Why conservation organizations must support alternative proteins

Animal-sourced foods pose the greatest threat to our planet's biodiversity. Alternative proteins offer the most promising—and under-resourced— solution to saving wild nature.

Note to readers: This is a Conservation X Labs working paper, written with help from several partners. Our goal is to ultimately publish this as a white paper in collaboration with other conservation and sustainability researchers, practitioners, and institutions dedicated to food system transformation for biodiversity. If you would like to participate in refining and publishing this report, please contact Nitin Sekar (nitin@conservationxlabs.org). We also very much welcome critical feedback and any evidence that differs from our thesis.

Executive Summary

The problem of animal-sourced foods

Animal-sourced foods (ASFs) are a leading threat to biodiversity because animals are an inefficient and polluting source of food. On average, farmed animals consume 16 calories for every calorie and 12 grams of protein for every gram they provide to humans. Agriculture occupies about 49% of the planet's ice-free land; ASFs use about 83% of agricultural land while supplying just 18% of calories and 37% of protein. 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. This could free up massive tracts of land for wildlife. ASFs also deplete and pollute water (two-thirds of freshwater withdrawals; 78% of eutrophication) and accelerate climate change. Agriculture accounts for 31–35% of global GHGs, and 57% of agricultural emissions are from ASFs. Overfishing is the leading cause of marine biodiversity loss and the second most frequent threat to freshwater species after habitat degradation. All these problems are on track to worsen: demand for ASFs is expected to rise 68-76% by 2050, resulting in major expansion of cropland and pasture, largely in tropical, species-rich regions. While solutions are on the horizon for energy use and transportation, there is no apparent off-ramp for our consumption of animal-sourced foods.

Strategies for food system transition

Conservation organizations have not sufficiently addressed the challenge of food system transition. Achieving consensus habitat restoration and protection goals in the Kunming-Montreal Global Biodiversity Framework and limiting climate change to within 1.5-2 degrees C require major modifications to our food systems, including reductions in food system emissions by about two-thirds from business-as-usual trajectories and restoring about 585Mha of land to natural habitats by 2050. Three broad strategies

could reduce the impacts of ASFs: (1) conventional diet change toward plant-based foods; (2) animal production reform to lower harms from livestock and fishing; and (3) disruptive replacement with alternative proteins that taste like ASFs but are made without (full-bodied) animals. We assess the prospects that each strategy will result in change of the magnitude necessary to achieve biodiversity and climate objectives. Given the diversity of food systems and the uncertainty around intervention effectiveness, a mix of approaches will be needed moving forward. While all three strategies involve deep challenges, alternative proteins are unique in their potential to provide major environmental benefits at scale via market mechanisms.

Conventional diet change

From a sustainability standpoint, widespread conventional diet change would be the best: shifts toward vegetarian or vegan diets free land and water and could reduce food-system emissions dramatically (up to 70% with reforestation). The challenge is scaling up, which requires consumers to learn to buy and cook new foods and willfully develop new tastes. Regulations to encourage such diet change—including by reducing subsidies for animal agriculture or pricing externalities—appear politically difficult to implement in most countries. Many interventions focused on persuasion and awareness are intensive and setting-specific, yielding modest, likely short-run reductions that (even if scaled) would be unlikely to result in required emissions reductions. Even cancer survivors that have a great deal to gain from change tend to reduce red meat consumption by just 20-30%, far less than the targets necessary for biodiversity. Choice-architecture interventions such as green defaults and institutional "Veggie Days" have proven more successful, particularly in educational settings. However, these successes are unlikely to be representative, and trying to scale them up will likely result in similar political barriers to regulatory reform. Conventional diet change interventions should be implemented wherever they are tractable—but may not be an effective primary strategy for conservation.

Animal production reform

Prominent proposals (e.g., regenerative grazing, intensification, feed additives, insect-based feeds, reduction of food loss and waste, improved fisheries governance) present either sustainability trade-offs or scaling limits (or both). Evidence for regenerative grazing benefits is inconsistent at best, and any benefits come at the expense of land that does not support biodiversity. Further intensification of animal agriculture can reduce some per-unit impacts but aggravate other environmental costs; where sustainability doesn't correspond with profits, it is unlikely to be implemented, and interventions that reduce prices could result in rebound effects that increase overall impact. Potent methane-reducing additives (e.g., Asparagopsis) face cost and practicality challenges, and they may pose problems to animal health, human health, and the environment. In principle, insect-based feeds produced on waste streams could reduce the impact of omnivorous farmed animals, but in practice, insects raised on variable waste streams tend to grow too slowly and experience higher mortality. Cutting food loss and waste (FLW) is valuable, with several interventions likely to scale with the market and enjoy popular support—but since FLW is scattered across the supply chain, comprehensively addressing FLW is challenging. Furthermore, even addressing all FLW would not allow us to achieve required climate targets, and rebound effects (reduced losses should mean lower prices) could offset over 50% of environmental benefits. Fishery management is also difficult to scale, and even optimally managed fisheries add only limited supply relative to projected demand. Many of these interventions (especially FLW reductions) offer important pieces to the puzzle—but reform of existing animal production systems is unlikely to achieve required results.

Disruptive replacement with alternative proteins

Alternative proteins offer a unique combination of sustainability benefits and prospects for reaching scale. Plant-based meats and biomass-fermented proteins already offer large average footprint reductions compared to ASFs in terms of land, carbon emissions, water use, and eutrophication. Modeling indicates that substituting 50% of key ASFs can halt most agricultural expansion, free vast areas (as large as India, Argentina, and Cameroon combined) for restoration, cut land-sector emissions deeply (62% including restoration), and measurably improve biodiversity intactness—especially in the tropics. Precision-fermented and cultivated products are earlier-stage; their impacts hinge on energy mixes, feedstocks, process design, and the geography of production, but both will improve substantially as grids decarbonize. As early-stage technologies, alternative proteins have major scope for improvements in efficiency and sustainability, far more than ASFs that have been optimized over centuries and are constrained by the physiological limits of full-bodied animals. The same efficiencies that make alternative proteins more sustainable should gradually help make them less expensive to produce than ASFs. When analyzed in comparison to other low-carbon technologies, alternative proteins enjoy low design complexity and require limited customization across contexts, meaning they most resemble solar panels and LEDs in propensity to scale. Photovoltaic cell costs decreased about 22.5% with each doubling in production capacity—at this rate, alternative proteins could become cost-competitive with ASFs reasonably quickly. As costs fall, alternative proteins can scale more effectively via markets. Several products are nearing taste parity in common formats, and there will be multiple avenues to gain social acceptance: a large proportion of consumers are likely to ultimately embrace a cheaper product that tastes and looks the same (and likely offers other benefits) as ASFs, at least in many contexts. Blended products and beachhead markets could ease the transition.

What conservation organizations can do

At present, technology is the primary barrier to alternative proteins reaching taste- and cost-parity with ASFs. As respected leaders in sustainability, conservation organizations have a key role to play in helping expedite the development of novel replacements and their social acceptance by a broad swathe of consumers. We also should carve out a role as technical advisers that ensure any new industries that grow from this disruption serve the interests of biodiversity conservation.

Making alternative proteins central to sustainability

Conservation organizations should work with the broader sustainability community to make sure alternative proteins reach maturity faster than solar power technologies did. Together, we should elevate alternative proteins across climate and biodiversity agendas; use procurement, standards, and open innovation (e.g., prizes) to accelerate core ingredients, processes, and adoption; and secure public R&D and demand-pull policies commensurate with the opportunity.

Ensuring alternative proteins serve conservation

In parallel, conservation organizations should also prepare to play three crucial technical roles to ensure that a transition towards alternative proteins leads to favorable biodiversity outcomes. We are uniquely incentivized to ensure that alternative proteins improve in terms of sustainability outcomes by, for instance, fostering a more advanced community of experts to perform third-party life-cycle analyses. Since geography determines environmental results, we can also ensure that the industry establishes its production centers to optimize benefits for biodiversity. Finally, since conservation has a strong connection with agricultural communities worldwide, we should help enable socially just livelihood transitions while fostering biodiversity conservation in areas liberated from animal agriculture or industrial fishing.

1. The problem of animal-sourced foods

Animal-sourced foods (ASFs) are arguably the greatest threat to the planet's biodiversity (1, 2). ASFs are leading drivers of the destruction of habitat, climate change, and the direct overexploitation of wild species (3–5). At the heart of the problem is that animals are a highly inefficient (6–8) and polluting (8) source of food. On average, farmed animals consume 16 calories for every calorie and 12 grams of protein for every gram they provide for consumption (9). Similarly low conversion rates limit the populations of wild carnivores and large-bodied species, making them particularly vulnerable to overfishing and overhunting (10–12). During their lives and slaughter, domestic animals produce large amounts of waste that dramatically alter our atmosphere, soils, and waterways (13). While animal agriculture, hunting, and fishing are ancient human vocations, they are unsustainable in a world with billions of people eating more animal-sourced foods than ever before (1, 14).

The transformation of the planet's ecosystems for agriculture provides the most visible evidence of how ASFs affect biodiversity. Agricultural lands occupy about 49% of the planet's ice-free terrestrial surfaces, compared to the just 1% used for urban areas (15). 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 (16); from 1990-2010, 61% of global forest loss was due to commercial agriculture (17), and 83% of new agricultural lands developed in the biodiverse tropics between 1980-2000 came from forests (18). Habitat loss and degradation decreases and fragments the area a species can occupy, resulting in smaller, more genetically isolated populations (14, 19). Agriculture is responsible for about 90% of habitat loss in global biodiversity hotspots over recent decades (20), and agriculture-driven habitat loss imperils 80% of all terrestrial threatened bird and mammal species (14) and is responsible for 74% of biodiversity loss within key biodiversity areas (KBAs) (21).

Animal-sourced foods are the primary cause of this habitat loss: meat, aquaculture, eggs, and dairy use up about 83% of agricultural lands while providing only 18% of calories and 37% of proteins from agriculture (17). This means farmed ASFs are—on average— 22 times less land-efficient than plant-based foods as a source of calories and 8 times less efficient as a source of proteins. In addition, aquaculture—especially shrimp and tilapia farming—have resulted in the conversion of over three million hectares of mangroves and other coastal habitats (2). When it comes to land use, there are exceptions to the plant-animal pattern—some pulses and nuts, for instance, use more space per unit protein than poultry, eggs, or farmed fish (17). 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 (17). 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 (22), and more than half of the total biodiversity loss within terrestrial KBAs is estimated to be caused by habitat loss due to ASF production (21).

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 (23). Cattle, buffaloes, and small ruminants use about two-thirds of the planet's agricultural lands as pasture (16), 65% of which is unsuitable for crops (17). At first glance, ruminants appear to provide a crucial service for a hungry planet, converting vegetation unpalatable to humans into meat and dairy that we can consume (24): ruminant systems along with backyard pig and poultry systems produce about 41 metric tons of animal protein while consuming only 37 metric tons of human-edible feed protein annually (23). But looking at the full picture, one sees a better solution for biodiversity: about 38% of croplands are currently used to produce feed for livestock (25), including 85% of the global soy crop that could provide complete proteins directly to people (23). 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 (17). This could free up massive tracts of land for wildlife.

Box I: Case study—The Amazon Rainforest

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 (54). 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 (155, 156)—never before has such a large area of old-growth forest been converted for human land use so quickly (1). 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 (157–162). While commercial crops like soy grown for animal feed explain 9-12% of deforestation, pasture has explained 63-90% of deforestation (155, 163, 164). 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 (161, 165).

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 (17), with the production of livestock feed accounting for about 41% of agricultural withdrawals (26). 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 (27). 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 (17). 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 (2, 22). 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 (2).

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 (17). This pollution produces algal blooms which have caused dead zones in the mouths of over 400 rivers worldwide (1, 28). 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 (22). Agriculture—especially beef—is responsible for 32% of the world's soil acidification (17) and soil erosion rates 10-100 times greater than the rate of soil formation (15), with some of the eroded sediment smothering coral reefs (1). 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 domestic animals—become the targets of retaliatory killings by ranchers (1). 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 (21).

ASFs also endanger biodiversity through the disruption of our climate. Agriculture is the second largest source of annual greenhouse gas (GHG) emissions (Tubiello and Conchedda, 2021) after energy, accounting for 31-35% of global emissions (9, 17). Again, animal agriculture is disproportionately responsible for this pollution: 57% of agricultural emissions are generated by the production of ASFs, 29% by plant-based foods, and 14% by other crops. On average, this makes ASFs 9.0 times worse per calorie and 3.3 times worse per gram of protein than plant-based foods. Livestock emits more GHGs than all cars, motorcycles, and other light passenger vehicles combined (29). These calculations are based on 100-year global warming potentials; over shorter periods of time, ASFs are even worse. ASFs are less climate-friendly than plant-based foods for five distinct reasons: the emissions from feed production exceed emissions from farming of plant proteins due to low feed-to-edible protein conversion ratios and less digestible feeds; feed and pasture are responsible for 67% of agriculture-linked deforestation; animals emit additional GHGs through enteric fermentation, manure, and methanogenesis in aquaculture ponds; the slaughtering process adds more emissions than processing other foods; and ASFs require more intervention to prevent spoilage (17). Again, ruminants have the largest effects, this time due to their association with deforestation for pasture and emissions due to methane from rumination (1, 9). Methane from enteric fermentation and nitrous oxide from manure trap 100 and 250 times more heat than carbon dioxide, respectively (though methane only survives in the atmosphere for about a decade) (30). Emissions from meat from dairy cow herds and beef herds average 3-8 times more than the average chicken or farmed fish (17, 27), and these ASFs are also almost always considerably worse for the climate than plant-based foods: chickens, pigs, and aquaculture-raised fish average 2-3 times more emissions per gram of protein than grains and tofu and 7-20 times more than peas, pulses, and nuts (17, 27). Even the lowest-impact aquaculture systems still emit more GHGs than average plant-based proteins (17).

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) (31). 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 (32). 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 (33). 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 (34). The diversity of likely and declared extinctions associated with climate change—for instance, the meltwater stonefly (35), the smooth clam (36), the quairading banksia (37), the golden toad, the Bramble Cay mosaic-tailed rat (38), Stresemann's bushcrow(39), Acropora coral species on the Great Barrier Reef (34, 40), and polar bears (41)– portend the dramatic effects ASFs are likely to have on biodiversity through GHG emissions, especially as they converge with habitat loss and other drivers.

Finally, the overexploitation of wild animals for food also impacts biodiversity. The multibillion-dollar bushmeat trade—which in at least one context has been linked to the lack of access to other proteins (42)–continues to be a major biodiversity concern, especially in Africa and southeast Asia (1). 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 (14). 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 (2, 3). Wild and mariculture-raised seafood plays a major role in the global food supply, providing some 17-20% of animal protein (2, 43)—some three billion people get vital nutrients from seafood, and about 660 million people are majorly dependent on marine and freshwater fisheries for food (2). About 90 million tons of seafood is taken from oceans and waterways annually, and industrial fishing occurs over about 55% of the ocean (2). 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 (2). 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 (2). Thirty-eight percent of marine fisheries are assessed as overfished (2). 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 (44). The approximately 1118 species affected by overexploitation (45) are diverse. 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 (34). Populations of migratory fishes, the main bulk of freshwater fishing hauls, have declined 81% since 1970 in large part due to overfishing (2, 46). High on the food chain, sharks and rays are particularly vulnerable to extinction from overexploitation (47). 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 (48). Freshwater sturgeons and eels (46), demersal fish like the orange roughy, predatory fish like the Patagonian toothfish and bluefin tuna (49), and mammals like the vaquita (50) are all at risk of disappearing due to our dependence on animal-sourced foods.

Even more alarming is what continued production of ASFs means for the biosphere in the future. The United Nations estimates that the global human population will grow to about 9.7 billion in 2050 and 10.4 billion in 2100 (51). 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) (16, 22, 52). 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 (16). Even accounting for likely improvements in agricultural productivity, demand for food is likely to translate to major increases in land utilized for crops and pasture, with estimates ranging from about 219 MHa (an area the size of Saudi Arabia) to 710 MHa (an area nearly the size of Australia) by 2050 (1, 14, 16, 26, 53). This agricultural expansion will come at the expense of most of the world's remaining forests and other natural habitats, almost entirely (about 98%) in the tropics (16, 22). 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 (1), and 61% of global habitat conversion is expected to occur in sub-Saharan Africa (14). 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 (54). 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 (22).

The increased intensification of crop and livestock production are expected to result in more water scarcity (1, 15), surface water pollution, and soil acidification (1). Nitrogen application and irrigation are expected to especially affect regions rich in bird species (22). Agriculture and related land use GHG emissions are expected to increase by 15% (1.1 gigatonnes of CO2 equivalents annually) from 2020 to 2050 (53), with land use-related emissions alone adding over 75 gigatons of GHGs to the atmosphere over that period (6). Agricultural methane emissions primarily from cattle are expected to increase 36% from 2020 to 2050 (26). The emissions from the global food system are expected to increase so much that—even if all non-food system GHG emissions were to immediately go to zero and remain that way until 2100—we would far surpass the limits necessary to maintain warming below 1.5 degrees C and have just a 67% chance of staying below 2 degrees C (55). 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 (2).

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 (53). 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% (56). 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 (14). 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% (32). Increased demand for protein will also likely affect wild species directly, with increased bushmeat hunting in remaining natural habitats (14) and about 88% of fish stocks overexploited by 2050 (44). For other major threats to biodiversity—like emissions from energy use and transportation—solutions are on the horizon (55); solar power is already cheaper than coal and electric vehicles are making rapid advances. When it comes to animal-sourced foods—the greatest threat to biodiversity—no such off-ramp yet exists from the highway of unsustainable consumption.

2. Strategies for food system transition

Conservation groups and the environmental community more broadly have not sufficiently addressed food system transition (55); ASFs are largely neglected even in major international agreements like the Global Biodiversity Framework and Paris Agreement (2). 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" (55). Animal-sourced foods in particular are complicated since they have historically provided micronutrients less available from plants (8, 57) and for communities unable to access fortified or well-balanced plant-based foods, they remain a critical source of nutrition (14, 58). Given the deep ties ASFs have to human culture and perhaps even evolution (59), tackling a food system transition is politically complex.

Yet overwhelming evidence suggests that most people can be perfectly healthy with dramatic reductions in—or even the elimination of— consumption of ASFs (60–63). Given the unparalleled and unmitigated threat that ASFs pose to global environmental systems, the conservation community must develop, finance, and execute a strategy for engendering a sustainable food system transition. This strategy must have a reasonable chance of achieving major outcomes in terms of protected and restored habitat, greenhouse gas emissions, and reduced capture of wild animals for food. The international community developed consensus habitat restoration and protection goals in the Kunming-Montreal Global Biodiversity Framework, targeting at least 30 percent of all terrestrial, inland water, marine, and coastal areas—especially biodiverse areas—for effective protection, ideally by 2030 (64). This would require an additional 1,670 Mha of terrestrial and inland waters be restored and protected to support biodiversity (65), a task that becomes much more feasible if the world's population can be fed on less than 49% of the world's ice-free surfaces (15). From a climate perspective, emissions from agriculture must be reduced by about two-thirds from a business-as-usual scenario over the next 25 years to give us a reasonable chance at limiting warming to within 2 degrees C (16, 55), and about 585 Mha of land must be restored to natural habitats to sequester enough carbon to help us limit warming to within 1.5 degrees C (16). In parallel, catch from wild fisheries should decrease by about 50% over ten years and then remain at those levels through 2050 to allow aquatic biodiversity to recover (66). These are not hard and fast targets—none of our projections are perfect, and we don't have to fully achieve these objectives to produce a better, more biodiverse world. But unless we achieve progress on the general scale of these targets, dramatic changes to our biosphere are almost certain.

These targets can help us identify the best available strategy for tackling the problem of animal-sourced foods. At present, there are three broad strategies available for achieving food transition:

1. **Conventional diet change** resulting in consumers eating fewer ASFs and more plant-based foods that are not intended to emulate ASFs. This strategy is focused almost entirely on consumer behavior change through regulation, education/awareness, persuasion, and the choice architecture presented to consumers.

2. **Animal production reform** resulting in reduced environmental harms from animal agriculture and industrial fishing. This strategy relies on innovations and interventions across various aspects of ASF production and distribution systems, ranging from livestock grazing practices to modifications to animal feed to reducing food loss and waste. Production reform often relies on some combination of technological innovation and behavior change by producers/suppliers. Consumers may also have to make behavioral changes—for instance, seeking out and purchasing sustainably produced meat or fish, even when it is more expensive.

3. **Disruptive replacement using alternative proteins** resulting in new nutritious and sustainable foods that can match or outcompete ASFs on taste, cost, and convenience. This strategy primarily relies on innovation, entailing the development of new products and supply chains that can substitute directly for ASFs. The goal is to create products that taste the same or better and cost the same or less than ASFs, requiring consumers to accept novel production methods in exchange for savings and/or other benefits.

Food systems are diverse and complex, making it unlikely that any one solution will fully address the challenges at hand. There is also no direct precedent for the type of food system transition currently required for biodiversity. As such, a mix of the above strategies is critical. 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.

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strategies is critical. 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.

As we explain below, our assessment is that alternative proteins are the conservation community's best chance to achieve a sufficiently effective and sustainable food transition over the coming decades. While all three strategies involve deep challenges, alternative proteins are unique in their potential to provide major environmental benefits at scale via market mechanisms.

Conventional Diet Change

Ecological potential

There is a remarkable level of consensus in the sustainability literature that a shift to conventional vegetarian and vegan diets would be a powerful and positive change for the Earth (1, 16, 67), 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 (2, 8, 17). 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 (2, 17). 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 (8, 68). A universal shift to a vegetarian diet would use 63% less agricultural land in the US (68); a complete shift to a vegan diet would reduce agricultural land use by about 74% in the US and 76% globally (17, 68). If all Americans were to adopt a fully plant-based diet, 62-70% less water would be used in agriculture (68). If the world were to go 95-100% plant-based, agriculture would require 42% less water (22) resulting in 19% less scarcity-weighted withdrawals (17), and 68% less nitrogen fertilizer (22) resulting in 49% less eutrophication (17). By 2100, this would result in measurably more water and less pollution in bird-species rich parts of the world and biodiversity hotspots (22).

Then there are the climate benefits. If every American were to shift to a vegetarian diet, it would reduce GHG emissions by 15-32% (68). A global shift to a vegan diet—combined with reforestation of released pasture and croplands—would reduce net emissions from our food system by up to 70% (6, 17). Projecting out to 2050 (with 2015 as the baseline), such a shift could help sequester 332-547 gigatons of CO2-equivalents—the equivalent of nine years of domestic fossil fuel use in high-income countries and 19 years in upper-middle income countries. Such a reduction is consistent with a 66% chance of limiting global warming to 1.5 degrees C while allowing 78 grams of protein a day for every person on Earth (6). All these benefits could be even greater if farmers globally are able to replicate the successes of the most efficient crop producers (17). To top it all off, in the US, the replacement of red meat with plant-based foods would reduce diet-related disease burden, saving the equivalent of 63B dollars (8).

More modest diet shifts can still be impactful, especially in terms of carbon and land benefits (e.g., (22)); for instance, universal acceptance of the Eat Lancet diet (about 70% less meat than business-as-usual) would lead to 61% of the carbon benefits of the vegan scenario (6). Seafood enthusiasts could shift 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 (2). Similarly, convincing even 25% of the world to give up ASFs would be a major victory—conventional diet changes are so good for biodiversity that any change at scale would be tremendously impactful. The question is whether such large proportions of the world's population can be moved to embrace conventional diet changes.

Reaching scale

Of all the strategies available, conventional diet change would rely on individual consumers changing their behavior in the most substantial ways—learning to buy and cook new foods and willfully developing new tastes. 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)" (67)—in other words, a combination of regulations, awareness and persuasion campaigns, and changes to the choice architecture of how foods are presented to consumers. The most effective instruments would arguably be regulations that financially incentivize diet shifts—for instance, policies that ensure that prices of all foods reflect their environmental costs, like a carbon tax on agriculture, or subsidies that make plant-based foods less expensive (69). The carbon taxes for agriculture implemented in Denmark and Switzerland demonstrate such policies are possible, at least in small and wealthy countries; as such, they should be pursued wherever the political stars align. 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 (17). 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 (69). In addition, there remain major questions about the most accurate way to monitor agricultural emissions (70), and acquiring the necessary technical capacity and ensuring compliance may also prove complicated.

More frequently, advocates of conventional diet change will have to rely on tools of persuasion and modifications to choice architecture to engender such changes, and there is quite a bit of evidence that these approaches—while valuable and likely to make a positive impact—will be unlikely to result in changes of the scale needed for conservation on their own. Persuasion and awareness tools seem to be effective in only targeted contexts: interventions to persuade individuals or small groups to shift their diet described in the literature—many of which are from the public health context—involve substantial levels of individualized or setting-specific attention (67) that result in modest behavioral changes (71). 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 (67). 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 (72, 73). 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. In this review, the most successful interventions led to reductions in red meat consumption in the range of 20-30%, with one Brazilian study tracking participants for a year. But as most of these studies featured participants with current or past conditions like breast cancer, colorectal cancer, or prostate cancer, they are unlikely to demonstrate the effectiveness of these interventions on the general public (73). If anything, the fact that diet shifts were so much lower than climate targets even in the face of serious medical conditions may suggest limitations of diet change persuasion as a tactic. Notably, even a 20% reduction in red meat consumption globally would translate to far less than the 2/3 reduction in agricultural emissions required to achieve climate goals.

As a tactic to drive conventional diet change, reshaping the way in which options are presented to consumers—or choice architecture— may provide opportunities to achieve progress at somewhat larger scales. The literature on the use of choice architecture to shift diets explores interventions like modified menu designs (e.g., placing vegetarian menu options higher on the menu, describing them more positively), green defaults (where customers would have to exert additional effort to access more climate-costly foods like meat), reduced meat portion sizes, and institutional “veggie days” (an international version of “meatless Mondays”) (71, 73–76). In principle, such interventions can generate more change per unit effort than the ultimately individualized persuasion work described above—once an institution is persuaded to implement a change, it can immediately affect thousands of customers and many more meal choices. At first glance, such choice architecture interventions seem like they could result in shifts similar to those required by the climate and biodiversity: at their best, vegetarian defaults at university canteens, meal plans, and conference sign-ups can reduce consumption of meat and fish by as much as 87.5% (75). However, these successes come with major caveats. First, the average reduction due to these interventions is likely quite a bit lower (73–76), with some efforts resulting in no or even negative effects (73). Second, studies generally fail to capture ways in which consumers may adjust their behavior in ways that mitigate or counteract the gains from these interventions. For instance, a “Veggie Day” intervention that led to a 41%-66% reduction in meat and fish consumption at university canteens on Thursdays also resulted in up to 24% of consumers seeking food elsewhere, including a 127% increase in sausage consumption at one nearby location (74). Studies have generally been unable to assess whether such institutional policies may result in a rebound effect, with meat-eating customers seeking more ASFs during their other meals as a way to compensate for their reduced consumption elsewhere (74). There are also questions about scale. Studies so far have been skewed heavily towards university canteens, and it is unlikely that students with limited options accurately capture how the broader public would react to these nudges. At some point, trying to change rules at institutions will run into the same political headwinds as the regulatory efforts discussed above. A Veggie Day that reduces meat consumption 87.5% at one meal may—even discounting leakage and rebound effects—effectively result in a 4.2% reduction in meat consumption over the course of a week. Yet when Germany's Green Party tried to institute a national Veggie Day, the blowback was apparently enough to contribute to the party's loss in 2013 elections, despite Germany's disproportionately sympathetic posture on environmental issues (74). Finally, while people worldwide are eating more and more "food away from home", the best available studies suggest that about 75-80% of calories are still consumed at home worldwide (77, 78), requiring a different set of interventions wherever consumers purchase groceries. All in all, while choice architecture interventions may very well play a key role in nudging along compliant consumers engaging with values-aligned institutions, there is no clear path by which they can engender necessary conventional diet changes at scale.

Vegetarian and vegan diets are a gold standard for sustainability, and finding more effective ways to engender conventional diet change in specific strategic contexts makes sense. But even once improved behavior change interventions are found, getting them implemented by various institutions or governments—especially where sustainability isn't a political or cultural priority—presents major collective action problems and transaction costs. At present, while conventional diet change has significant value, it is unlikely to scale sufficiently to meet crucial climate and biodiversity targets.

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 (25). A diversity of approaches exists to making agriculture and fishing more sustainable, including changing how animals are reared to decrease emissions or land use, modifying their biological processes to reduce waste, regulating how wild animals are caught to enable sustainability, and attempting to reduce food loss and waste (8).

While several animal production reform interventions deserve more attention, they all face at least one of two challenges: (i) they address only a subset of the biodiversity-related concerns posed by ASFs, sometimes trading off gains in one key environmental sphere for losses in another, and (ii) they are not easily scalable, especially via market mechanisms. These problems limit the degree to which animal production reform can address the inefficiencies and pollution inherent to ASFs.
Current evidence suggests that moving to regenerative grazing involves (at best) trade-

offs across environmental outcomes. 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 (79). 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 (1, 79, 80). All of this is claimed to help improve biodiversity (81).

The evidence does not suggest that regenerative grazing consistently offers these benefits. A literature review of 75 data sets across 44 years comparing regenerative grazing practices to conventional (continuous) grazing found no consistent change in plant or animal productivity, soil compaction, soil water levels, or soil microbial levels (80). 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 (80); another review found that rigorously case-controlled studies with multiple measurements show no improvement in carbon sequestration from regenerative grazing (Hayek and Clark unpublished). Any carbon benefits that do exist are likely to be temporary, as carbon sequestered in soils can "rapidly be lost through management change, seasonal or climate fluctuations, or fires" (82). Furthermore, any gains in soil carbon come at the expense of land (17), requiring 2.5 times as much land as commodity agriculture in one case where net emissions were substantially reduced by soil carbon sequestration (81). While one might hope that this more extensive use of land may result in more sharing with biodiversity, the evidence doesn't bear that out: compared to conventional grazing, regenerative grazing was associated with decreases in nesting activity of passerine birds and songbird diversity and abundance (80), with no apparent benefits for herpetofauna (79). For plants, productive forage grasses and exotic species often seem to benefit from regenerative grazing over perennial forbs and native species (79). Overall, the diversity and abundance of birds, amphibians, and mammals decrease consistently with increased stocking rates of livestock, including in regenerative grazing settings (80); there isn't support for the claim that regenerative grazing leads to larger and more diverse faunal populations (79). The greater land required by regenerative grazing would better serve biodiversity if maintained as natural habitat (82).

Further intensification of animal production is another suggested approach for making farming more sustainable that offers environmental trade-offs. Intensification occurs on a spectrum, moving from completely pasture-raised livestock on one end towards industrialized farming operations on the other, with various degrees of mixed production in the middle (83). 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 (83). Compared to free-range cattle in the US, feedlot-finished beef cattle are believed to emit 47% less methane (84), and intensification can reduce total emissions from dairy by about 10% (85). One estimate suggests that global GHG from beef and dairy could be reduced by 17-32% through best-practice intensification (83). Intensification also generally makes animal production more land-efficient (1, 86). A global shift of cows from pastures to feedlots and stalls could reduce the land footprint of beef by 35-73% (83, 84). 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 (1, 16, 53, 55). 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. One study found 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 (70, 83). 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 (85). In essence, intensification trades off one type of ASF-related pollution for others, and interventions to address these additional emissions (e.g., (30)) 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 (87). 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 (24). Such universal intensification is anyway unlikely due to infrastructure and capital constraints (83, 87).

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 (17). 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 (24). A variety of feed additives exist, most decreasing methane emissions by about 12-32% (24, 88)—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% (89). The primary active ingredient, bromoform, inhibits methanogenesis even when red algae forms only 2%-10% of feed (89). Despite the reductions of methane from red algae additives (89), they are unlikely to result in the improvements necessary to bring ASF emissions down by 2/3 by 2050 for three reasons (24). 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 (87)—bromoform in particular can catalytically destroy ozone, complicating the environmental calculations for at least this key additive (89). 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 (17, 85); feed additives are also generally impractical for pasture-raised cattle (87).

Most importantly, feed additives are unlikely to scale because they don't offer consistent benefits to cattle producers or consumers (87). 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 (89). 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 (87). 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 (89), the path to success for such innovations is narrow.

Another creative proposal for making animal agriculture and aquaculture more sustainable is to introduce insects—especially black solder fly larvae (BSFL), yellow mealworm, and the house cricket (90)—as feed for chickens, pigs, and fish, all of which eat insects naturally (91). In principle this could improve the sustainability of ASFs by efficiently converting various forms of waste or waste streams into nutrients accessible to livestock and fish, reducing the ecological footprint of animal feed (91–94). For instance, BSFL—which are well-researched and have a pan-global distribution— could be raised on household waste or agricultural refuse, digesting what would otherwise lead to emissions through disposal as compost or in landfills (92). Even better, 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 (91, 92), 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 (90, 94).

In practice, insect-based feed runs into challenges both in terms of sustainability and scalability. While several early life-cycle analyses suggested insect-based feed was sustainable (92, 94), a review of 352 studies found that such results were generally driven by unrealistic or unjustified assumptions (90). 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 (90, 95). Neither is particularly sustainable: in the former case—which is more common in the real world (90)— insects end up consuming products that could be fed directly to livestock or even to people (93, 95), effectively just adding a full trophic level of ecological costs to ASF footprints (For a note on eating the insects directly, see Box II). 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 (90). Furthermore, the irregular nutritional composition of insects raised on waste streams make them less reliable as feed (90). The added environmental costs from these irregularities then often outweigh the environmental benefits of using waste (91). This fundamental problem is aggravated outside the tropics: most insects require temperatures of 25-30 degrees C to thrive (90), meaning that insect agriculture outside the tropics requires increased emissions from facility heating (91, 94). All this isn't to say insects can't ever improve the sustainability of ASFs (93)—just that there is considerable variability, with insect-based feeds generally having a larger footprint than soy- or fish-meal (90). 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 (91). 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 (92), 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 (90, 96). If insects can in fact help reduce the footprint of ASFs, a variety of problems related to sustainability and cost must be simultaneously addressed.

Perhaps the most uncontroversial recommendation for reforming our current animal production system—and food systems in general—is to minimize food loss and waste (FLW). Food loss refers to food that is discarded from the farm through to retail, while food waste is discarded by consumers and service providers (69). FLW affects about a third of all food produced globally each year (2, 8, 15, 97), representing about 24% of global agricultural emissions and 6-10% of total emissions (67, 98, 99). While ASFs are more prone to spoilage, more energy is also invested in preventing losses (17); globally, FLW affects about 20-27% of meat products, with FLW of seafood somewhat greater and of dairy somewhat lower (97). In total, ASFs account for about 12% of FLW (100). In industrialized countries, where animal mortality during breeding and transport are lower, over 50% of FLW is due to consumer waste (97). Interventions to reduce FLW include measures to extend shelf-life (refrigeration, packaging, preservation), make supply chains faster, better predict required inventories, and shift consumer environments to help reduce waste (98, 101). Any reduction in waste represents progress in terms of land, water, and other inputs (69), and whenever there are opportunities to implement modern technologies to improve supply chains (like refrigeration (2)), they should be taken. However, a primary or sole focus on reducing FLW to reduce the impact of food systems on biodiversity is unlikely to be sufficiently impactful for two reasons. First, note that FLW is a smaller target than ASFs, with FLW responsible for less than half the emissions of ASFs. Whatever the inefficiencies of our food distribution systems, they are less than the inefficiencies of producing foods using animals. While FLW of plant and animal products in the US involve about 30-40% losses, the inefficiencies of producing beef, pork, and poultry compared to nutritionally equivalent plant-based foods effectively result in 96%, 90%, and 50% losses (respectively) (8). This means, for instance, that of all the nutrients supplied to a cow during its production for beef, only 4% ultimately are consumed by people; the rest are used by the cow itself or excreted into the environment, often in noxious forms. (Of course, this also means that interventions that reduce the premature mortality, other loss, or waste of ASFs are likely to be particularly impactful ways to reduce FLW, (102)).

Box II: Crossing strategies: What if we just ate the insects directly?

Over two billion people are believed to eat 1,900 species of insects worldwide (166), and insect protein has been used in protein powder, crisps, crackers, energy bars, cookies, pasta, bread, and even burgers (90). In fact, a buffalo fly-based burger by the company Bugfoundation outperformed pea, soy, and mycoprotein-based burgers in blind taste tests (112). 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 (27, 112), 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 (95, 167). As with insect-based feed, this ignores the slower growth rates and higher mortality of insects grown on waste streams (90, 95); ultimately, a review of LCAs found that insects at present have ecological footprints that vary widely but largely resemble those of other animal products (90). 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 (112, 140, 143, 167, 168). This lack of social acceptance is why only 5% of investment in industrial insect agriculture has been geared towards human consumption (167). 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 (90). 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—no matter which strategy they fall under.

Second, food loss and waste occurs in varied ways across supply chains, so reducing FLW requires the implementation of a wide range of solutions that differ across region; this patchwork of interventions include some that are likely to scale readily after initial investments, and others that seem unlikely to do so. Interventions like refrigeration, improved stocking practices, and inventory algorithms that reduce spoilage could benefit retailers and may scale with the market, while other interventions (e.g., improved packaging) may actually cost producers more (101, 102). 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. This is all positive in terms of food security, but such rebound effects could offset 53-71% of the environmental benefits that come from reducing food losses (69, 98, 99). As with food loss efforts, interventions to reduce food waste are diverse and likely to vary in their scalability. In some ways, reducing food waste resembles diet change interventions, relying heavily on persuasion and changes to choice architecture and the behavior of individual consumers. In one review of downstream FLW interventions, the largest reported waste reduction was a 57% change induced by having a buffet offer smaller plates to consumers; education campaigns and school dietary guideline changes resulted in 12-33% waste reductions. As with conventional diet change, many studies took place over short periods of time in specific contexts and often involved self-reported results, meaning they may exceed long-term effects (103). Some measures may also run against the self-interest of vendors—for instance, smaller plates could reduce profits for venders that charge by weight—inhibiting scale-up. On the other hand, interventions to reduce food waste enjoy one benefit over conventional diet change: they are less likely to be politically controversial, making interventions like (for instance) shifting from milk cartons to milk dispensers in school (104) more palatable and scalable. Ultimately, reducing FLW is an important way to reduce the footprint of food systems, and the diversity in impact and scalability of FLW interventions suggests that the most impactful ones should be prioritized—but FLW interventions alone cannot be the sole or primary tools for addressing the threats our food system poses to biodiversity.

Reforming fishing also offers limited opportunities to achieve necessary changes at scale. This is not due to a lack of interventions that work in principle; as one commentator notes, “overfishing is an interesting problem in that the solution is conceptually simple and universal: we need to kill fewer fish” (44). Marine protected areas and similar governance tools have demonstrated that fisheries can be salvaged in a way that serves the interests of both biodiversity conservationists and the fishing community (105, 106). Properly designed MPAs enable fish stocks to recover to a point of maximum productivity—think about the steepest part of an “S”-curve—that can then allow fishers to catch animals at a maximum sustained yield. But there are problems both in terms of the best-achievable gains and the likelihood of reaching that scale. Getting to 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 collect more than the share allocated to them (107); 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 (108, 109). And even if we were able to achieve such global governance, managing all fisheries to maximize food production would result in an approximately 16% increase compared to current catch levels (43), quite a bit less than the over 50% increase in expected demand. This means that, even if we can achieve this best-case scenario for fishing, we would again face the risk of overfishing, expanded aquaculture (and its attendant problems), or both. (97)

Animal production reform efforts are—like conventional diet change—an important element of a comprehensive approach to addressing the biodiversity threats posed by ASFs. In some contexts and for some actors, implementing feed additives, tackling food loss and waste, and establishing sustainable fishing regimes will yield the greatest available local results for biodiversity conservation. But generally, making marginal alterations to our current ASF production systems results in gains of a magnitude insufficient to achieve our climate and habitat objectives—and even these gains are unlikely to be achieved at scale. As such, it is important that animal production reform efforts do not come at the expense of more ambitious—and ultimately more effective—strategies for change (25).

Disruptive Replacement With Alternative Proteins

Ecological footprint

Disruptive replacement of ASFs with alternative proteins offers both sizeable reductions to the environmental footprint of our food system and an opportunity to achieve impacts at scale. Alternative proteins made from plants, microbes, mycelium, and cultivated animal cells are likely to offer more efficient and less polluting food sources than ASFs. Since these novel replacements are intended to taste identical to (and be nutritionally equivalent or superior to) ASFs, they could—if produced cheaply enough—take considerable market share from ASFs, offering a path to scale unavailable to other interventions. Perhaps the biggest questions then are how quickly alternative proteins can achieve taste parity (or better), how low the prices of novel replacements need to be to offset consumer neophobia, and whether taste-competitive alternative proteins can achieve those prices.

The term alternative proteins encompasses ASF analogues produced by various technologies without the use of full-bodied animals: plant-based meats, biomass fermentation, precision fermented, molecular farming, and cultivated meats. Plant-based meats and biomass fermentation involve using plants, bacteria, and fungi to produce the flavors and textures of ASFs. Precision fermentation and molecular farming involve recombinant DNA, with microbes and plants (respectively) reprogrammed to produce specific animal proteins. Cultivated meat involves rearing animal cells without the animal. The underlying logic across platforms is that plants, fungi, bacteria, and animal cells all may have the potential to be more efficient and less polluting than rearing livestock (110). Alternative proteins would be expected to be less environmentally friendly than many conventional plant-based products—after all, they often require either more processing (111), an intermediate organism like bacteria or fungi, or both. But the hope is that these production systems can achieve better feed to food conversion rates (where relevant), lower land and water requirements, and less noxious waste than ASFs.

Currently, evidence suggests that plant-based meats and biomass fermentation products are the most sustainably produced alternative proteins, offering notable potential gains for biodiversity if they are produced at scale. Life-cycle analyses comparing products based on mass and/or nutritional composition find that plant-based meats (mostly made from soy and pea, but also amaranth flour, buckwheat flour, pumpkin seed, and others) will use about 64-97% less land than beef (27, 57, 68, 86, 112), 56-60% less land than pork (27, 86), 10-43% less land than poultry (27, 86), and 33% less land than farmed fish (27). Plant-based meats are also better from a climate perspective, resulting in emissions reductions of 77-98% compared to beef (27, 57, 68, 86, 111, 112), 57-87% compared to pork (27, 57, 86, 111), 50-83% compared to chicken (27, 57, 86, 111), 50% compared to fish (27), 91% compared to cheese (111), and 76% compared to eggs (111). Water usage across products is reduced 74-99% (57, 68), with scarcity-weighted water use declining 43% compared to terrestrial livestock and 83% compared to farmed fish (27). One study found that switching to a plant-based burger saved 217 liters per burger (57). Eutrophication is also found to decline 36-41%, with a 95% reduction compared to farmed fish (27, 112), though for one plant-based product there was no significant difference from beef (112). Biomass fermentation offers similar benefits, with life cycle analyses assessing the footprints of microbial proteins produced by hydrogen oxidizing bacteria and mycoproteins. These fermented products require 73-94% less land than beef (27, 112), 56-85% less land than pork (27, 57), 43-71% less land than chicken (27), and 33-67% less land than fish (27). Greenhouse gas emissions from these products are 80-93% lower than beef (27, 28, 112), 14-81% lower than pork (27, 28, 57), 38-67% lower than chicken (27, 28), 24-67% lower than fish (27, 28), 68% lower than cheese, and 30% lower than eggs (28) (though one comparison of mycoprotein with fish and chicken found no difference (27)). Some mycoprotein products even outperform some plant-based meats on climate outcomes, as mycoproteins can sometimes be supported with a smaller crop area and require less processing to acquire a meaty taste (28). Water usage during the production of mycoproteins may be as much as 87% less than the reference animal-sourced food—or 5,219 liters less per kilogram of product (57)—and scarcity-weighted water use is reduced 14-92% across products (27). One mycoprotein product led to an increase in freshwater eutrophication but decrease in marine eutrophication, while the other fermented products resulted in reduced eutrophication by 14-97% (27, 112).

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 (68); the replacement of animal proteins with an alternative protein with properties averaged across four products in the US (113); the replacement of beef with sugar-fed mycoprotein globally over the coming decades (26); and the replacement of beef, pork, chicken, and milk with plant-based alternative proteins through 2050, assessed using the GLOBIOM model (53). Consider the projections for habitat. All studies find that substitution reduces forest loss (53), with a 20% global substitution of mycoprotein for beef reducing deforestation for pasture by about 100Mha (26) and a 50% reduction further reducing or even fully halting the conversion of natural land for agriculture (26, 53). The Congo Basin, Central America, and the Amazon Basin benefit the most from these shifts (26). Two studies find a 12% decline in the area under agriculture if half of the examined ASFs are replaced (53, 68). A 50% substitution of beef with plant-based meats in the US should release an area about the size of Georgia from agriculture (68), 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) (113). 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 (53)—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 (68) and the more recent global assessments placing estimated reductions at 31-83% (26, 53). 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" (53). In aggregate, the land and emissions gains are roughly those required to limit warming to within 1.5 degrees C (16), 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 (26, 53, 68).

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 (113). 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 (53). Notably, about half of the gains achieved by substituting beef, pork, chicken, and milk can be achieved just by replacing beef (53).

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 (114), and land savings from precision-fermented ovalbumin, a key egg protein, were 87-89% (115). These two studies also found notable greenhouse gas emissions savings ranging from 31-69% largely based on geography (114, 115). 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 (116). 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 (115). Depending on location and the feedstock used for beta-lactoglobulin, scarcity-weighted water use could decrease 81% or increase by ten-fold (114, 116). The biggest cause of variation in carbon footprint was the percentage of electricity generated by renewable energy, which varied across locations (115, 116). All in all, whether precision fermentation out-performs 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 (117, 118). As a result, it is unsurprising that LCAs of cultivated meat over the years have come to drastically different conclusions (27, 117–119). It is also remarkable that the most rigorous LCAs—one more optimistic (117), one more pessimistic (118)—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 (117). 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 that beef cattle (117). 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 CO2-eq per kg of meat) and the main estimate of the optimists (14.3 kg CO2-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 (117, 118). 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 (117). 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 (118). While this is almost certainly too pessimistic (120), 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) (118) and the likely considerable nitrogen pollution that will come from waste streams (121). And even the most positive projections suggest cultivated meat will not soon rival chicken in emissions (117).

There are also two reasons to believe that the ultimate ecological footprints of all alternative proteins—especially those produced using precision fermentation and cultivated meat—will improve considerably in the coming years. First, as early-stage technologies, alternative proteins have major scope for improvements in efficiency and sustainability (116), almost certainly more than ASFs that have been optimized over centuries and are constrained by the physiological limits of full-bodied animals (86, 116). There is room to source inputs for precision fermentation and cultivated meat from nearby (86, 111, 116), transition to more sustainable ingredients (86, 114), make conversion of feedstocks more efficient through improved strains (110, 111), develop more sustainable fractionation and extrusion methods (86), and improve the sustainability of refining factors (111). 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 (122–124). Second, unlike ASFs whose climate impacts stem largely from biological processes and land use change (17), alternative protein carbon footprints have scope for dramatic, automatic improvement as grids around the world shift from fossil fuels to renewables (26, 28, 110, 116). Electricity accounts for 80% of emissions in plant-based meat production (68), similar levels in biomass fermentation (26), and about 34% of emissions for precision fermentation in Poland (where 75% of power comes from coal and the rest is largely renewables) (115). Even moving from a European electricity mix to a Swedish one decreased the global warming potential of mycoprotein production by 15% (28). A grid powered by renewable energy would reduce the climate footprint of cultivated meat by 80%, resulting in emissions 45% less than pork (but still slightly more than chicken) (117). In contrast, for meat, eggs, and milk, electricity is responsible for closer to 5-10% of emissions (9, 17), meaning electrification will not substantially reduce ASFs' carbon footprint. As a general strategy for decarbonization, experts recommend that we transition to systems that rely on electricity (125). Alternative proteins make such a transition possible for our food systems.

There is room for skepticism of the sustainability assessments made so far for alternative proteins. Presently, there are only a limited number of life cycle analyses and model projections; most but not all are peer-reviewed. Sometimes, comparisons have been made between processed alternative proteins and unprocessed ASFs (28). Even with the limited number of life cycle analyses available, there is substantial variation in the life cycle impacts found across products, and the ranges of alternative protein impacts often overlap with those of the most environmentally friendly animal products (110, 111). As noted, assumptions regarding how alternative proteins will be produced at scale are often needed to allow fair comparisons with ASFs (e.g.,(116))(78). 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 (115). These life cycle analyses also do not capture the likely environmental costs of replacing other animal products, like leather (26). While new biodiversity-friendly methods for producing alternative oils and fats are on the rise, the present sourcing of coconut and palm oil for alternative protein products presents a biodiversity threat of its own that—while accounted for in the most comprehensive study (53)—still merits some caution where specific species are endangered by palm plantations (57, 68). A shift to alternative proteins may result in a reduction of cropland compared to the business-as-usual scenarios (26, 53), 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 (57). 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 (118, 121) and precision fermentation (116), 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 (57). 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 (127) from the 1960s onwards have prevented large areas of natural habitat from being deforested. One global assessment found that the Green Revolution helped protect 144Mha of natural habitat from being deforested (128), 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 (129). 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.

Reaching scale

All in all, disruption by alternative proteins possesses the potential to provide major benefits to biodiversity in terms of habitat, climate, water, and other ecological variables. This potential—much like that of traditional diet change—is only meaningful if these products can come to substitute for ASFs at scale. In contrast with conventional diet change, the plan is to design and produce alternative protein products that are indistinguishable from ASFs in terms of taste and far more sustainable. The same efficiencies that make alternative proteins more sustainable should gradually make them less expensive to produce, as plants and microbes require lower inputs per unit product than animals. The hope is that, faced with gustatorily equivalent products that are healthier and cost-competitive with ASFs, consumers will begin to embrace the new products. As consumption of the replacements increases, production will increasingly benefit from experience curves and economies of scale. Prices will continue to drop, making novel replacements increasingly irresistible to consumers, ultimately allowing alternative proteins to take an ecologically meaningful market share from ASFs, serving the interest of biodiversity.

But will this really happen, especially given that early alternative protein companies seem to have stalled earlier this decade? One way to answer this question is by thinking of these novel replacements as low-carbon technologies and trying to understand how they compare to their predecessors. Researchers have classified a variety of low-carbon technologies based on their degree of design complexity and need for customization. Mass-produced technologies like solar panels and LEDs are low design complexity and require very little customization across contexts; while the manufacturing equipment itself can be complex, individuals are able to gain the necessary understanding to replicate production in different firms or countries, making it possible for new companies to form and serve growing global markets, driving competition and innovation. In contrast, technologies like combined cycle power plants, building envelope retrofits, and nuclear power plants are either too customized or too complex to readily serve mass markets. Greater design complexity makes it easier for firms to carve out "specialized niches that are protected from competitive pressure", and customization requirements can mean that knowledge of the technology doesn't spillover easily to new geographies or markets (130).

Alternative proteins fall squarely in the same corner of this grid as photovoltaics and LEDs: they can be mass-produced, and there is little need for customization of the core product. On the terrestrial side, the products they seek to replace are strikingly un-diverse—98% of meat consumed globally consists of poultry, pig meat, cattle and buffalo, and mutton (131), with broiler chickens and intensively-produced pigs constituting about 81% and 61% of the global markets for chicken and pork, respectively (132). Global fish aquaculture is also mostly limited to carps, catfishes, tilapias, salmons, and their relatives (133, 134). As alternative proteins gain more exposure to markets, they are likely to emulate the journey of PV modules for which costs decreased by about 22.5% with each doubling in installed production capacity (134).

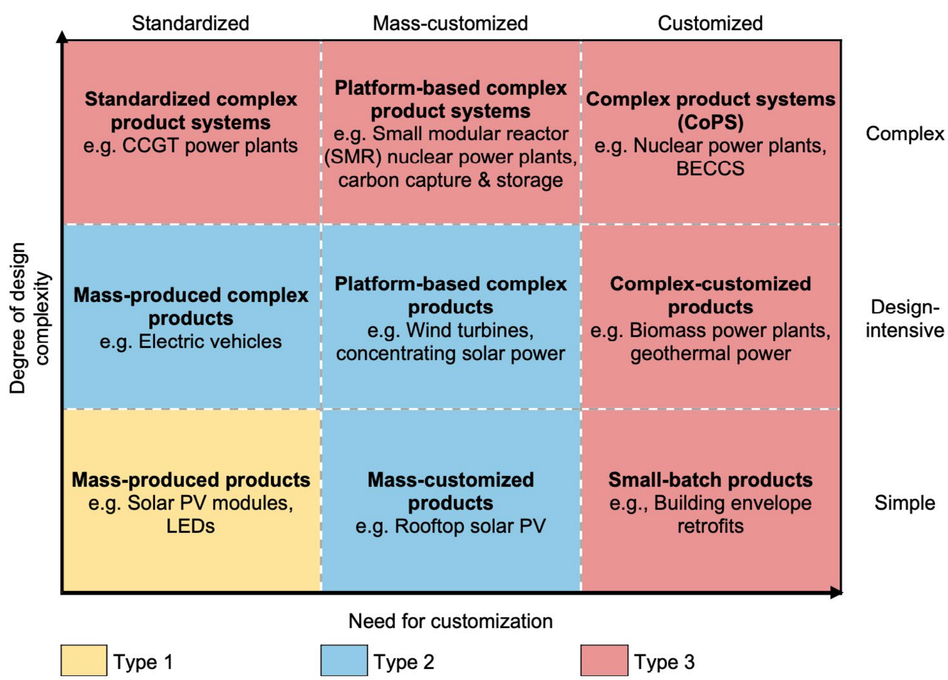

Figure 1: Schematic Characterization of Different Energy Technologies Based on Their Design Complexity and Need for Customization (Malhotra, A., & Schmidt, T. S. (2020). Accelerating low-carbon innovation. Joule, 4(11), 2259-2267)

As may be predicted by this analogy, novel ASF replacements seem to be improving at a rapid pace. A randomized controlled trial of 122 alternative protein products found that 20 (mostly plant-based) products—unbreaded chicken fillets, burgers, chicken nuggets, breakfast sausages, and turkey and ham deli slices— have rated as well or better than their ASF benchmarks in blind taste tests (112). Taste is a necessary if insufficient condition for disruption, and the imminence of taste parity greatly improves the probability that alternative proteins can scale soon enough to achieve biodiversity objectives. Furthermore, the remaining barriers to cost-parity appear solvable. For instance, 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 (135), 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 (136), 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.

Despite these parallels, there are persistent doubts about whether alternative proteins will follow this path to scale. 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 (137, 138), 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 (139). 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 (61); 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 (140). Policies like those passed by Los Angelos 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 (141). For instance, a study shows that Chinese and Indian consumers may be more willing to swap out meat for plant-based or fermented analogues (142). Notably, consumers in multiple contexts seem to be substantially more willing to switch to plant-based alternative proteins than cultivated meat (112, 140, 143), though this may change as cultivated meat products become more familiar.

Although alternative proteins bear a striking resemblance to low-carbon technologies that have scaled, it is not at all certain that the switch to novel replacements will succeed. Food transition certainly requires a diversity of approaches including advocacy for policies like carbon taxes that penalize externalities, conventional diet change campaigns with willing institutions, continued experimentation with feed additives that may slightly decrease livestock footprints, and promotion of the most scalable interventions to reduce food loss and waste. Nonetheless, of the three broad strategies explored, disruptive replacement with alternative proteins is the most likely to succeed. In terms of sustainability, alternative proteins—at this time, especially plant-based and fermented products—present tremendous opportunities to reduce the environmental footprint of food not available through animal production reform. These benefits will continue to increase as production becomes more efficient and grids across the globe get cleaner. In terms of scalability, shifting to novel replacements would require consumers to make a much smaller leap than conventional diet change or learning to select more sustainable ASFs, especially since the latter will generally be more expensive than conventional ASFs. The net result is that alternative proteins enjoy an unparalleled opportunity to reach scale through market forces without major shifts in regulation or culture, presenting the most viable opportunity to engender a meaningful reduction in the biodiversity footprint of our food systems.

3. What conservation organizations can do

At present, the primary barriers preventing alternative proteins from reaching taste- and cost-parity with ASFs are technological. Innovations in food sciences, microbiology, genetics, industrial design, and related fields are needed to develop the core ingredients and products required for disruption. Since these skillsets are outside the purview of most conservationists, it may not be immediately evident what our field can do to enable the competitive replacement of animal-sourced foods.

What we have learned from the slow maturation of photovoltaic cells and other low-carbon technologies is that innovation does not happen in a vacuum—it is part of a broader social and political project. As respected leaders in sustainability, conservation organizations have key roles to play in helping expedite the development of novel replacements and their social acceptance by a broad swathe of consumers. We also should carve out a role as technical advisers that ensure any new industries that grow from this disruption serve the interests of biodiversity conservation.

Making Alternative Proteins Central to Sustainability

While the story of how solar power became economically competitive with fossil fuels is an inspiring one, it is also a cautionary tale: since governments offered only fleeting support for the technology through the 20th century, it took photovoltaics over fifty years to reach cost parity with coal (141). While this outperformed most predictions from even a decade ago (134), it was longer than ideal—and if we want alternative proteins to fulfill their potential protecting biodiversity (e.g., (53)), we need progress to be much faster. As leaders in sustainability, the conservation community must ensure that investments in research and development for alternative proteins occur rapidly and such that they satisfy public (instead of just private) interests.

The alternative proteins 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 (29, 144), innovation has largely been led by private sector companies instead of governments. In fact, despite the fact that many alternative proteins have demonstrated proof of concept by effectively achieving taste parity (145) and shown social viability by appearing on menus at Burger King, 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. All-time public investment in alternative proteins is only about 0.3% of annual investments in renewable energy (146). Since the private sector-led effort is not proceeding fast enough to achieve climate or biodiversity goals (e.g., (121)), governments must begin treating alternative proteins like other low-carbon technologies. 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 (147)—and we must make sure decision-makers understand that promoting alternative proteins is the most important thing they can do for biodiversity (113). The renewable energy sector provides an abundance of policy tools that lawmakers could implement. For technologies that are still in early stages (125)—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 (29). 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 (2, 148). 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 (121). 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 (134). 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 (2).

Conservation organizations must also use our credibility to help legitimize alternative proteins with the general public. Using campaigns like those to discourage purchase of ivory or shark-finned soup (149), the conservation community should help the public understand that purchasing alternative proteins will help protect iconic species and landscapes around the world. We need not conduct such campaigns in isolation—in coordination with partners from the public health, climate, and water conservation communities (15), we 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 (67). Since a campaign around alternative proteins can focus on what people should do instead of what they shouldn't do—and since, again, switching to alternative proteins is a lighter lift than conventional diet change—such campaigns are likely to be even more successful.

Finally, conservation technology organizations like Conservation X Labs can contribute both to necessary technological advances and greater legitimacy for alternative proteins in the conservation space through direct engagement in innovation. The use of open innovation tools—like prizes and challenges—provide a unique opportunity to generate excitement for solving crucial problems around cost-competitive ingredients and production technology. Since a diversity of approaches and sectors offer viable approaches to these problems, open competition to resolve challenges in alternative proteins technology is likely to efficiently result in new solutions.

Ensuring Alternative Proteins Serve Conservation

Getting more governmental and philanthropic support for the most promising alternative proteins must be our first priority. But in parallel, conservation organizations should also prepare to play three crucial technical roles to ensure that a transition towards alternative proteins leads to favorable biodiversity outcomes. We are uniquely incentivized to ensure that alternative proteins improve in terms of sustainability outcomes, establish the industry's production centers to optimize benefits for biodiversity, and develop socially just and technically effective ways to help areas liberated from animal agriculture or industrial fishing foster biodiversity conservation.

The conservation community should foster the development of a robust, rigorous community of experts in life cycle analyses (LCAs) specialized in both ASFs and alternative proteins. Since conservation organizations are focused entirely on the sustainability of food production, we are an ideal third party for overseeing transparent evaluations of how novel replacements compare with legacy products in terms of land use, the climate, water quality and availability, and biodiversity (86, 111, 121). LCAs can both help innovators in the alternative proteins space identify what parts of their process result in the greatest environmental harms and help policymakers understand which novel replacements will best promote public interests (111, 118). 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 (28, 111). 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 (28, 95, 111, 115, 116). 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 (83), with a particular shortage of LCAs from Saudi Arabia, Kazakhstan, or Mongolia likely exerting a downward bias on emissions estimates from ruminant land use (17). Conservation organizations could also help ensure that LCA methodologies are standardized to allow fair comparisons among alternative proteins and between alternative proteins and ASFs (57); 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 (87). Conservation organizations are also well-situated to incentivize participation in LCAs, as favorable findings could help sustainable producers gain support.

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 (69, 85), 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 (18, 129). 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 (18, 150). This is in effect what happened with palm oil in southeast Asia and with soy in South America (57, 150), 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 (151, 152). 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 (151). 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 (26, 53), 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 (18, 26). 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 (57, 153), suggesting that intensive crop agriculture may be more susceptible to effective regulation than extensive cattle ranching. If conservation had to pick between crop and livestock industries as our opponent, we would pick the former.

Finally, if alternative proteins succeed in taking market share from ASFs, conservation organizations must make sure that the next most attractive livelihood and land use options in biodiverse areas are sustainable. While alternative proteins will offer new livelihoods for those growing feedstocks, producing inputs 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 (8). With agriculture alone employing about 2 billion people, this means a transition to alternative proteins could present social concerns—and as former pastoralists and fishers seek new livelihoods or political recourse, it could present environmental concerns as well (16). Conservation organizations can get ahead of these transition pains by building on work we 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 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 (113) or biodiversity (e.g., ecotourism or carbon credits) (6), 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 (154). Globally competitive alternative proteins provide an unparalleled chance to make the animal-sourced foods less profitable, addressing the greatest threats to wildlife on the land and in the seas—but conservationists will still have to work to ensure that the new ground reality favors both biodiversity and the people that have thus far made conservation possible.

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