agricultural lands while providing only 18% of calories and 37% of proteins, making them at least 8 times less land-efficient as a source of protein than plants.[10] Livestock grazing uses around 3.3 billion acres of land, including around 70% of the world's native grasslands.[11] Much of the land used to graze ruminants cannot be used to grow arable crops;[12,13] as such, farmed animals are often seen as providing a crucial service for a hungry planet, converting vegetation unpalatable to humans into meat and dairy that we can consume.[12] However, about 38% of croplands are currently used to produce feed for farmed animals,[14] including 85% of the global soy crop that could provide complete proteins directly to people.[15] If combined with the 35% of global pastures that could be used to grow crops, the world's croplands could produce enough proteins and calories to replace meat, aquaculture, eggs, and dairy with 76% less total agricultural land and 19% less arable land than currently used.[10] This could remove a major strain on biodiversity and free up massive tracts of land for wildlife: lightly used pasture is the primary driver of biodiversity loss in terrestrial Key Biodiversity Areas (KBAs).[16]

Production of seafood also contributes to habitat loss. Aquaculture—both shrimp and fishponds, the source of more than half of our seafood [17]—is responsible for about 28% of measured global loss of mangroves, with total space used for shrimp farming and feed amounting to over 5Mha.[18] Bottom-trawling to harvest seafood has scraped up about 14% of the ocean's continental shelves,[19] affecting about 4.9 million km^2 of the sea floor annually.[20]

Globally, agriculture is also the second largest source of annual greenhouse gas emissions after energy,[21] accounting for 31-35% of global emissions based on 100-year global warming potentials. [10,22] Again, ASFs are disproportionately responsible, with 57% of agricultural emissions generated by production of ASFs and only 29% by plant-based foods. Since ASFs provide 18% of calories and 37% of proteins, this makes ASFs on average 9.0 times worse for the climate per calorie and 3.3 times worse per gram of protein than plant-based foods. This difference has five main causes: emissions from feed production are higher than those of food production; feed production and pasture are linked to two-thirds of agriculture-driven deforestation; animals emit additional GHGs through enteric fermentation, manure, and methanogenesis in aquaculture ponds; slaughter requires more emissions than other food processing; and ASFs require more energy to prevent spoilage.[10] While beef and dairy are 3-8 times worse than chicken or farmed fish, even these lower-footprint ASFs average 2-20 times more emissions than tofu, peas, pulses, and nuts.[10] Animal agriculture is also responsible for 78% of the eutrophication of marine and freshwater ecosystems, with the lowest-polluting ASFs causing more eutrophication than average plant-based protein sources. [10] Finally, overexploitation of wild animals—both "bushmeat" and seafood—is directly driving about 26.6% of threatened species towards extinction.[8] The problem is especially acute in aquatic systems (see SOM).[23,24] At least 38% of marine fisheries are overfished,[25] hunting and fishing threatens 21% of freshwater species facing extinction,[26] and overexploitation has played a major role in 26% of recorded marine extinctions.[23] Large amounts of biomass from marine organisms and terrestrial feed crops are used as feedstock for aquaculture.[27] Declines in the availability or affordability of fish catch in biodiverse tropical nations has also led to increased harvesting of terrestrial bushmeat, demonstrating the interaction of threats to wild nature.[28,29]

Humanity cannot hope to achieve globally agreed biodiversity and climate objectives without tackling ASFs.[30] Compared to baselines between 2005-10, demand for meat and fish is expected to rise about 72% and 56%, respectively, by 2050.[31–33] This demand for food is likely to translate to land use change, transforming natural habitat between the size of Saudi Arabia (219 MHa) and Australia (710 MHa) to farms and pasture by 2050.[2,3,32,34,35] Ninety-eight percent of this agricultural expansion will occur in the biodiverse tropics (see SOM).[32,33] GHG emissions from agriculture will increase by about 15% from 2020 to 2050. Even if all non-food system GHG emissions were to immediately drop to zero and remain there until 2100, food system emissions would keep the planet beyond 1.5°C warming and leave just a 67% chance of remaining below 2°C.[36] Bushmeat hunting is expected to increase in remaining natural habitats as well,[3] and by 2050 about 88% of fish stocks will be overexploited.[37] These trends take us in the opposite direction of global consensus targets. Remaining close to a 1.5°C increase requires reducing agricultural emissions by about two-thirds from a business-as-usual scenario and restoring about 585 Mha of agricultural lands to natural habitats by 2050. [32] Achieving the Kunming-Montreal Global Biodiversity Framework's habitat protection targets would involve an even greater restoration of 1,670 Mha of terrestrial and inland waters to natural cover. [38] In parallel, harvesting from fisheries must decrease by 50% over ten years and remain at that level through 2050 for aquatic species to recover. [39]

Conservation organizations and funders, corporations, and governments must prioritize the development of interventions and strategies that make these dramatic changes possible (see SOM).[30] At present, there are three broad strategies available for achieving a protein transition: conventional diet change, animal production reform, and disruptive replacement using alternative proteins. Food systems are diverse and complex, making it unlikely that any one solution will fully address the challenges at hand. Still, any change will require investment of time, money, and effort, and the conservation community must decide how to allocate resources across these three strategic directions to optimize the likelihood of achieving a protein transition that meets biodiversity and climate targets. To guide these investments, we assess the three strategies for protein transition based on their sustainability and scalability.

Strategies for a protein transition

Conventional diet change

In principle, widespread conventional diet change—in which consumers eat drastically fewer ASFs— may very well be the best possible way to reduce the impacts of our food system on nature and biodiversity. A complete shift to a fully plant-based diet is projected to reduce agricultural land use in the US by about 74% and globally by 76%.[10,40] Such a shift—combined with reforestation of released croplands and pastures—could reduce net emissions from agriculture by about 70% by 2050 while allowing every person on Earth to consume 78 grams of protein a day. Such a reduction is consistent with a 66% chance of limiting global warming to 1.5 °C.[41] Full abstention from meat or animal products is not necessary to realize big biodiversity gains—for instance, universal acceptance of the Eat Lancet diet (about 70% less meat than business-as-usual) could lead to 61% of the carbon benefits of the fully plant-based scenario (see SOM).[30,41]

The challenge is that conventional diet change as a strategy relies on individual consumers making dramatic alterations to the foods they buy and how they cook and eat. So far, none of the tools available to engender such behavior change—regulations, awareness and persuasion campaigns, and modifications to choice architecture—have a strong record of reaching scale and making a dent in the increasing demand for meat. If implemented, carbon taxes for agriculture or reduction of subsidies supporting ASFs would generate incentives for conventional diet change. The impending tax on emissions from farmed animals in Denmark demonstrates such policies may be possible, especially in small and wealthy countries. However, policies that increase the cost of food or take away public support from food producers experience major political headwinds.[42–44] Persuasion, awareness, and choice architecture interventions have also only demonstrated effectiveness in limited contexts. Two literature reviews found that interventions to shift individual diets away from ASFs (usually red meat) for health reasons seldom led to average reductions in red meat consumption greater than 30%,[45,46] even when participants were cancer patients who needed to change diets to improve their chances of survival.[46] Since the interventions used were often highly individualized (e.g., personal nutrition advice or counselling) and only monitored outcomes over the course of weeks or months (not years), it seems unlikely even these modest gains are achievable at scale. Choice architecture interventions—for instance, placing plant-based menu options more prominently, reduced meat portion sizes, or plant-based defaults at conferences and cafeterias—seem capable of shaping the behaviors of larger numbers of people at lower per-unit costs. Indeed, making vegetarian menu items the default at university canteens and conferences have reduced meat and fish consumption by up to 87.5%.[47] While such efforts are clearly important in the broad effort to make our food systems more sustainable, choice architecture interventions face limitations beyond the narrow frame in which they have been tested.[46–49] Evidence suggests consumers may adjust their behavior outside of the restaurant or cafeteria to counteract the gains of some interventions; for instance, one program that led to a 41-66% reduction in ASF consumption at university canteens one day a week resulted in a 127% increase in sausage consumption at a nearby location.[48] In addition, the general public may be put off by even modest proposals to modify their choices in a way that university students and conference attendees are not, and the animal agriculture industry has actively resisted any proposals that would result in reduced ASF consumption.[50] A "meatless Monday" that reduces meat consumption 87.5% at one meal may—even discounting leakage and rebound effects—effectively result in only a 4.2% reduction in a consumer's meat consumption over the course of a week. When Germany's Green Party tried to institute a national meatless day, the blowback contributed to the party's loss in the 2013 elections, notwithstanding Germany's disproportionately sympathetic posture on environmental issues.[48] Despite the consensus that conventional diet change *could* address the sustainability challenges of our food systems, such changes are unlikely to reach the scale necessary to achieve established climate and biodiversity objectives.

Animal production reform

Perhaps because shifting diets seems so difficult and unlikely, quite a bit of attention has been given to making production of ASFs more sustainable. [14] A diversity of approaches exists to make agriculture and fishing more sustainable, including changing how animals are reared, modifying how they are fed, regulating how wild animals are caught, and attempting to reduce food loss and waste. [51] Efforts to reform animal production and distribution systems tend to enjoy more industry support (which could aid scalability),[52] and some proposed interventions would result in meaningful progress. Yet most interventions face challenges in terms of sustainability, scalability, or both.

Regenerative grazing, which seeks to enable domestic animals to better mimic the behavior of wild herds of ungulates,[53] is often offered as a remedy to the high environmental costs of ASFs.[54] Indeed, in specific instances where wild herbivores are absent and the counterfactual is land abandonment, maintaining small herds of extensively grazed domestic cattle can have biodiversity benefits.[55] At scale, however, several major reviews found regenerative grazing resulted in no consistent improvement in plant or animal productivity, soil compaction, soil water levels, soil microbial levels, or carbon sequestration compared to conventional continuous grazing regimes.[56] Any carbon benefits that do exist may very well be temporary, as carbon sequestered in soils can "rapidly be lost through management change, seasonal or climate fluctuations, or fires". [57] In the best-case scenarios, carbon benefits from regenerative grazing come at the expense of habitat, requiring 2.5 times as much land as conventional regimes.[58] This more extensive use of land may not be practical for feeding over eight billion people, especially since it offers limited apparent benefits to biodiversity. Compared to conventional grazing, regenerative grazing was associated with decreases in passerine and songbird diversity and abundance; [56] no apparent benefits for herpetofauna; [53] and the promotion of productive forage grasses and exotic species over perennial forbs and grasses. [53]

Some have recommended the exact opposite course of action as a solution, suggesting further intensification of animal production could improve environmental outcomes, especially for cattle. Indeed, assuming infrastructure and capital constraints could be addressed, [59,60] a global shift of cows from pastures to feedlots and stalls could reduce the land footprint of beef by 35-73%. [59,61] However, where such a shift is feasible, intensification often trades off one type of major ASF-related problem for others: housing animals at high densities may lead to higher-than-expected increases in emissions from manure management and indigestion by cattle made ill by living at high densities;[59,62] the pollution of water bodies with unsafe levels of microbial pathogens, veterinary pharmaceuticals, and excess nutrients;[63] and increased land-use change in the tropics driven by demand for more concentrated feed can mean that intensification leads to a net increase in GHG emissions.[64] Furthermore, the increase in illness of animals living at high densities can heighten the risk of zoonotic outbreaks and antimicrobial resistance,[65] potentially resulting in mass culls and disruptions to supply chains. Even with gains from intensification, ruminant products are more resource intensive than other ASFs.[10] Since the gains are limited to begin with, they are more likely to be swamped by rebound effects as more efficient meat production makes ASFs cheaper, driving increased consumption (see SOM).[60]

Particularly creative reforms have involved changes to how farm animals are fed. In an attempt to reduce methane emissions that are a major source of greenhouse gases from beef and milk production, producers have developed feed additives that inhibit methanogenesis.[12] While the most effective additives decrease methane emissions per unit product from beef by 67-98% and from dairy cattle by 30-35%,[12] even in a very optimistic scenario, the cost of feeding cattle would increase about 20%, making the resulting products uncompetitive.[66] Notably, additives are only feasible for cattle on feedlots, and there are also concerns about the effects of emissions from the production of these additives, how they may affect the ozone layer, and their effects on animal health and thus marketability.[60,66] Another proposal has been to reduce the footprint of ASFs by introducing insects—especially black soldier fly larvae (BSFL), yellow mealworm, and the house cricket [67]—as feed for chickens, pigs, and fish, all of which eat insects naturally. [68] In principle this could improve the sustainability of ASFs by efficiently converting various waste streams into nutrients accessible to farmed animals, reducing the ecological footprint of animal feed. [68–71] In practice, insects can either be grown quickly and efficiently using nutritious feeds, or slowly using waste streams. [67,72] Neither is particularly sustainable: in the former case—which is more common in the real world [67]— insects end up consuming products that could be fed directly to farmed animals or even to people, [70,72] effectively adding a full trophic level of ecological costs to ASF footprints. In the latter case, the nutritional content of waste streams can vary dramatically. With many substrates, insects struggle to acquire all the nutrients they need to grow, decreasing their growth rates and often resulting in higher mortality. Furthermore, the irregular nutritional composition of insects raised on waste streams make them less reliable as feed.[67] These irregularities add to the environmental costs of raising insects, generally outweighing the environmental benefits of using insects as feed. Finally, the ecological risks from escape of farmed insects are quite significant.[73,74] These challenges also apply if insects are considered for direct consumption as a substitute for more common ASFs (see SOM).[67,68]

Production reform has also been proposed in the context of wild fisheries. Marine protected areas are demonstrated to enable fish stocks to recover to a point of maximum productivity,[75,76] but achieving this best-available state would require major changes in governance of fisheries across the world, with systems for common pool resource governance structured to effectively punish agents who violate boundaries or collect more than the share allocated to them.[77] Such governance systems must be painstakingly implemented worldwide, an especially difficult task in international waters and where politically powerful fishing fleets face off against weak states or community-governed fisheries.[78,79] Notably, even if these interventions were successfully scaled, they would also result in more modest environmental gains than those required to sustainably feed the planet.[80]

The most uncontroversial reforms to ASF production involves the reduction of food loss and waste (FLW), which represents about a third of all food produced globally and about 24% of global agricultural emissions.[9,81–84] Reducing FLW includes interventions to extend shelf-life, make supply chains faster, better predict demand, and shift consumer environments and behaviors to help reduce waste.[83,85] Some FLW interventions like refrigeration, improved stocking practices, and inventory algorithms that reduce spoilage could benefit retailers and scale with the market. However, food loss and waste occur in varied ways across supply chains, so reducing FLW requires the implementation of a wide range of solutions that differ across regions and products, and many of the required interventions (like improved packaging) may cost producers more and be unlikely to scale.

[85,86] Furthermore, interventions that reduce food losses could result in rebound effects: reduced food losses can lead to increased supplies of food, reducing prices and resulting in increased consumption that offsets 53-71% of the environmental benefits that come from reducing food losses.[42,83,84] Behavior change interventions to reduce food waste face similar challenges to those related to diet change.[87] Since FLW is responsible for less than half as many emissions as ASFs, the benefits from scalable FLW interventions—while perhaps easier to achieve—are likely insufficient to meet consensus sustainability targets.

Overall, several methods of animal production reform are likely to play a role in the broader effort to reduce the footprint of our food systems. However, since improving the environmental outcomes of ASF production is often more costly in terms of time, money, space, or resources, animal production reform does not appear to satisfy the sustainability and scalability requirements necessary for a primary protein transition strategy.

Disruptive replacement with alternative proteins

At first glance, the apparent diversity of food systems and preferences across the globe tempts policymakers to suggest highly localized, varied solutions to the problems caused by ASFs.[14] In reality, while culinary practices are diverse, 98% of meat consumed globally consists of meat from poultry, pigs, cattle, buffalo, sheep, and goats.[88,89] Global fish aquaculture is also dominated by carps, catfishes, tilapias, salmons, and their relatives.[90,91] Furthermore, as much as 60% of beef products globally are ground, processed, or minced.

[92,93] The consumption of a limited number of meat types often in structurally simplified forms suggests an opportunity to replace meats with functionally equivalent substitutes, much as is happening in the energy and transportation sectors.

Alternative proteins (APs) offer significant promise in this regard. APs have two key attributes: they are meant to have sensory characteristics identical to that of ASFs, but they are made without raising, capturing, or slaughtering animals. A variety of technological platforms can help achieve this: plant-based products, biomass fermentation (using microbes such as mycelia, yeasts, algae, or bacteria to produce protein-rich food), precision fermentation (modifying microbes to produce animal protein ingredients), molecular farming (modifying plants to produce animal proteins), or cultivated meat (meat produced directly from animal cells).[94] While these technologies vary widely in their maturity, existing life-cycle analyses suggest alternative proteins will be capable of achieving the sustainability gains necessary to achieve food system emissions reduction and land restoration objectives (see *Figure 1*). Across studies and technologies, the median land savings of producing alternative proteins were projected to be about 88% compared to beef, 56% compared to pork, 43% compared to chicken, 33% for fish, and 25% for dairy proteins across technologies. [40,95–98] Similarly, alternative protein production is projected to result in GHG emissions reductions of about 84% compared to beef, 60% compared to pork, 38% for chicken, 37% for fish, and 46% for dairy. [40,95–99] In the most comprehensive assessment of what a switch to alternative proteins (specifically, plant-based meat and dairy) would mean for the planet using the GLOBIOM model, researchers found that a 50%

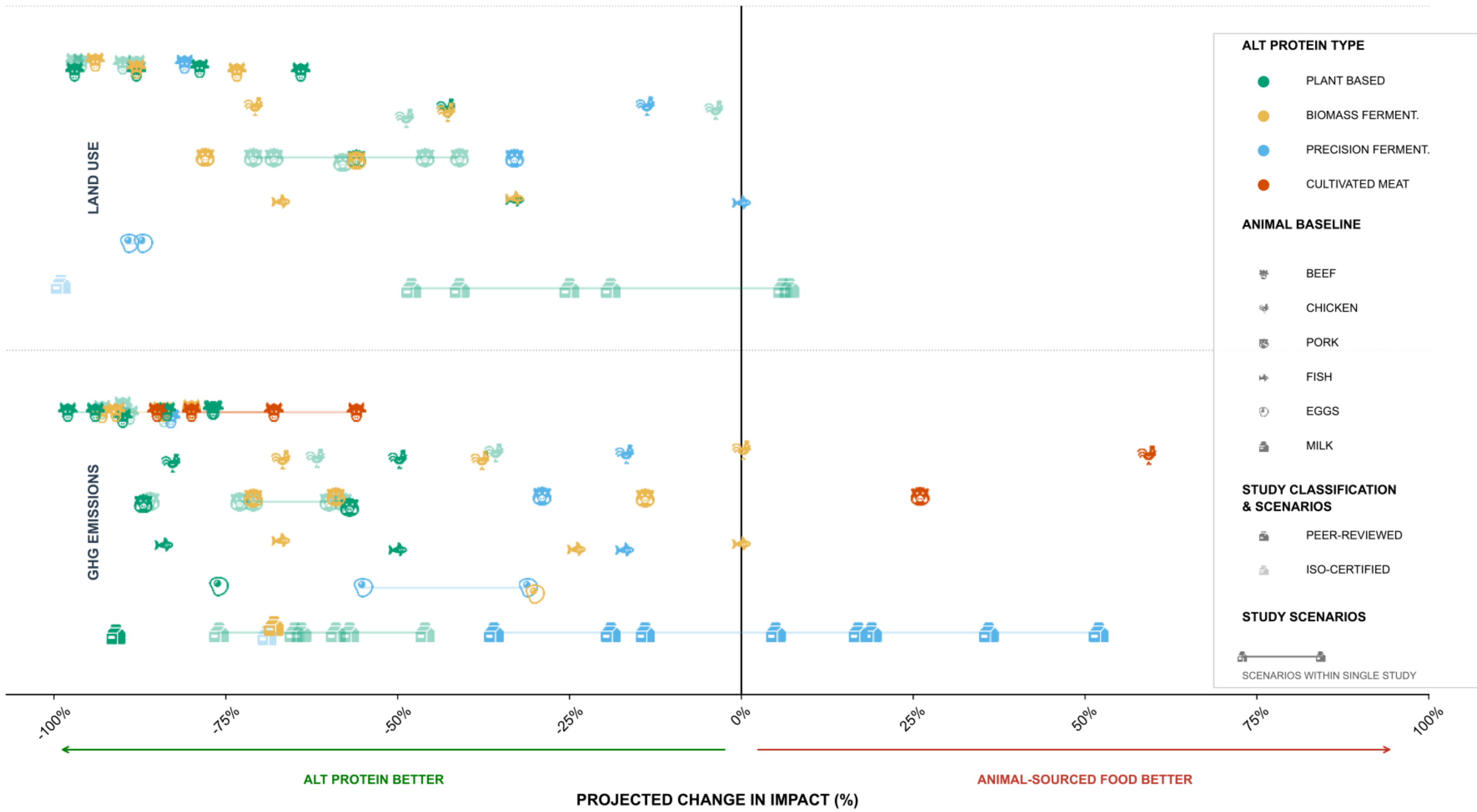


Figure 1: *A compilation of the results of peer-reviewed and ISO-certified comparisons of the projected land footprint and greenhouse gas emissions of alternative proteins and animal-sourced foods (point estimates).*[40,100–115] *Each icon indicates how the environmental impact of an alternative protein product compares to that of an animal product it is intended to help supplant. Despite being early-stage technologies with substantial room for optimization, alternative proteins are often projected to out-perform animal products by substantial margins, but improvements are larger and more consistent for higher-footprint products (e.g., beef) than for lower-footprint ones (like milk). In several cases, different scenarios from the same*

paper found drastically different impacts, demonstrating that the context of production can determine whether environmental impacts are an improvement over ASF production. Note that units were consistent within each comparison but varied across studies including the following: land use (m^2 org arable-y/g protein, m^2 org arable-y/kg product, m^2a crop eq./kg protein, m^2a crop eq./kg product, m^2a crop eq./l product, m^2.y/kg product, Pt/g protein, and NIEI LU_{meal}); greenhouse gas emissions (kgCO_2eq/g protein, kgCO_2eq/kg product, kgCO_2eq/l product, tCO_2eq/ton protein, NIEI GWP_{meal}).

switch to plant-based products by 2050 could result in a 31% reduction in GHG emissions and the liberation of 653Mha— an area the size of India, Argentina, and Cameroon combined— from agriculture compared to business-as-usual. The restoration of lands formerly under agriculture to natural ecosystems would result in an effective total 75% reduction in agricultural emissions.[34] These gains would be roughly those required to limit warming to around 1.5 °C and contribute substantially towards the goals of the Kunming-Montreal Global Biodiversity Framework.[116] Some of the resources spared could also accommodate the production of alternative seafood, reducing pressure on fisheries (see SOM).

Notably, not all alternative proteins can currently be produced more sustainably than all ASFs. For instance, fermentation-derived milk protein (beta-lactoglobulin) was found to always require less land than the same protein from cow milk, but the feedstock used and geography of production determined which product had lower emissions and water use (see *Figure 2*).[117] The best available assessments of cultivated meat suggest that—in likely but as-of-yet undemonstrated scenarios—the product may have lower emissions than beef but higher emissions than chicken (see SOM).[115] Still, there is reason to believe these products will improve with time. As early-stage technologies, alternative proteins have far more scope for efficiency gains than ASFs that have been optimized over centuries and are constrained by complex physiological limits.[118] The easiest gains are likely to occur as grids around the world shift from fossil fuels to renewables. While electricity accounts for up to 80% of emissions from alternative protein production,[35,40,119] it only accounts for 5-10% of

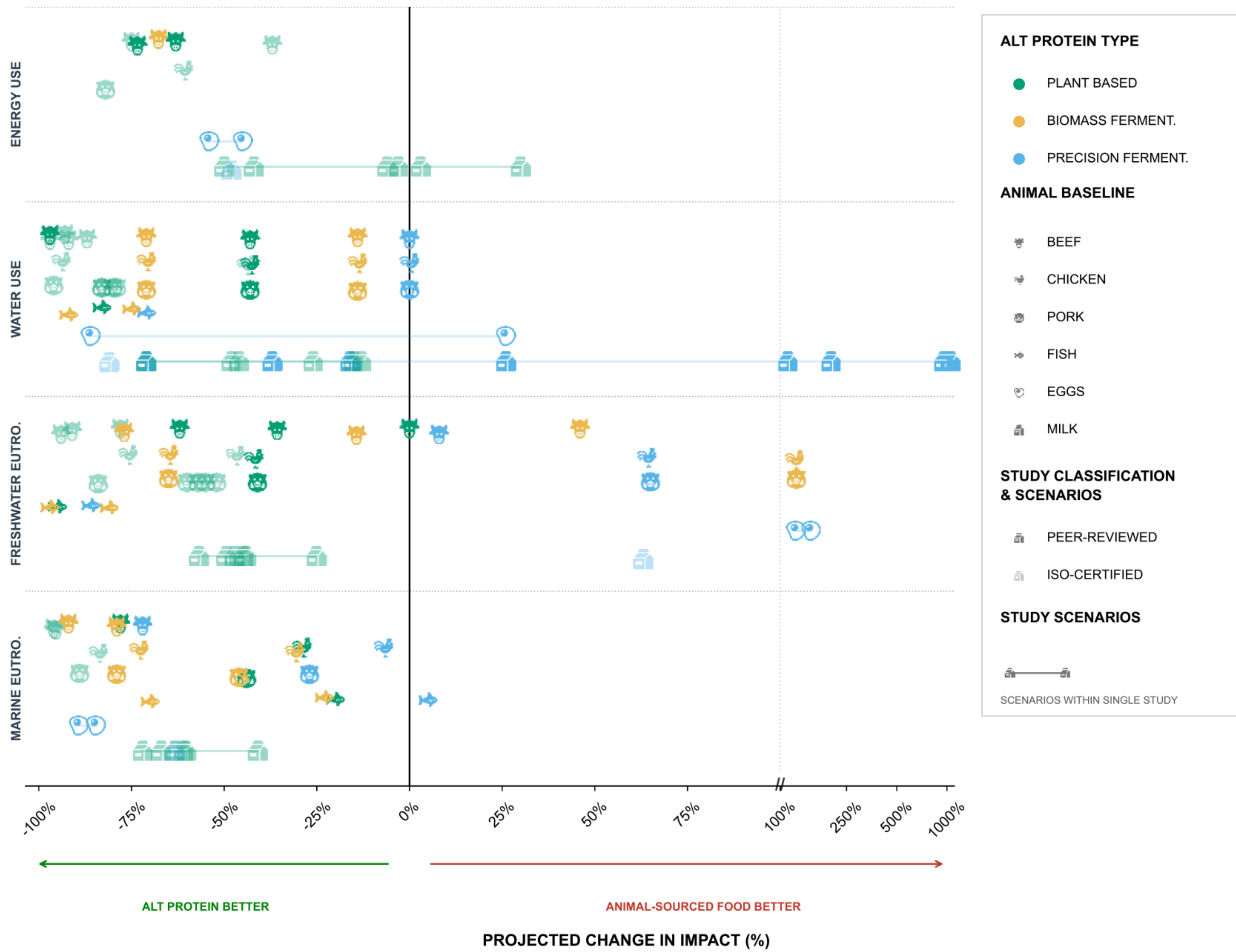
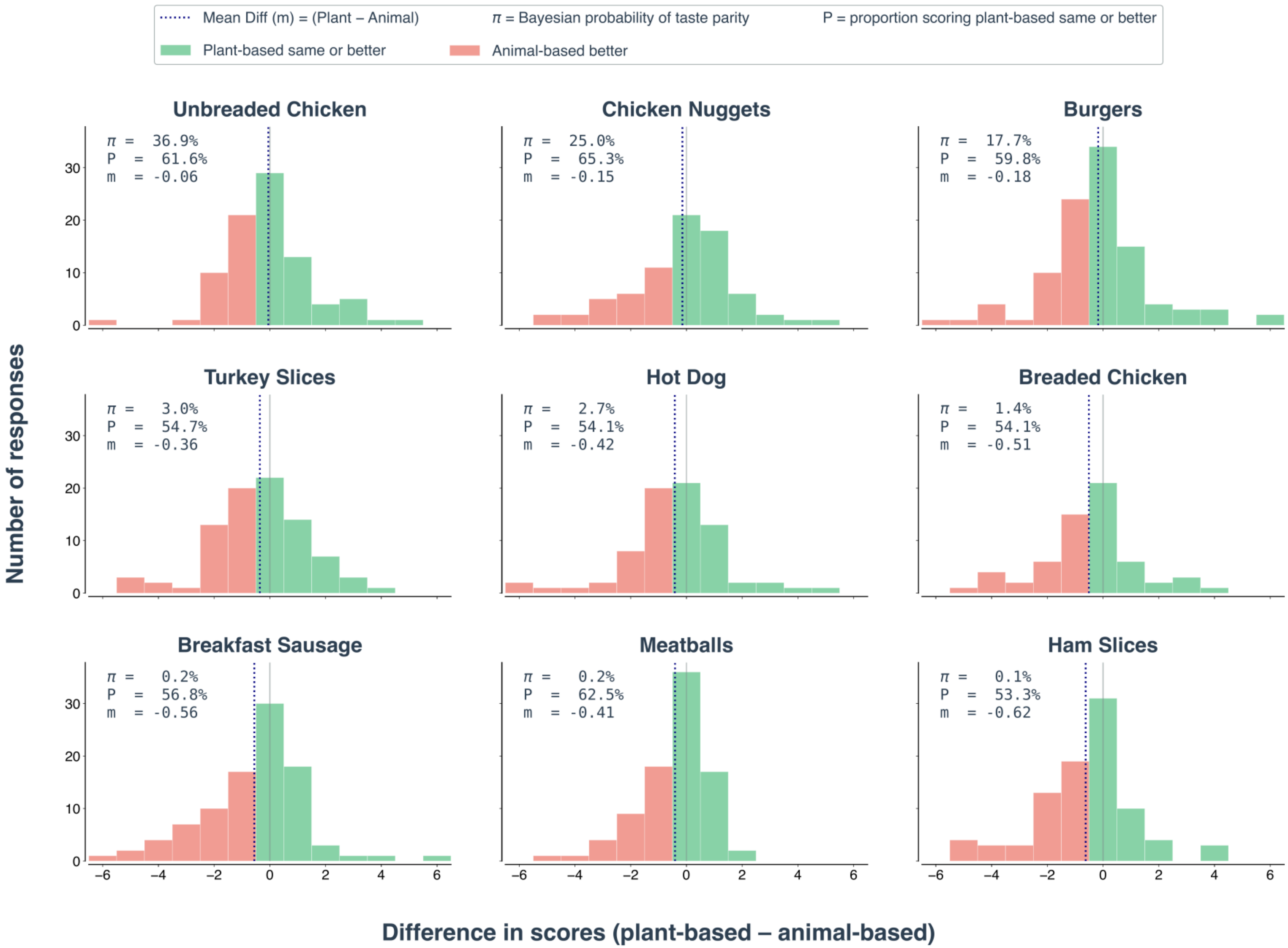

ENERGY USE
WATER USE
FRESHWATER EUTRO.
MARINE EUTRO.
-100%
-75%
-50%
-25%
0%
25%
50%
75%
100%
250%
500%
1000%
ALT PROTEIN BETTER
ANIMAL-SOURCED FOOD BETTER
PROJECTED CHANGE IN IMPACT (%)
ALT PROTEIN TYPE
PLANT BASED
BIOMASS FERMENT.
PRECISION FERMENT.
ANIMAL BASELINE
BEEF
CHICKEN
PORK
FISH
EGGS
MILK
STUDY CLASSIFICATION & SCENARIOS
PEER-REVIEWED
ISO-CERTIFIED
STUDY SCENARIOS
SCENARIOS WITHIN SINGLE STUDY

Figure 2: *A compilation of the results of peer-reviewed and ISO-certified comparisons of how the projected energy, water, and eutrophication footprints of alternative proteins compare to those of animal-sourced foods (point estimates).*[40,102–112,114] *Each icon indicates how the environmental impact of an alternative protein product compares to that of an animal product it is intended to help supplant. Again, findings are generally positive for alternative proteins, though precision-fermented products in particular do not necessarily perform better than the ASF foods they are intended to replace. Note that units were consistent within each comparison but varied across studies including the following: energy use (MJ/g protein, MJ primary/g protein, kg oil eq./kg product, kg oil eq./l product); water use (m^3/kg product, m^3 depriv./g protein, world m^3eq/ton protein, liters/kg product, m^3eq/l product, NIEI WU_{meal}); freshwater eutrophication (kg P-eq/kg protein, kg P-eq/kg product, g P-eq, kg PO_4 P-lim/g protein, g PO_4-eq P-lim/kg product, kg P eq/l product, NIEI FE_{meal}); marine eutrophication (kg N eq./kg product, kg N eq/kg protein, kg N eq/l product,NIEI ME_{meal}).*

emissions from meat, eggs, and milk, [10,22] suggesting far greater sustainability gains for APs as grids decarbonize. In effect, alternative proteins can transform our food systems as electric cars are beginning to reshape transportation.[94]

None of these sustainability benefits are of use if the consumer base for alternative protein products remains small. Even though all-time public investment in alternative proteins is only about 0.3% of annual investments in renewable energy,[120] alternative proteins have made remarkable progress in less than two decades, including the availability of products in major fast-food chains around the globe. Yet markets and investors have begun to express doubt that APs can replace ASFs at scale. Supporters of alternative proteins note that their theory of change rests on the availability of APs that can out-compete ASFs on taste, price, and convenience (and perhaps nutrition), and that it is too soon to dismiss alternative proteins because such APs are still in development. There is strong reason to believe achievement of taste- and price-competitive APs is feasible both technically and practically. A randomized controlled trial of 122 plant-based and fermentation-derived alternative protein products found that over 50% of omnivores rated 20 AP products (e.g. deli slices, chicken nuggets, sausages, and burgers) as highly or better than their ASF counterparts (Figure 3).[121] This is despite an absence of fit-for-purpose ingredients; for instance, while there have been concerted attempts to develop cultivars of durum wheat particularly well-suited for use in pasta,[122] the soy used in current AP products is effectively a byproduct from oil extraction primarily used as animal feed, not an ingredient optimized for use in alternative proteins.[123] A variety of methods ranging from traditional breeding or



Mean Diff (m) = (Plant – Animal)
π = Bayesian probability of taste parity
P = proportion scoring plant-based same or better
Plant-based same or better
Animal-based better
Unbreaded Chicken
π = 36.9%
P = 61.6%
m = -0.06
Chicken Nuggets
π = 25.0%
P = 65.3%
m = -0.15
Burgers
π = 17.7%
P = 59.8%
m = -0.18
Turkey Slices
π = 3.0%
P = 54.7%
m = -0.36
Hot Dog
π = 2.7%
P = 54.1%
m = -0.42
Breaded Chicken
π = 1.4%
P = 54.1%
m = -0.51
Breakfast Sausage
π = 0.2%
P = 56.8%
m = -0.56
Meatballs
π = 0.2%
P = 62.5%
m = -0.41
Ham Slices
π = 0.1%
P = 53.3%
m = -0.62
Number of responses
Difference in scores (plant-based – animal-based)

401

Figure 3: *The results of randomized blinded trials comparing nine animal-based products and their leading plant-based competitors, demonstrating that taste parity is reasonably close despite limited investment in alternative proteins technology. Omnivore participants were asked to score each product on overall taste, effectively using a 1-7 scale.*[124] *These histograms show the differences in scores (plant-based – animal-based). A majority of respondents in each case scored the two products the same or scored the plant-based product better, suggesting market potential if costs become competitive. We also assessed products based on a stricter definition of taste parity: that the population average of the differences in scores was less than or equal to zero. A Bayesian paired-t test with a non-informative prior was used to estimate the probability that each product has achieved taste parity. As of 2025, the probability of taste parity was already 36.9% for the best-performing product.*

AI-powered genetic modification of crops to advanced protein isolation techniques could help produce ingredients with the right flavors, functionalities, and amino acid profiles for use in APs, helping drive down costs and achieve taste and nutritional parity with ASFs.[125,126]

In practice, achieving cost-competitiveness requires a virtuous cycle of increasing investments and consumer acceptance. The history of other low-carbon technologies suggests that alternative proteins are a strong candidate for such a path. An analysis of low-carbon innovations found that their potential to scale rested heavily on their degree of design complexity and need for customization. Technologies like nuclear energy, geothermal plants, or even wind turbines must be tailored to specific locations and are relatively complex, making it difficult for technologists and companies to build off of each other's progress. In contrast, mass-produced technologies like solar panels and LEDs have low design complexity and require relatively little customization, allowing companies to learn and improve faster across contexts.[127] With companies striving to minimize the number of ingredients in their final formulations and a small number of animal products dominating international markets, alternative proteins may most resemble solar panels and LEDs. The costs of such standardizable technologies tend to decline by a fixed percentage with each doubling of cumulative production.[128,129] Just as the development of solar power technologies moved from the US to Japan, Germany, and China as policy priorities shifted,[130] the relative transferability of alternative proteins production also means that the technology can continue to develop in other countries if the ASF industry or consumer sentiment stymies progress in any one place. Research has already demonstrated diversity in consumer responses to alternative proteins, with Chinese and Indian consumers potentially more willing to swap out meat for plant-based or fermented analogues.[131] The history of margarine—which faced major cultural and dairy industry resistance but came to claim about 70% of market share—demonstrates the power of price in enabling disruption in the food sector.[132]

There is room for reasonable skepticism around alternative proteins both in terms of sustainability and scalability (see SOM). Presently, there are only a limited number of (mostly prospective) life cycle analyses and model projections, and there is already substantial variation in the life cycle impacts found across products, with the ranges of alternative protein impacts often overlapping with those of the most environmentally friendly animal products.[100,133] Furthermore, while prior disruptive technologies offer a hopeful precedent, the disruptive effects of margarine and solar panels required six to ten decades from development.[130,132] Given the active efforts of incumbent industry to persuade the public to see alternative protein products as unhealthy or unnatural,[134] it isn't obvious how much consumer acceptance of alternative protein products can be accelerated. Despite these limitations, alternative proteins offer the best opportunity for a sustainable solution because they sidestep the fundamental inefficiencies of animals, and they offer the clearest path to scale because efficiencies should drive down costs. Ultimately, given that most customers continue to consume meat produced through heavy intervention with hormones and antibiotics in large part due to their price,[135] it is reasonable to hypothesize that a critical proportion of global consumers will accept sensorily indistinguishable (and likely healthier[136]) products that are even cheaper.

Priority actions for the conservation community

All three strategies for protein transition involve deep challenges, and the sustainability community must not rely on any one approach to address the challenges posed by ASFs. Still, alternative proteins are unique in their potential to provide major environmental benefits at scale. As such, the conservation community may achieve the best outcomes by making the development and acceptance of alternative proteins a primary priority.

The conservation community can make four major contributions to enable establishment of a sustainable, competitive alternative proteins sector. These responsibilities would fall to a variety of actors working to protect biodiversity including conservation NGOs, environmental advocacy groups, biodiversity thought leaders and researchers, and sustainable development institutions.

First, conservationists can advocate for more public investments in alternative proteins resembling those made in renewable energy. This could include funding for research and development, as well as demand-side mechanisms like advanced market commitments and sustainable procurement policies (see SOM). The alternative protein sector has followed a curious path so far; even though observers like the Boston Consulting Group and World Bank have ranked alternative proteins as one of the most effective investments for addressing climate change,[137,138] innovation has largely been led by private sector companies instead of governments. The market share of alternative proteins is about 30 times higher than the proportion of agricultural research funds being invested in R&D for alternative proteins, and all-time public investment in alternative proteins is only about 0.3% of annual investments in renewable energy. [120] Conservation organizations have cultivated strong constituencies across the political spectrum—for instance, in the US Congress, the international conservation caucus is one of largest bipartisan caucuses. [139] Conservationists could use these relationships to encourage decision-makers to treat alternative proteins like other low-carbon technologies crucial for biodiversity, as well as highlight the benefits alternative proteins can provide in terms of food security[140,141] and pandemic prevention.[135,142]

The other element in the virtuous cycle for new technologies is consumer acceptance. Conservation institutions could use our credibility to help legitimize alternative proteins with the broader environmental community. At present, leading environmental groups have under-emphasized the role alternative proteins can play in enabling a sustainable protein transition.[14,30] Using campaigns like those to discourage purchase of ivory or shark-finned soup,[143] the conservation community could help the public understand that purchasing alternative proteins will help protect iconic species and landscapes around the world. Conservation organizations can similarly encourage food companies to commit to purchasing and investing in alternative proteins. Biodiversity conservation groups need not conduct such campaigns in isolation—in coordination with partners from the public health, climate, and water conservation communities, [9] they can help demystify and normalize alternative proteins for the general public. In fact, environmentalists may have a special ability to do so: two studies showed that participants were more willing to change their diets in response to environmental messaging than health messaging.[45] Since a campaign around alternative proteins can focus on a positive, relatively straightforward substitution instead of a complete change in the composition and preparation of meals, such campaigns may be more successful.

Third, the conservation community can ensure that alternative proteins live up to their potential as sustainable substitutes for ASFs . Since conservation organizations' primary interest with respect to food production is its sustainability, they are well-positioned to organize transparent third-party life cycle assessments of how novel replacements compare with legacy products and other proposed solutions in terms of land use, the climate, water use and pollution, and biodiversity impacts.[98,99,144] These assessments can then be used to ensure producers mitigate harms and that production facilities are seeded where the biodiversity benefits are the greatest. As seen in the context of precision fermentation, the geography of production can determine environmental impacts.[117] In addition, situating new industry to enable a shift from ASF production in biodiverse regions could reduce local and regional stress on nature. Two separate studies in Brazil found that, when agriculturalists were exposed to economic incentives to shift from cattle ranching to farming of crops (including soy), regional deforestation decreased;[145,146] a shift to alternative protein production could have a similar effect (see SOM).

Finally, conservation should promote and implement policies that ensure a just transition to alternative proteins for communities currently dependent on ASFs. While alternative proteins will offer new livelihoods for those growing input crops and feedstocks, producing ingredients like fats and flavors, and working in manufacturing facilities, the efficiencies of alternative proteins and general move towards automation will probably mean a net reduction in agricultural and fishing jobs.[51] With over 1.5 billion people likely engaged in some way with the production of ASFs,[147–149] this means a transition to alternative proteins would have implications for a large number of livelihoods.[32] Conservation organizations must help ensure that any transition towards more sustainable protein sources is just, much as is required in the shift towards renewable energy.[13] Much of what is required for a just transition relates to work conservationists have already been doing in recent decades: partnering with communities to understand their aspirations, helping them bolster their claim to their lands and resources (with an emphasis on free, prior, and informed consent), identifying new sustainable livelihood opportunities that meet their aspirations, and providing technical and economic support for sustainable natural resource management. While some new livelihoods will be related to alternative proteins [150] or biodiversity (e.g., ecotourism or carbon credits) [151], others will not; while some will involve contributing directly to a bioeconomy, like agroforestry-based reforestation efforts, others will foster new professional opportunities in urban areas.[152,153] Special care must be taken to ensure communities directly dependent on animals for subsistence maintain access to these resources. Globally competitive alternative proteins provide an unparalleled chance to reduce the impacts of our food system, addressing the greatest threats to wildlife on the land and in the water and achieving the goals outlined in the Kunming-Montreal Global Biodiversity Framework—but conservationists will still have to work to enable a timely transition and ensure that the new ground reality favors both biodiversity and the people that have thus far made conservation possible.

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Alternative proteins are likely essential for biodiversity conservation

Supplementary online material

Authors: Nitin Sekar,[1] Alex Dehgan,[1,2] Paul Bunje,[1] Cleo Verkuijl,[3] Shayna Fertig,[4] Kavya Jain,[1] Jeremy Radachowsky,[5] Glenn Hurowitz,[6] Christopher A. Jordan,[7] Wes Sechrest,[7] David Goodman,[8] Eric Dinerstein.[1,9]

[1] Conservation X Labs, 1050 30th St NW, Washington, DC, USA 20007.
[2] Rob Walton School of Conservation Futures, Arizona State University.
[3] Stockholm Environment Institute US, Somerville, MA, USA.
[4] Good Food Institute, PO Box 96503, PMB 42019, Washington, DC 20090-6503, USA
[5] Wildlife Conservation Society, Mesoamerica & Western Caribbean Regional Program, Avenida 15 de Marzo, Casa No. 3, Flores, Petén 17001, Guatemala
[6] Mighty Earth, 1701 Rhode Island Ave NW, Suite 3-123, Washington, DC 20036, USA
[7] Re:wild, PO Box 129, Austin, TX, USA, 78767
[8] School of Geography and the Environment, University of Oxford, Oxford, UK.
[9] Landseed.earth, Cabin John, MD, USA, 20818

Introduction

Our main text for “Alternative proteins are likely essential for biodiversity conservation” was derived from a longer report developed in the process of prioritizing interventions to address the biodiversity harms of animal-sourced foods. Due to space constraints, much of this report had to be excluded from the main text. We reproduce additional details and concepts here.

Animal-sourced foods and biodiversity

Why ASFs are inefficient

The inefficiencies of animal-sourced foods (ASFs) follow from the inefficiencies of energy moving across trophic levels. On average, farmed animals consume 16 calories for every calorie and 12 grams of protein for every gram they provide for consumption. [22] Similarly low conversion rates limit the populations of wild carnivores and large-bodied species, making them particularly vulnerable to extirpation due to overfishing and overhunting. [154–156]

Agriculture and habitat loss

Worldwide, agriculture has already resulted in the conversion of 70% of global grasslands, 50% of savannas, 45% of temperate forests, and 27% of tropical forests; [32] from 1990-2010, 61% of global forest loss was due to commercial agriculture,[10] and 83% of new agricultural lands developed in the biodiverse tropics between 1980-2000 came from forests. [157] Habitat loss and degradation decreases and fragments the area wild species can occupy, resulting in smaller, more genetically isolated populations. [3,158] Agriculture is responsible for about 90% of habitat loss in global biodiversity hotspots over recent decades, [159] and agriculture-driven habitat loss imperils 80% of all terrestrial threatened bird and mammal species.[3] Ruminants—animals that evolved four-chambered stomachs to digest low-quality vegetation, like cattle and goats—provide about 49% of humanity's animal-sourced proteins and dominate land use.[15] Cattle, buffaloes, and small ruminants use about two-thirds of the planet's agricultural lands as pasture, [32] 65% of which is unsuitable for crops. [10]

There is perhaps no place in the world where the biodiversity costs of animal-sourced foods are more apparent than the Amazon rainforest. Covering an area the size of the contiguous United States, the region is home to over 10% of the earth's terrestrial biodiversity, stores about 200 gigatons of carbon, hosts rivers containing 20% of global freshwater, contributes up to 50% of the rainfall of the region, and helps cool the earth. [160] Nearly 20% of the Amazon—an area larger than Peru—has been deforested in the last 50 years, with an additional 17% of forests degraded [161,162]—never before has such a large area of old-growth forest been converted for human land use so quickly. [2] A scientific consensus—built through over 146 studies from 1970-2019—has concluded that the vast majority of the destruction has resulted in pasture for cattle.[163–168] While commercial crops like soy grown for animal feed explain 9-12% of deforestation, pasture has explained 63-90% of deforestation.[161,169,170] The situation highlights the unique threat that cattle pose to biodiversity—in the remote Amazon, where production and transportation infrastructure is lacking, land speculators have had essentially one option to finance their territorial ambitions. Low-density cattle enable speculators and ranchers to draw income from and strengthen claims to the land they have illegally seized as they await the arrival of infrastructure developments.[167,171]

It is worth noting that animal-sourced foods aren't always worse than plants with respect to land-use. Some pulses and nuts, for instance, use more space per unit protein than poultry, eggs, or farmed fish. [10] But most plant proteins are substantially more space efficient: for instance, on average, beef requires 75, mutton 84, pork 5, chicken 3.2, and farmed fish 1.7 times more area per gram of protein than tofu. [10] These inefficiencies drive habitat loss, which in turn result in biodiversity loss: in recent decades, sixty-five percent of agricultural expansion has been associated with the increased production of animal products.[33]

Animal agriculture and habitat quality

Animal agriculture doesn't just reduce the quantity of land remaining for other species—it reduces the quantity and quality of the water, soils, and biotic resources available for biodiversity. Agriculture is responsible for about two-thirds of freshwater withdrawals for irrigation,[10] with the production of livestock feed accounting for about 41% of agricultural withdrawals.[35] While aquaculture is relatively land-efficient, it is the worst offender when it comes to water usage, with fish meal requiring about 3.5-4 times as much scarcity-weighted water per nutritionally-adjusted serving as other ASFs and 5-10 times as much as plant-based foods.[95] Unlike other industries which often pump water back into ecosystems after use, animal agriculture removes substantial quantities during water-scarce times of the year and often fails to return it.[10] The disruption of hydrological flows has changed the courses of rivers, caused diebacks of floodplain forests, drained wetlands, and altered water chemistry, resulting in steep declines in the populations of riparian plants, amphibians, and other aquatic vertebrates.[25,33] For instance, eighty percent of the water in the Colorado River is used for agriculture, with 55% of all water consumption being used for cattle feed. At this rate, the river may lose 55% of its flow by 2100.[25]

Agriculture is also responsible for 78% of the eutrophication (nitrogen and phosphorous pollution that leads to oxygen depletion) of marine and freshwater ecosystems, with the lowest-polluting ASFs causing more eutrophication than average plant-based protein sources.[10] This pollution produces algal blooms which have caused dead zones in the mouths of over 400 rivers worldwide.[2,172] Nitrogen pollution also affects terrestrial biodiversity through multiple mechanisms, for instance reducing plant and prey diversity in a way that has impacted rare bird species.[33] Agriculture—especially beef—is responsible for 32% of the world's soil acidification[10] and soil erosion rates 10-100 times greater than the rate of soil formation,[9] with some of the eroded sediment smothering coral reefs.[2] Finally, even where they apparently share space with wildlife at relatively low densities, livestock can complicate their conservation, reducing native vegetation available for wild herbivores and endangering large carnivores that—having killed one or more farmed animals—become the targets of retaliatory killings by ranchers or government authorities.[2] In fact, because lightly used pasture accounts for 50% of land use within key biodiversity areas, light use of pasture is the primary driver of KBA biodiversity loss, responsible for the potential loss of 382 plant species and 91 vertebrate species.[16]

How agriculture affects biodiversity through climate change

Through their effects on the climate, ASFs exacerbate a variety of stressors faced by biodiversity. Climate change forces species to contend with major shifts in temperature and precipitation, more extreme events, acidification of water bodies, the spread of diseases and invasive species, and disruptions to food availability (for instance, due to changes in plant phenology).[173] Climate change has probably irreversibly altered many terrestrial, coastal, and aquatic ecosystems, and extreme heat has already led to mass mortality events and the losses of hundreds of local populations.[174] The interaction of climate change and intensive agricultural land use appears to be responsible for a 27% reduction in the number of insect species and 50% reduction in insect abundance in regional species assemblages.[175] Climate change is the second most reported driver of marine extinctions after pollution (which, as we've noted, is also often driven by animal agriculture), contributing to 38% of marine extinctions including those of coral and mollusk species.[23] The diversity of likely and declared extinctions associated with climate change—for instance, the meltwater stonefly,[176] the smooth clam,[177] the quairading banksia,[178] the golden toad, the Bramble Cay mosaic-tailed rat, [179] Stresemann's bushcrow,[180] *Acropora* coral species on the Great Barrier Reef, [23,181] and polar bears[182]—portend the dramatic effects ASFs are likely to have on biodiversity through GHG emissions, especially as they converge with habitat loss and other drivers.

Overexploitation of wild animals for food

The multibillion-dollar bushmeat trade continues to be a major biodiversity concern, especially in Africa and southeast Asia.[2] In many contexts, the harvesting of wild animals for food is important for nutrition,[1] and in at least one context has been linked to the lack of access to other proteins.[183] Nevertheless, hunting and other forms of direct mortality are a major risk factor for 40-50% of all threatened bird and mammal species and have led to catastrophic declines of Asian and sub-Saharan mammals and numerous local extirpations.[3] The situation is even starker in aquatic ecosystems: overfishing is the leading cause of marine biodiversity loss and the second most frequent threat to freshwater species after habitat degradation.[5,25] Wild and mariculture-raised seafood plays a major role in the global food supply, providing some 17-20% of animal protein [25,80]—some three billion people get vital nutrients from seafood, and about 660 million people are majorly dependent on marine and freshwater fisheries for food.[25] About 90 million tons of seafood is taken from oceans and waterways annually, and industrial fishing occurs over about 55% of the ocean.[25] This dependency affects biodiversity in multiple ways; overfishing can disrupt ecosystems by removing predator and prey species that support or limit other species, and industrial fishing in shallow and coastal zones can destroy sensitive habitat.[25] The biggest issue by far, though, is that too many animals are killed either for consumption or as bycatch, the 10% of total catch (or 9 million tons) composed of non-target species that goes unused.[25] Thirty-eight percent of marine fisheries are assessed as overfished.[25] In 2012, 68% of fisheries were providing less than their maximum sustained yield, 118 fisheries had mortality rates more than 10 times the sustainable target, and three had mortality rates 100 times that of sustainable levels.[37] The approximately 1118 species affected by overexploitation are diverse.[184] Among marine species driven to extinction: 46% of Osteichthyes (bony fish), 87% of Chondrichthyes (cartilaginous fish), 74% of marine mammals, and 62% of marine birds were overexploited.[23] Populations of migratory fishes, the main bulk of freshwater fishing hauls, have declined 81% since 1970 in large part due to overfishing.[24,25] High on the food chain, sharks and rays are particularly vulnerable to extinction from overexploitation.[185] Sawfishes—iconic and endangered shark-like rays—possess fins highly valued in the global shark fin trade, and they are presumed extinct in 46 of the 90 nations whose waters they once inhabited primarily due to overfishing.[186] Freshwater sturgeons and eels,[24] demersal fish like the orange roughy, predatory fish like the Patagonian toothfish and bluefin tuna,[187] and mammals like the vaquita [188] are all at risk of disappearing due to our dependence on animal-sourced foods.

Future increases in ASF consumption and biodiversity

The United Nations estimates that the global human population will grow to about 9.7 billion in 2050 and 10.4 billion in 2100.[189] Estimates based on regional trends suggest that, compared to baselines between 2005 and 2010, demand for meat in 2050 will increase at least 68-76% to 455 metric tons annually (including an 88% increase in ruminant meat) and demand for fish will increase to 140 MT (about 56% more than present).[31–33] If people in India, southeast Asia, the Middle East, and Africa defy regional trends and come to consume even 60% as many calories from ASFs as Americans do today, meat consumption would increase about 92% from 2010 to 2050.[32]

All this will drive agricultural expansion, especially in the tropics. Since 15 of the world's 17 megadiverse countries are in the tropics, this is a major risk factor for biodiversity—Ecuador, Brazil, China, and the Philippines are expected to lose a further 10%, 10%, 18%, and 20% of their country's total area to agriculture in the next 25-35 years,[2] and 61% of global habitat conversion is expected to occur in sub-Saharan Africa.[3] Reduced forests in the Amazon may become unable to generate enough atmospheric moisture from evapotranspiration to support the system, and some 10%-47% of the rainforests of the region may tip into degraded grasslands.[160] By 2100, the spread of agriculture is expected to lead to the conversion of 9% of global natural lands, 24% of natural lands in the tropics, and 20% of natural lands in biodiversity hotspots.[33]

The increased intensification of crop and livestock production are expected to result in more water scarcity,[2,9] surface water pollution, and soil acidification.[2] Nitrogen application and irrigation are expected to especially affect regions rich in bird species.[33] Agriculture and related land use GHG emissions are expected to increase by 15% (1.1 gigatonnes of CO2 equivalents annually) from 2020 to 2050,[34] with land use-related emissions alone adding over 75 gigatons of GHGs to the atmosphere over that period.[151] Agricultural methane emissions primarily from cattle are expected to increase 36% from 2020 to 2050.[35] Researchers trying to frame these findings suggest that if everyone ends up eating like Americans by 2050, we would need about 5.6 Earths' worth of resources to support ourselves.[25]

Unsurprisingly, all of this is bad news for biodiversity. One study found that, in a business-as-usual scenario, the Biodiversity Intactness Index would decline by 2.1% globally by 2050.[34] Another geographically explicit model of future agricultural land clearance forecasted that 87.7% of nearly 20,000 species would lose habitat to agriculture by 2050, with 1,280 species projected to lose over 25%.[190] These effects are likely to be concentrated in the tropics. By 2060, extinction risks due to changes in food systems will be higher than ever before for at least one major taxonomic group in half the countries assessed, with large-bodied mammal species and birds in sub-Saharan Africa and tropical

Asia in particular risk.[3] A two-degree Celsius increase would expose at least 5-10% of animal species and seagrasses in the tropics to potentially dangerous temperature conditions; in parts of Indonesia, it would be closer to 80%.[174] Increased demand for protein will also likely affect wild species directly, with increased bushmeat hunting in remaining natural habitats [3] and about 88% of fish stocks overexploited by 2050.[37]

Why conservation has not prioritized protein transition

Conservation groups and the environmental community more broadly have not sufficiently addressed the challenge of transitioning to more sustainable proteins;[36] ASFs are largely neglected even in major international agreements like the Global Biodiversity Framework and Paris Agreement.[25] This failing could be explained by many factors: feeding people can seem more fundamental even than fueling up a car or lighting a home, and perhaps emissions from food "seem to be an unavoidable environmental cost of feeding humanity".[36] Animal-sourced foods in particular are complicated since they have historically provided micronutrients less available from plants [51,97] and for communities unable to access fortified or well-balanced plant-based foods, they remain a critical source of nutrition.[1,3] Furthermore, large swathes of the modern economy—including powerful corporate interests—amounting to as much as $3.3 trillion are tied to the production or capture of animals for food.[191,192] Given the deep ties ASFs have to human culture, economic systems, and perhaps even evolution,[193] tackling a protein transition is logistically and politically complex.

Strategies for a protein transition

Ecological potential of conventional diet change

There is a remarkable level of consensus in the sustainability literature that conventional diet change would be a powerful and positive change for the Earth,[2,32,45] and that such a change would do more to address climate change and habitat loss than increasing the efficiency of agriculture, mitigating pollution from ASF production, or addressing food waste.[10,25,51] Conventional plant-based diets offer all that is needed for adequate protein: in their dry form, plant-based foods like peanuts, peas, and pulses often have more protein per kilogram than many meats; grains, which provide 41% of global protein intake, offer complementary amino acids; and soy provides protein in amounts and quality broadly comparable to many meats, especially in its concentrated forms.[10,25] By providing protein two to 20 times more efficiently, plant-based foods free up agricultural land that can be used to grow more food or restore ecosystems that sequester carbon, support pollinators, cycle nutrients, stabilize the soil, and mitigate floods.[40,51] The benefits of a transition to a plant-based diet go beyond reduced emissions. If all Americans were to adopt a fully plant-based diet, 62-70% less water would be used in agriculture.[40] If the world were to go 95-100% plant-based, agriculture would require 42% less water [33] resulting in 19% less scarcity-weighted withdrawals,[10] and 68% less nitrogen fertilizer [33] resulting in 49% less eutrophication.[10] By 2100, this would result in measurably more water and less pollution in bird-species rich parts of the world and biodiversity hotspots.[33]

From a direct exploitation standpoint, consumers could also make a difference by shifting from long-lived, slow-growing species like Chilean sea bass and bluefin tuna to species low on the food chain like oysters or scallops, leading to efficiencies and sparing vulnerable species.[25]

Constraints to engendering widespread conventional diet change

Observers have discussed the possibility of "a multifaceted policy that evokes motivation and capability through the use of mass media campaigns to educate, teach, and persuade individuals; establishes service provision in communities to influence their physical capability and self-efficacy to partake in the behaviour change; and influences the physical opportunity to acquire foods (i.e., taxes, rules, or guidelines on red and processed meat consumption or improving access to plant-free meat alternatives)" [45]—but it is unclear whether such programs can get the political or financial support needed to succeed. In principle, reallocating portions of the half a trillion dollars of agricultural subsidies currently supporting animal-sourced foods towards plant-based foods could help achieve key biodiversity objectives without increasing taxes.[10] However, experience from the energy and transportation sectors have demonstrated the political difficulty of implementing such policies—in most contexts, policies that increase the cost of food or take away public support from food producers would face major political headwinds.[42]

As noted in the main text, it's also unclear how scalable mainstream behavior change interventions are. In other words, the cost-benefit ratios of these interventions are high and make scale-up difficult (at best). Consider the interventions described in one systematic review on efforts to promote environmentally sustainable diets. One intervention (sample size 32) included one-on-one information sessions involving a slideshow on emerging social norms and the ill effects of meat consumption, as well as text message reminders and links to recipes. In another study with 115 participants, the intervention included meat substitutes, informational leaflets, recipes, and success stories of people who reduced their intake. For the studies reporting a significant decrease in red meat consumption, the average reduction was 1.47 portions a week— an approximately 15-20% reduction in red meat consumption—with multi-part interventions proving the most successful.[45] Given that these studies monitored outcomes only over several weeks, took place only in European and North American countries, and involved small numbers of participants receiving personalized attention and often self-reporting outcomes, it seems unlikely even these modest gains would translate to lasting reductions at anything near a global scale.[46,194] In another systematic review of interventions to promote low-footprint proteins, interventions were similarly laborious: personalized nutrition advice or counselling; group sessions over the course of months; lessons on shopping, cooking, and mindfulness; follow-up calls and telephone consultations.

The emphasis on animal production reform

Perhaps because shifting diets seems so difficult and unlikely, quite a bit of attention has been given to making production of ASFs more sustainable. One study found that over 90% of experts in food systems believed their country was focused on altering how food was produced or tackling food loss and waste, with less than 10% focused on diets or nutrition.[14] The animal agriculture industry also tends to focus on technologies that could make meat production more sustainable.[52]

What exactly is regenerative grazing?

Though somewhat fluidly defined, regenerative grazing seeks to enable domestic animals to better mimic the behavior of wild herds of ungulates, with aspirations for three central mechanisms of impact: breaking up soil through greater hoof action; grazing evenly for a short period with long periods of recovery in between; and the distribution of nutrients through animal excreta.[53] Alterations of the timing and density of livestock grazing are intended to improve productivity while offering a host of sustainability benefits: improved soil carbon sequestration, increased soil water content, and increased grass productivity due to greater nutrient flow. [2,53,56] All of this is claimed to help improve biodiversity.[58]

Additional ecological effects of regenerative grazing

The review found some evidence of higher carbon sequestration in C4 (more heat-tolerant) grasslands but noted that these calculations didn't account for the additional emissions coming from livestock;[56] another review found that rigorously case-controlled studies with multiple measurements show no statistically significant improvement in carbon sequestration from regenerative grazing.[195] Overall, the diversity and abundance of birds, amphibians, and mammals decrease consistently with increased stocking rates of livestock, including in regenerative grazing settings;[56] there isn't support for the claim that regenerative grazing leads to larger and more diverse faunal populations.[53] The greater land required by regenerative grazing would better serve biodiversity if maintained as natural habitat.[57]

Environmental effects of further intensification of animal agriculture

Intensification occurs on a spectrum, moving from completely pasture-raised livestock on one end towards industrialized farming operations with thousands or even hundreds of thousands of animals raised in confined spaces on the other, with various degrees of mixed production in the middle.[59] The basic idea is to gain efficiencies through standardization and economies of scale, treating animals as production units to be optimized. An industrial production system involves confining animals to a relatively small space like a stall or feedlot where they are fed an optimized diet including silage, high-quality concentrates, feed supplements, vitamins, and medicine. Since the digestibility of feed provided is greater than pasture, methane emissions from cattle are reduced and animals produce more meat or milk, generally leading to a reduction of methane emissions per unit of product that offsets the increased emissions from producing optimized feed.[59] Compared to free-range cattle in the US, feedlot-finished beef cattle are believed to emit 47% less methane,[61] and intensification can reduce total emissions from dairy by about 10%.[64] One estimate suggests that global GHG from beef and dairy could be reduced by 17-32% through best-practice intensification.[59] Intensification also generally makes animal production more land-efficient.[2,98] A global shift of cows from pastures to feedlots and stalls could reduce the land footprint of beef by 35-73%.[59,61] These could constitute substantial environmental gains, and since intensification can be accompanied by increased profits, many of these benefits could potentially be scaled by market forces.

But there are several reasons to temper hopes for major gains for biodiversity. First, there are several questions related to bookkeeping: intensification of animal agriculture has been an ongoing process since the last century, and many models of business-as-usual climate and land use change have already assumed that it will continue.[2,32,34,36] Thus, at least some gains from intensification do not get us closer to our target reductions. This matter is further complicated by questions about whether the projected emissions savings from intensification are overestimates or underestimates. In the main text, we mentioned the study finding that emissions from industrial farms may be 39-90% higher in reality than previously estimated based on bottom-up assessments: housing animals at high densities may lead to higher-than-expected increases in emissions from manure management and indigestion by cattle made ill by living at high densities.[59,62] Another study found that life-cycle analyses may underestimate soil carbon release caused by production of high-quality feed, and that, in many scenarios, increased land-use change in the tropics driven by demand for more concentrated feed can mean that intensification leads to a net increase in GHG emissions.[64] In essence, intensification trades off one type of ASF-related pollution for others, and interventions to address these additional emissions (e.g., [196]) may not boost productivity or profits, making them more difficult to scale than intensification itself. Furthermore, more efficient meat production makes ASFs cheaper, meaning suppliers may produce more meat, reducing sustainability gains.[60] As intensification does not fundamentally address the core problems of animals as a source of food—namely, their inefficiency and pollution—the gains it offers are limited. One assessment found that even 100% acceptance of the most sustainable intensification interventions would not enable low- and middle-income countries to meet their 1.5C targets by 2050, as any gains are offset by increased methane emissions due to greater demand for meat and milk.[12] Such universal intensification is anyway unlikely due to infrastructure and capital constraints.[59,60]

Feed additives

Feed additives demonstrate the sustainability limitations and scalability problems of even the most promising efforts to reform animal production. Methane release by ruminants is a primary reason that they are so much worse than other ASFs for the climate, accounting for 30-70% of their GHG emissions across the intensification spectrum.[10] Thus feed additives that reduce or eliminate methane emissions from cattle by blocking the activity of methanogenic bacteria in their guts could dramatically reduce their climate impact.[12] A variety of feed additives exist, most decreasing methane emissions by about 12-32% [12,197]—but the most effective additives, red algae from the *Asparagopsis* genus, decrease methane emissions per unit product from beef by 67-98% and from dairy cattle by 30-35%.[66] The primary active ingredient, bromoform, inhibits methanogenesis even when red algae forms only 2%-10% of feed.[66] Despite the reductions of methane from red algae additives,[66] they are unlikely to result in the improvements necessary to bring ASF emissions down by 2/3 by 2050 for three reasons.[12] First, the actual gains of using feed additives will be lower once the GHG costs of growing, harvesting, processing, storing, and transporting seaweeds on large scale have been included [60]—bromoform in particular can catalytically destroy ozone, complicating the environmental calculations for at least this key additive.[66] Second, methane emissions only constitute one of the many inefficient and polluting aspects of meat production, meaning beef would still involve a massive land footprint and remain worse for the climate than poultry and pork;[10,64] feed additives are also generally impractical for pasture-raised cattle.[60]

Most importantly, feed additives are unlikely to scale because they don't offer consistent benefits to cattle producers or consumers.[60] Even if the cost of red algae were to be reduced to less than $5 USD a kilogram, the cost of feeding cattle would increase about 20% due to these additives.[66] So far, none of the major additives tested offer consistent productivity gains to offset the additional costs of additives, meaning that ASFs produced with these more sustainable tools will be unable to compete with less sustainable products. Furthermore, long-term exposure to bromoform may cause liver and intestinal tumors in livestock, threatening farmer profits.[60] Unless sustainability gains can be linked to lower costs for consumers and profits for producers, scaling such interventions would—like diet change—rely on changes to regulation or consumer preferences. The question is whether innovation may result in additives that both reduce methane emissions and improve productivity. Given various constraints around cost, environmental footprint, human health, and animal health,[66] the path to success for such innovations is narrow.

Insects as feed

As noted in the main text, the proposal that insects grown on waste streams be used as feed is a leading idea for creating a more circular food system. For instance, it has been proposed that BSFL raised on pig or cattle manure could reduce both emissions from animal waste and reliance on plant-based feeds,[68,69] helping address two of the five aspects that make ASFs less sustainable than plant-based foods. Since insects are ectothermic ("cold-blooded"), they are more efficient at converting input into output than our warm-blooded livestock in ideal conditions, presenting a plausible opportunity to convert waste into feed for a low environmental cost.[67,71]

Also as we noted, a review of 352 studies found that such results were generally driven by unrealistic or unjustified assumptions.[67] At its core, insect agriculture appears to present a trade-off: insects can either be grown quickly and efficiently using nutritious feeds, or slowly using waste streams.[67,72] This fundamental problem is aggravated outside the tropics: most insects require temperatures of 25-30 degrees C to thrive,[67] meaning that insect agriculture outside the tropics requires increased emissions from facility heating.[68,71] All this isn't to say insects can't *ever* improve the sustainability of ASFs [70]—just that there is considerable variability, with insect-based feeds generally having a larger footprint than soy- or fish-meal.[67] For instance, in one context, BSFL raised on pig manure and fed to chickens did lead to a small reduction in acidification potential (but not carbon emissions or water use) compared to soy and fish meal.[68] Since facility heating contributes substantially to carbon emissions, renewable energy can help reduce the footprint of insect production. However, the conditions under which insect-based feed offers such benefits are limited, and the benefits themselves do not appear to be of the magnitude necessary to meet biodiversity requirements. Finally, insect-based feed is not yet cost-competitive with legacy feeds, impeding scalability of benefits. While in principle exploration of other insect species or genetically modified insects could address some of these problems,[69] these may pose a different ecological concern: the prospect of insect escape into natural systems, where non-native or genetically modified insects may pose unintended consequences to a region's biodiversity. Unlike a runaway cow, escaped insects may be impossible to capture before they multiply.[67,198] If insects can in fact help reduce the footprint of ASFs, a variety of problems related to sustainability and cost must be simultaneously addressed.

What if we just ate insects directly?

Over two billion people are believed to eat 1,900 species of insects worldwide,[199] and insect protein has been used in protein powder, crisps, crackers, energy bars, cookies, pasta, bread, and even burgers.[67] In fact, a buffalo fly-based burger by the company Bugfoundation outperformed pea, soy, and mycoprotein-based burgers in blind taste tests.[96] All this suggests insects blur the lines across our three strategies—eating more insects could (in some cultural contexts) be seen as a form of conventional diet change, insect-based feed could be seen as reform of ASF production systems, or insect-based products that mimic the taste of meat could be seen as a disruptive novel replacement like alternative proteins.

Insect-based foods present both sustainability and scalability challenges. While early life cycle analyses found insect protein to be 26-69% more land- and carbon-efficient than plant-based and fungal proteins,[95,96] these analyses were based on the assumption that insects would be fed from waste streams but grow at the same rate as they would if fed human foods like carrots, wheat bran, and oats.[72,200] As with insect-based feed, this ignores the slower growth rates and higher mortality of insects grown on waste streams;[67,72] ultimately, a review of LCAs found that insects at present have ecological footprints that vary widely but largely resemble those of other animal products.[67] All this suggests that, despite their markedly different physiologies from our usual food animals, insects might broadly belong in the "animal-sourced food" category. Just like any other animals, they act as largely inefficient middle-men between us and plants.

Furthermore, insects face unique scalability challenges. Consumers in multiple contexts are particularly averse to eating insect-based meat analogues.[96,200–203] This lack of social acceptance is why only 5% of investment in industrial insect agriculture has been geared towards human consumption. [200] Since eating large volumes of insects appears to not appeal to consumers, food producers have tried to normalize the consumption of insects by making snacks with some insect protein. Unfortunately, since insect protein is largely replacing plant-based proteins in these products, they actually *increase* the footprints of these foods.[67] Since it is unclear whether consumers will ever move from insect-based snack bars to insect-based burgers, and insect agriculture is presently not *that* sustainable, insects are unlikely to be the best approach to protecting biodiversity.

Precision fermentation and cultivated meat: less mature technologies

In contrast with plant-based meats and biomass fermented products, precision fermentation and cultivated meat represent less mature technologies. This means both that the production of these alternative proteins is less refined and efficient, and that any effort to estimate the ecological footprints of these products when they are produced at scale involves significant assumptions. At present, life-cycle analyses suggest that the ecological footprints of precision-fermented products only improve on those of ASFs in some contexts, especially with respect to climate and water effects. A study on the land requirements to produce a precision-fermented milk protein used in a wide variety of products (beta-lactoglobulin) found they were 99% less than the land required to produce the protein from cow milk,[117] and land savings from precision-fermented ovalbumin, a key egg protein, were 87-89%.[119] These two studies also found notable greenhouse gas emissions savings ranging from 31-69% largely based on geography.[117,119] A third study comparing precision-fermented lactoglobulin to milk protein from efficient dairy herds in New Zealand found the former would result in emissions savings of 19-36% in New Zealand, but emissions 5-52% higher in Australia and Alabama, USA. In Germany, emissions were 14% less than New Zealand dairy if the genetically modified *Trichoderma reesei* fungus was fed sucrose but 17% more than animal dairy if the fungus was fed glucose.[118] Geography also matters when it comes to scarcity-weighted water use, with fermentation for ovalbumin reducing scarcity-weighted water use by 86 percent in Germany and increasing water use by 26% in Poland.[119] Depending on location and the feedstock used for beta-lactoglobulin, scarcity-weighted water use could decrease 81% or increase by ten-fold.[117,118] The biggest cause of variation in carbon footprint was the percentage of electricity generated by renewable energy, which varied across locations.[118,119] All in all, whether precision fermentation outperforms ASFs depends on location and production methods, at least with respect to egg and dairy proteins. As these are among the least polluting animal-sourced foods, one may expect bigger benefits when precision fermentation is able to help replace other meat- or fish-sourced ingredients and products.

Since the cultivation of animal cells for food is an even more novel technology than precision fermentation, efforts to estimate the ecological footprint of a mature cultivated meat industry involve considerable uncertainty. Researchers conducting LCAs must make assumptions about, for instance, the nature and grade of inputs animal cells will ultimately need for growth at scale, the energy and material costs of sterilizing the media that nourishes cells, the conversion rate of media to animal cells, the mass that animal cells will ultimately gain in media, and the ecological footprints of waste streams from production.[114,115] As a result, it is unsurprising that LCAs of cultivated meat over the years have come to drastically different conclusions.[95,114,115,204] It is also remarkable that the most rigorous LCAs—one more optimistic,[115] one more pessimistic [114]—seem to be in broad agreement about the approximate environmental footprint of cultivated meat in the coming 5-10 years. On land use, cultivated meat is likely to substantially out-perform ASFs, using 55-67% less land per kilogram of meat than chicken, pork, and beef from dairy cattle and 90% less land than beef from beef cattle.[115] The same authors find notable improvements over conventional meat in terms of fine particulate matter and acidification, and that cultivated meat will use 15-87% more blue water than chicken, pork, and dairy beef and 66% less blue water than beef cattle.[115] The biggest question mark at present seems to revolve around climate impacts and electricity use, where there has been more scrutiny. The lower estimates of the pessimists (12.3-19.2 kg CO_2-eq per kg of meat) and the main estimate of the optimists (14.3 kg CO_2-eq per kg of meat) are very similar, with both effectively falling between the lowest carbon footprints of dairy beef and beef from beef cattle and exceeding the carbon footprints of other meats.[114,115] But the researchers vary dramatically in their assessment of the likely environmental footprint of the media used to grow cells. The optimists rely on the assumption that cultivated cells will be able to acquire most of the amino acids they need from soy hydrolysates instead of amino acids produced through precision fermentation; the latter would mean that the environmental impacts from precision fermentation (discussed above) would form the floor of cultivated meat's impacts, and total GHG emissions could be 5-10 times those estimated in their study.[115] At the other extreme, the most pessimistic projections rely on the assumption that cultivated animal cells will continue to use growth media optimized for other purposes and require inputs purified to pharmaceutical grade-levels, and they assume this will increase emissions by a factor of 20.[114] While this is almost certainly too pessimistic,[205] the studies do seem to ultimately agree that cultivated meat could very plausibly have a carbon footprint considerably lower than that of beef cattle and most dairy cattle if scientists can figure out a safe and efficient way to provide cells the feed they require to grow. There are also additional challenges around the development of bioreactors much larger than those currently available in the pharmaceutical industry (and related sterility challenges)[114] and the likely considerable nitrogen pollution that will come from waste streams.[144] And even the most positive projections suggest cultivated meat will not soon rival chicken in emissions.[115]

There is room to source inputs for precision fermentation and cultivated meat from nearby,[98,99,118] transition to more sustainable ingredients,[98,117] make conversion of feedstocks more efficient through improved strains,[99,206] develop more sustainable fractionation and extrusion methods,[98] and improve the sustainability of refining factors.[99] Companies in the synthetic biology space are also developing new growth factors that can be used at lower concentrations, media that requires no complete proteins at all, and new adherent bioreactors that allow animal cells to grow in a context more like that found in nature.[207–209]

Modeling the environmental outcomes of alternative proteins at scale

When one considers the potential sustainability benefits of replacing ASFs with existing plant-based and mycoprotein products, the prospective gains seem commensurate with the changes needed to protect global biodiversity. Four projections (three of them peer-reviewed) independently examine how the environment may be affected if alternative proteins supplant ASFs at scale: the replacement of beef with plant-based meats in the US;[40] the replacement of animal proteins with an alternative protein with properties averaged across four products in the US;[150] the replacement of beef with sugar-fed mycoprotein globally over the coming decades;[35] and the replacement of beef, pork, chicken, and milk with plant-based alternative proteins through 2050, assessed using the GLOBIOM model.[34] Consider the projections for habitat. All studies find that substitution reduces forest loss,[34] with a 20% global substitution of mycoprotein for beef reducing deforestation for pasture by about 100Mha and a 50% reduction further reducing or even fully halting the conversion of natural land for agriculture.[34,35] The Congo Basin, Central America, and the Amazon Basin benefit the most from these shifts.[35] Two studies find a 12% decline in the area under agriculture if half of the examined ASFs are replaced.[34,40] A 50% substitution of beef with plant-based meats in the US should release an area about the size of Georgia from agriculture,[40] and a 50% substitution across all animal proteins with the average alternative protein should release an area 20% bigger (about the size of the state of South Dakota).[150] Substituting 50% of beef with mycoprotein globally will release a little less than 100Mha of pasture globally by 2050, while a 50% substitution of ASFs with plant-based meats may liberate as much as 653Mha of land from agriculture [34]—an area the size of India, Argentina, and Cameroon combined. The assessments of likely emissions reductions vary more widely, with the oldest study suggesting the 50% replacement of the studied ASFs would result in a net reduction of 6% in US food system emissions [40] and the more recent global assessments placing estimated reductions at 31-83%.[34,35] In the most comprehensive assessment, researchers find that if land released from agriculture is restored to natural ecosystems, the net reduction in carbon emissions from business-as-usual would be 62%, "reaching 92% of the previously estimated land sector mitigation potential".[34] In aggregate, the land and emissions gains are roughly those required to limit warming to within 1.5 degrees C,[32] perhaps leaving enough ecological space to also relieve pressure on fisheries through the production of alternative seafood. Fifty percent transitions from ASFs are also estimated to result in a 5-10% reduction in agricultural water use.[34,35,40]

The two studies that directly examine the matter find these shifts should benefit biodiversity. In the US, a fifty percent shift from all ASFs to alternative proteins could help enable restoration in 64% of 216 threatened forest, grassland, and wetland ecosystems.[150] Internationally, the 2.1% decrease in the Biodiversity Intactness Index forecasted for 2050 in the business-as-usual scenario is reduced by 57% if half our ASFs are replaced with plant-based meats. If 90% of our ASFs are replaced with plant-based meats, the reduction in biodiversity intactness would be just 0.3% by 2050, with biodiversity actually beginning to bounce back between 2030 and 2040. These gains are especially concentrated in crucial parts of the world: sub-Saharan Africa, Brazil, and the rest of South America would have the largest share of spared and restored land, and sub-Saharan Africa, China, and Southeast Asia would gain the most in terms of biodiversity intactness.[34] Notably, about half of the gains achieved by substituting beef, pork, chicken, and milk can be achieved just by replacing beef.[34]

(More) caveats about ASF – AP sustainability comparisons

Since assessments of the sustainability of alternative proteins are often based on projections, the assumptions made in these LCAs heavily influence results. Sometimes, comparisons of environmental impacts have been made between processed alternative proteins and unprocessed ASFs.[172] As noted, assumptions regarding how alternative proteins will be produced at scale are often needed to allow fair comparisons with ASFs (e.g.,[118]). Decisions about how to allocate emissions to different outputs from a production process in a life cycle analysis—based on mass or based on price—can change the estimated environmental savings.[119] These life cycle analyses also do not capture the likely environmental costs of replacing other animal products, like leather.[35] Finally, a shift to alternative proteins may result in a reduction of cropland compared to the business-as-usual scenarios,[34,35] but even optimistic projections predict that we will still require an expansion in croplands from the current baseline, meaning that work must still be done to address concerns due to inputs like pesticides.[97] Research must also be done on minimizing waste streams from alternative proteins.[126]

Still, as demonstrated by both the numerous peer-reviewed articles and critical assessments of cultivated meat [114,144] and precision fermentation,[118] the scientific community is independently assessing these novel technologies. Overall, research from unconnected institutions show plant-based meats, biomass-fermented products, and precision fermentation (in some contexts) to be far more sustainable than ASFs, and the findings are consistent with our understandings of the inefficiencies and polluting nature of ASFs compared to plants, bacteria, and fungi.[97]

The Green Revolution as a precedent for an alternative proteins transition

While the forecasted land savings at scale—about 653Mha—may seem fantastical, they square roughly with our experiences from the Green Revolution. Yield increases of 36-208% for crops like wheat, rice, and maize from the 1960s onwards have prevented large areas of natural habitat from being deforested.[210] One global assessment found that the Green Revolution helped protect 144Mha of natural habitat from being deforested,[211] while another assessment just of improvements in productivity from 1991 to 2010 found that productivity improvements prevented about 173 Mha of deforestation—close to 10% of the area covered by tropical rain forests.[212] These gains came just from improving the productivity of plants, which are already efficient, and against the backdrop of major increases in the production of ASFs—it is reasonable to expect the gains from replacing animals with alternative proteins would be on the order estimated by studies so far.

Some specific key areas for innovation in alternative proteins

Studies suggest that 20-40% of ingredient costs go to modifying the flavors of the (mostly plant) protein ingredients used in the products so that they taste more like ASFs. These expenses are necessary because fit-for-purpose ingredients do not exist on the marketplace—there has not been adequate effort to create varieties of soy, pea, chickpea, or other ingredients that have flavor profiles suitable for alternative proteins products.[126] In essence, alternative protein companies are doing the equivalent of building electric vehicles with the parts of an internal combustion engine. Yet developing inexpensive ingredients with better flavor profiles is feasible,[213] either through traditional breeding methods or genetic modification of high-protein crops. Furthermore, there are many different ways to tackle the remaining challenges faced by alternative proteins. For example, the microbes most frequently used for biomass and precision fermentation are unlikely to be the best ones available; researchers could seek out improved strains through directed evolution of species currently popular in food science, explore microbes used in traditional fermentation around the world,[214] or screen the world's abundant biodiversity for new compounds and species that can serve specific roles in taste and texture. In contrast to the highly constrained problem of, say, feed additives for reducing methane emissions, there are likely multiple ways to help achieve taste- and cost-competitiveness for novel replacements.

Can alternative proteins scale in the same way as solar when food is so different?

What if consumers respond differently to novel foods than new gadgets and gizmos? This question is effectively about social acceptance, and whether there is a path to normalize the substitution of ASFs with alternative proteins in our burgers, filets, and deli sandwiches. There is no guarantee that novel replacements will fulfill their ecological potential—but the international nature of commodity meat products and global diversity of consumer interests offer countless opportunities to normalize the substitution of ASFs with alternative proteins. As much as 60% of beef products are comminuted, processed, or minced,[92,93] and consumers already accept mixed products in which plant-based protein extenders (pulses, cereals, tubers, fruits, mushrooms) replace up to 50% of the meat in these products.[215] Such blended products can then also help consumers become accustomed to alternative proteins in their diets. The evidence that ASFs—especially red meats—are often less healthy than their plant-based and fermented replacements provides a ripe opportunity to promote substitution;[216] a review of over 90 studies in Western countries found that health was likely to be one of the most central consideration when picking food after taste, and a substantial proportion (21% in one study) say they would purchase a plant-based burger instead of an animal-based one if they tasted the same.[202] Policies like those passed by Los Angeles county, which require that all departmental food procurement be plant-based by default for health and sustainability reasons show that such substitution is being mainstreamed. Finally, if culture wars in one place impede progress, the international domination of a few ASFs mean that novel replacements can go elsewhere to continue the drive towards low costs and consumer acceptance, like solar power did when the US turned its back on the technology in the 1980s.[130] For instance, a study shows that Chinese and Indian consumers may be more willing to swap out meat for plant-based or fermented analogues.[131] Notably, consumers in multiple contexts seem to be substantially more willing to switch to plant-based alternative proteins than cultivated meat,[96,202,203] though this may change as cultivated meat products become more familiar.

Priority actions for the conservation community

What alternative proteins technological development requires

For technologies that are still in early stages [217]—for instance, precision fermentation, cultivated meat, and molecular farming—technology push investments like funding for new labs, focused research organizations, building human capacity, and even demonstration-scale production facilities can help fund the basic research necessary to overcome key hurdles to market.[137] For later-stage technologies like those involving some plant-based meats, demand-pull interventions that incentivize private investment like production tax credits, guaranteed tariffs, or public food procurement may be the most effective.[25,218] Alternative proteins could learn from the Roadmap for Semiconductors, an industry-wide committee that ensured innovation tracked with Moore's law, or the US Renewable Fuel Standard program, which coordinated the displacement of oil with biofuels in the US.[144] Once technologies are advanced enough to compete on the market, international donors like the Green Climate Fund and World Bank could help derisk the development of new infrastructure, just as they have in the solar, wind, and battery sectors.[91] Policies that help make alternative proteins more competitive without increasing prices for voters should be more achievable than those that attempt to place a price on externalities. Of course, whenever possible, chipping away at direct subsidies for fishing, beef, and other ASFs could also make alternative proteins more attractive to consumers.[25]

Improving LCAs for alternative proteins

At present, there are several notable problems with available life cycle analyses. First, there aren't enough of them, even for more advanced alternative proteins like plant-based meats and mycoproteins.[99,172] Relying on a small number of LCAs is not ideal because many are developed by organizations with an interest in portraying their production systems as sustainable, and because environmental outcomes can vary dramatically based on geography.[72,99,118,119,172] The lack of geographical representation is a problem beyond novel replacements: there is also a shortage of LCAs on conventional agriculture and ASFs from some parts of the world. Most LCAs on dairy and beef are concentrated in Europe, North America, Oceania, and Brazil,[59] with a particular shortage of LCAs from Saudi Arabia, Kazakhstan, or Mongolia likely exerting a downward bias on emissions estimates from ruminant land use.[10] Conservation organizations could also help ensure that LCA methodologies are standardized to allow fair comparisons among alternative proteins and between alternative proteins and ASFs;[97] LCAs should comprehensively address the environmental impacts of all proteins, as improvements in one part of the process could result in more pollution or inefficiency at other points.[60] Conservation organizations are also well-situated to incentivize participation in LCAs, as favorable findings could help sustainable producers gain support.

Ensuring production of alternative proteins benefits biodiversity

As the alternative proteins industry begins scaling up production, conservation organizations should ensure that production facilities are seeded where the biodiversity benefits are the greatest. Priorities can be based in part on environmental effects elucidated through life cycle analyses, which should include geographically explicit considerations of resource use,[42,64] but should also include considerations of livelihoods and political economy. Some production systems may incentivize people to leave industries that threaten biodiversity, like cattle ranching and mining. Others, like palm oil, could have the opposite effect, incentivizing further habitat destruction. Historically, the effects of new agricultural technologies on forests have depended on four factors: whether they increased productivity in areas already occupied by people or near forests; whether the technological change required more or less labor; whether demand for the agricultural products in question were elastic; and whether the product and region in question were exposed to global markets. [157,212] Technologies that enable production of goods with elastic demand or for export in biodiverse areas have led to more habitat destruction, encouraging people looking for work to expand agriculture into forests and grasslands.[157,219] This is in effect what happened with palm oil in southeast Asia and with soy in South America,[97,219] with agricultural expansion coming at the expense of extraordinarily biodiverse rainforests. At this stage, what these historical trends mean for alternative proteins is ambiguous for two reasons. First, it is too soon to know whether the most successful inputs and feedstocks for these products will be crops that are likely to expand into biodiverse areas. More compellingly, because alternative proteins may compete directly with less land-efficient ASFs, it is plausible that a transition from ASF production to alternative protein production in biodiverse regions would actually lead to a net reduction in habitat destroyed for agriculture. There is evidence for this possibility in Brazil: two separate studies found that, when agriculturalists were exposed to economic incentives to shift from cattle ranching to farming of crops, deforestation decreased.[145,146] Of particular interest is a study in Tapajós, Brazil, which found that, as the ratio of the price of soy to the price of beef increased, credit-constrained farmers controlling land invested more in soy production, hiring those that otherwise would have been active in deforestation. A 2.6% increase in soy cultivation helped prevent the deforestation of 5,300 sq. km of forest in the Tapajós Basin from 2002 to 2012.[145] In essence, a more land-efficient protein industry took resources from a less land-efficient one. If alternative proteins can take global market share from beef, models indicate a similar phenomenon should occur,[34,35] with land sparing happening both globally and in any place where habitat destruction for cattle is occurring—even if the crops for the new alternative protein products are grown in the same place. Nonetheless, conservation organizations should try to ensure a new alternative proteins industry establishes where governance can help safeguard biodiversity. [35,157] This does not restrict the new industry to the Global North, but requires a more nuanced analysis. Research has found that the Round Table on Sustainable Palm Oil and the Brazilian Soy Moratorium have been more effective at preventing deforestation than the G4 Cattle Agreement, [97,220] suggesting that intensive crop agriculture may be more susceptible to effective regulation than extensive cattle ranching. Thus, even where crop agriculture presents local biodiversity threats, those threats may be easier to mitigate than those of livestock.