Chickpeas, crickets and chlorella: our future proteins

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UNIVERSITY & RESEARCH

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The vision

Global transitions to a more biobased economy are underway. As part of these transitions, WUR calls for a shared strategy on production and consumption of protein. By 2050, humans will consume more animal protein than ever, driven by an increasing population and improved standards of living. This consumption level will deplete our natural resources. Hence, a transition towards eating protein from more diverse, resource-efficient sources is needed. We envision a future in which protein production will be part of a sustainable, affordable, trustworthy and high-quality food system. Purposeful combinations of plants, animals, and microorganisms will be tailored to local conditions. To achieve this even in areas of scarce resources, breakthrough innovation, societal shifts and supportive regulatory changes are required. An integrated European platform supporting changes from farm to table will ensure that EU member states continue to lead the ongoing protein transition.

Need for change

4 drivers of protein transition

1. Environmental impact reduction

The total food production chain contributes more than **25%** of global Green House Gasses (GHGs), is responsible for **33%** of global terrestrial acidification, the majority of global eutrophication, and covers nearly 40% of the world's ice-and desert-free land[1,2]. To reach the SDG's in reducing carbon emissions and to mitigate climate change, agriculture systems must be transitioned toward sustainable nutrition sources.

For more information https://sustainabledevelopment.un.org

2. Zero hunger for a growing population

Protein malnutrition co-exists with protein overconsumption, and population growth is likely to exacerbate the imbalances. Stunting due to protein malnutrition still affects **23%** of the world's children[3]. Continuing current trends, by 2050 the world will need **30-50%** more protein to meet demand[4]. More equitable food systems are required to prevent increasing hunger and malnutrition.

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1 https://doi.org/10.1146/annurev-environ-020411-130608

2 https://doi.org/10.1126/science.aaq0216

3 UNICEF/WHO/World Bank Joint Child Malnutrition Estimates, March 2019 edition.

4 https://doi.org/10.3390/foods6070053

3. Resilient production systems

More than **70%** of the world's undernourished people live in areas of highest susceptibility to climate change[5]. As climate change accelerates, food scarcity will put more pressure on already-fragile areas and might contribute to instability and migration. Resilient protein systems are urgently needed in these fragile areas.

"When people become prosperous, they eat more meat. That is a given."
Cees Veerman, former Minister of Agriculture, the Netherlands

4. Public health

Western diets shifted from 40% of protein from animal sources in the 1960's to more than 60% today[6]. A return to a more plant-based diet in line with global dietary guidelines could prevent 5.1 million deaths by 2050 by reducing chronic-disease mortality[7].

4 trendy myths

1. We don't have enough protein to feed the world.

Not true. Insufficient supply is not the primary cause of current —or likely future— deficiencies. The current amount of protein production per annum is approximately 202,000,000 tonnes. The required amount to provide 9.6 billion people with each 50g protein per day (which provides 10% of calories from protein in a 2000-kilocalorie diet) is 175,200,000 tonnes per annum. Protein-related deficiencies exist due to an inequitable distribution of high quality proteins, with areas of overconsumption coexisting with areas of low access to specific essential amino acids. It is therefore not accurate to talk of a protein gap or even future need. If, on the other hand, global trends for increasing consumption continue, and inequitable distribution persists, future protein demand is likely to increase by 30-50% or more by 2050[8].

2. Animals are inefficient: everyone should eat vegan.

Not true. The global animal sector uses about 40% of all arable land for feed production— land which could be used to grow crops for direct human consumption. As the global population grows, becomes wealthier, and demands more animal-sourced foods, including meat, fish, dairy, and eggs, feed-food competition is likely to worsen. We acknowledge three primary scenario narratives in this domain[9]. The first is the 'efficiency' narrative, which argues that the focus should be on reduction of the environmental footprint of animal-sourced foods production as measured per kg of product. (It is worth noting that the related sub-narrative of carbon-capture beef production is hotly debated. It is true that conversion of ploughed farmlands to grassland results in a 50- to 60-year period of carbon capture. However, these gains plateau and subsequent ploughing leads to repeated carbon release. Carbon-capture beef production is therefore not a realistic long-term solution.) The second primary narrative is the 'reduction' narrative, in which the focus lies on reduction of animal-sourced foods consumption. Both of these narratives neglect the essential role of animals in biomass recycling. The alternative narrative is one of 'circularity' which focuses on optimizing the total system. In this scenario, animals contribute significantly to the human food supply by consuming non-human-edible biomass and converting these streams to high

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5 www.fao.org/3/a-i6030e.pdf

6 The protein shift: will Europeans change their diet? ING Economics Department. 2017.

7 https://doi.org/10.1073/pnas.1523119113

8 https://doi.org/10.3390/foods6070053

9 Van Zanten et al., 2018 Defining a land boundary for sustainable livestock consumption. In global change biology

quality food proteins. An optimized system based on the circularity narrative minimizes competition between feed and food, frees up 25% of global arable land, and reduces the total environmental footprint of food and agriculture compared to an animal-free system.

3. Plant-based alternatives have a lower footprint.

Partially true. Plant-based alternatives for animal-sourced foods may have the *potential* to have a lower footprint, but the current generation of plant-based alternatives rely on highly-purified, highly-processed plant proteins. Once yield losses and energy inputs are taken into account, some of the current generation of plant-based foods are less sustainable than the traditional animal-based products they aim to replace. Less refined functional ingredients and milder processing methods are needed to achieve the full potential of plant-based foods.

4. Plant proteins are of lower quality.

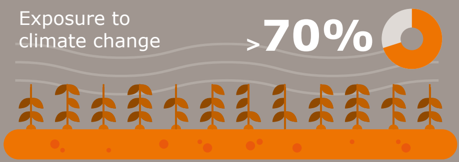
Partially true. The nutritional quality of a protein depends in the first case on the type and amount of amino acids present. While there are exceptions, in broad lines animal protein sources tend to provide a complete set of all nine essential amino acids. While most single plant sources do not individually provide complete amino acid nutrition, all essential amino acids are available as part of a plant-based diet. As long as plant sources are appropriately combined a plant-based diet can provide complete amino acid nutrition. Grains tend to be deficient in lysine and enriched in methionine. Pulses are typically deficient in methionine and cysteine, and lysine rich. A second factor in nutritional quality relates to bioavailability, which describes the ease with which proteins can be digested and used by the body. Scientific evidence indicates that plant-based proteins tend to have a lower bioavailability than animal-source proteins. In some cases, this is due to the presence of anti-nutritional factors which interfere with digestion. Further research is required to fully elucidate factors influencing protein bioavailability of emerging protein sources, e.g. pulses, algae, and others, and to develop strategies to increase bioavailability where needed. Finally, most animal-source foods are also good sources of micronutrients such as iron, calcium, and vitamin B12, and consumers who choose for a fully vegan diet require supplementation to prevent deficiencies.

The Future of Proteins
chickpeas, crickets and chlorella

1 Why is a transition needed?

Environmental impact
Food production contributes more than **25%** of global GHG emissions and covers nearly 40% of ice- and desert-free lands.

Zero hunger
By 2050 the world population will demand **30-50%** more protein.



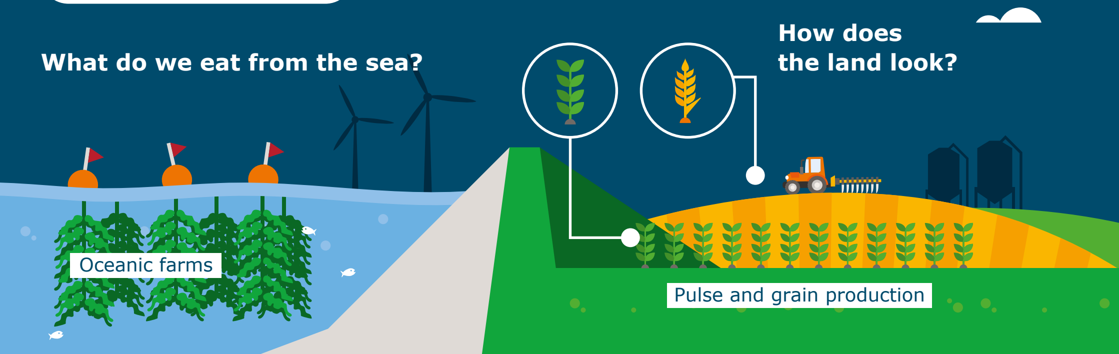
Resilient production
More than **70%** of the world's hungry live in areas with greatest exposure to climate change.

Public health
Current dietary patterns result in up to **5.1 million** additional deaths through chronic disease mortality compared to a more plant-based diet in line with dietary guidelines.

3 Europe in 2050?

What do we eat from the sea?

How does the land look?

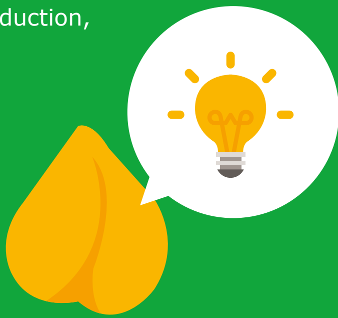


2 What can we do?

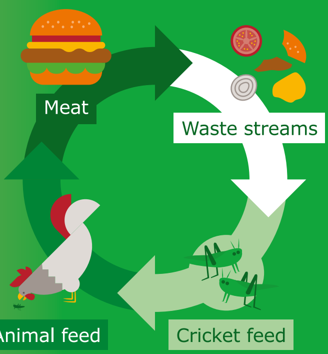
To achieve a systems change, technology, production, and consumption developments must align.

Technologies: improved crops

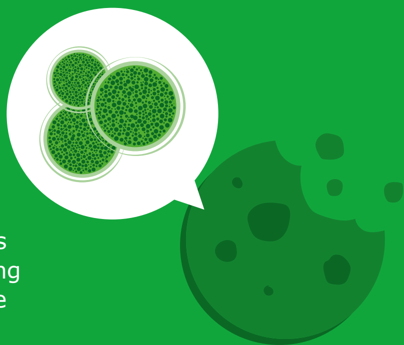
Efficient, nitrogen-fixing crops, like **chickpeas** should be optimized for protein yield, complete nutrition, and total use.



Production: animals in a circular system



Animals, including insects like **crickets**, should be repositioned to upcycle loss, eliminating competition between feed and food.



Consumption: a diverse palette of options

A broader collection of protein-rich plants should be made widely available, including aquatic crops like **chlorella** which can be produced with minimal resources.

What do we eat?

How is our food sourced, processed, and distributed?

Action routes

4 technology routes to increased protein availability

1. Improved crops

Directed plant-breeding presents an enormous opportunity to increase yields, to provide improved nutrition without changing supply chains or eating patterns, and to mitigate the impact of the looming climate crisis. Only a few of the world's crops have been optimized for protein yield, and to-date none have been optimized for complete amino acid nutrition. Some efforts are underway to breed climate-resilient staple crops, but these efforts are isolated and not comprehensive. The few breeding efforts to improve protein content have mainly been directed at the plant organs (fruits, leaves, and seeds) that are directly used for food. The remaining plant organs, such as stems and leaves of many crops, contain considerable amounts of proteins that could be explored for food and feed applications. Before such proteins can be economically extracted and used in the food chain, breeding steps are required to facilitate this process. Pulses, including faba beans, lentils, or **chickpeas** may have the first focus as they are suitable for cultivation across much of Europe and have the added benefit of nitrogen fixation.

"Food security has been mainly looked at from the point of view of the amount and of the energy, but not from the quality and the diet diversity, vitamins and minerals— type of nutrients really assessed. Probably, those agricultural interventions should be aimed at filling the nutrient gaps rather than creating new accesses in some areas."
Francesco Branca, WHO

2. Innovative aquatic production systems

The world's oceans cover 71% of the earth's surface yet provide only 7% of the world's current protein supply. Oceanic resources today are not pro-actively managed; intervention is mostly limited to crisis response. By 2050 70% of the world's population will live in coastal areas (up to 100km from the sea). Coastal and oceanic resources can be effectively managed as productive agricultural systems. For example, wind farms being built as part of the green energy transition could be combined with food production systems based on aquatic crops like

seaweed, kelp, or microalgae. Technology investments are needed to develop new oceanic production and harvest concepts. Furthermore, while algae are highly efficient in converting nutrients to protein, the energy required to extract proteins is currently prohibitive from an economic and sustainability perspective. Low-energy innovative conversion technologies are needed before the full potential of these crops can be reached.

3. Biosynthesis and recombinant proteins

Protein production can be decoupled from land and sea resources by exploiting novel protein sources from bacteria, yeasts, and fungi via industrialized production. These systems have the potential for far higher yields, grow based on flexible inputs, and can be a complementary part of circular systems. Fungal mycoproteins are already widely consumed as meat alternatives. The energy input and associated cost of mycoproteins is likely to fall with technology innovations currently in development. With genetically modified organisms, it is possible to express animal-identical or custom-designer proteins from bacteria or yeast. This type of proteins are generally referred to as recombinant proteins. Large-scale production of recombinant protein is being pursued by a number of start-ups worldwide. These include large scale production of specific functional proteins and recombinant milk- or egg-identical proteins. These technologies are not yet economically feasible for bulk proteins, but improvements in production yield and purification efficiency are likely to make them viable in the coming years.

4. Reduced food loss and waste

Food loss and waste are significant contributors to protein inefficiency. The amount of food lost or wasted varies per continent from 42% in North America and Oceania to 15% in Latin America. In Europe, 22% of food is lost or wasted, of which 52% is post-consumer waste. Production of this wasted food contributes 110 Mton GHG emissions per year to the European total. The role of protein becomes clear when these emissions are allocated to specific product categories; the single biggest contributor is wasted bovine meat, followed by milk, wheat, and pork (pig meat). A contrasting picture emerges from sub-Saharan Africa, where food loss and waste represents 23% of total production, but 96% of the total is pre-consumer loss. Converting lost and wasted food to GHG emissions, the lost and wasted food from sub-Saharan Africa contributes 140 Mton GHG per year[10]. In regions where **waste** is the primary challenge, two solution routes can be envisioned. One is upcycling of waste via circular by-design systems, covered in the subsequent section of this document. A second, complementary, solution direction is to ensure maximal yield by extracting proteins from post-industrial streams like spent brewers grain, potato processing water, and rapeseed press cake. The regions of highest food **loss** will benefit most from circular-by-design food systems, supported by growth in food processing capacity. The large-scale food processing systems developed in the West cannot —perhaps should not— be copied one-to-one. Starting at the supply side, smallholder farmers are not able to provide the volumes required for large-scale processing. Cooperative structures present a possible solution but take time to build, especially in areas with low social capital. In the meantime, flexible, modular, and even mobile processing systems present the greatest opportunity. These small-scale food processing units reduce transportation costs, reduce post-harvest degradation, can be moved according to seasonal production patters, and strengthen local economies. Processing for preservation has obvious benefits for food safety and stable supply. Processing for ease of use for crops like pulses may also reduce the drivers toward calorie-rich and nutrient-poor alternative packaged foods.

10 Porter, S.D., D.S. Reay, P. Higgins, E. Bomberg (2016), Sci. Total Environ., 571, pp. 721-729.

4 production system redesigns

1. Animals in a circular system

Feed and food are currently competitive but they need not be; animals can consume biomass that is not suitable for humans including grassland and leftovers such as crop residues, co-products from industrial processing, and food losses and waste[11]. Through animal husbandry and aquaculture, these streams can be converted to highly nutritive foods. Ruminants are particularly valuable for their ability to convert grassland into milk, meat, and manure. Pigs and insects like black soldier flies, mealworms or **crickets**, could be effective in converting post-industrial side streams and post-consumer waste, but European regulations currently prevent use of many of these streams. Insects and fish have higher reproduction rates and no energy allocation for the maintenance of a constant body temperature, making them efficient recyclers. Rearing only the amount of animals that can be fed on industrial side streams, waste, and marginal lands, would result in an available maximum of 23g terrestrial animal protein per person per day. Capture fishery and aquaculture can add to the available total. Capture fishery is the only large-scale food production based on a natural resource, requiring no feed input (apart from some bait use). Capture fishery production is necessarily limited by biologically sustainable levels, currently specified by the EU Maximum

Sustainable Yield framework. We estimate that captured fishery levels within biophysical boundaries on the short term would yield an additional approximately 2g protein per person per day. The current average global supply of terrestrial animal protein per capita per day is 32g. Achieving an optimized production system therefore requires a small decline in animal protein consumption per person, but more importantly, a complete system redesign to eliminate competition between food and feed. It is important to note that feed-food competition is not the only trade-off in biomass flows. Biomass used for food or feed might also be used for biomaterials or even energy production. The governing hierarchical model for biomass allocation is an important ethical choice. The model applied here represents a hierarchy in which our primary need for food dictates the preferred outlet for consumption-suitable streams, and feed is applied as a means for upcycling to food. Biomass and energy are outlets only for non-food and non-feed streams.

> *"Insects have a very good conversion rate from feed to meat. They make up part of the diet of two billion people and are commonly eaten in many parts of the world... Eating insects is good for the environment and balanced diets."*
> *Kofi Annan, former UN secretary*

2. New nitrogen cycles

Nitrogen is converted to proteins by living organisms. Nitrogen which is used as input to protein production is therefore an important resource. On the other hand, over-enrichment of nitrogen in fresh water systems is a common problem in areas of intense agriculture. Circular production systems aim to convert all available nitrogen to protein, increasing total system yields and reducing runoff into the local water systems. At this time, no country- or continent-based coherent nitrogen system design has been developed. Initiatives are needed to create quantitative understanding of nitrogen cycles and to design nitrogen-optimized protein source portfolios. The classic nitrogen cycle primarily used in agriculture runs from fertilizer, via plant production, feed production, and animal husbandry, to manure which is then applied as fertilizer. When plants are able to fix nitrogen from the air, as pulses are able to do, it is possible to create nitrogen fertilizer-independent production systems and thus partially decouple soil quality from animal production.

11 Van Zanten et al., 2019. The role of farm animals in a circular food system. Global Food Security. Accepted.

3. Production as part of the living environment

Agricultural landscapes have become an iconic part of the cultural identity of many European member states. To be socially accepted, the transition to more sustainable protein production must maintain local quality of life for both farmers and residents. Food production and recreation can co-exist in coastal areas, heathlands, and food production forests. These diverse production areas are increasingly studied for their synergistic efficiencies and increased biodiversity using companion plants and animals. As yet, these systems have not been optimized for protein production, and attention is needed to increase their protein yields. Additionally, as the global population continues to move to ever-larger urban areas, attention is needed to provide access to fresh foods in the cities. Datafication can be used to harmonize supply and demand, but long supply chains for fresh foods also contribute to GHG emissions. An alternative is cultivation of complete nutritional crops indoors, in urban greenhouses or vertical farming. These options require the development of suitable varieties for these new production systems, and circular design at the scale of the city. Aquaculture, or cultivation of protein-rich streams like algae, can be synergistic with fresh fruit- and vegetable-production. Production of proteins close to the consumer would also open new opportunities to develop new fresh protein crops or crop organs.

4. Global entrepreneurship toward sustainable systems

An artificial dilemma is sometimes presented in countries and regions with relatively efficient and low-footprint production: "if production is reduced here, it will shift to other countries with less optimized systems and consequently increase emissions." It is true that opportunities to reduce agricultural footprints are most effective when considered from a global perspective; introducing strict legislation in Europe will likely only push production abroad to regions with lower sustainability standards. However, this artificial dilemma neglects the possibility of exporting knowledge and investing in maturation of production in under-developed regions. In areas with underdeveloped supply chains, it is possible to leapfrog over inefficient linear production systems directly to optimized circular systems. Targeted local initiatives should tackle region-specific issues. The next wave of global agricultural development is likely to focus on sustainable intensification in the Southern hemisphere. European countries should pro-actively work to transfer knowledge to local entrepreneurs, contribute to rapid maturation of supply chains, and secure environmentally and economically sustainable systems worldwide.

4 pillars of consumption shifts

1. A diverse palette of options

Consumers have demonstrated a willingness to rapidly embrace new foods; recent years have seen explosive growth in consumption of crops like quinoa, kale, and a number of so-called superfoods. Industry, environmental, and societal stakeholders can collaborate to encourage consumption of high-yield, weather-tolerant plants. Wageningen researchers work on new sources like duckweed, which grows exponentially on freshwater worldwide; sea buckthorn which demands few resources and grows in sandy soil; and **chlorella** and other strains of algae which require only sunlight and nitrogen-rich water. Private sector actors can also play a role in increasing consumption diversity; the World Wildlife Fund has been pursuing collaboration with food industry partners to introduce a variety of new foods, including cactus, parsley root, and pumpkin flowers. A diverse and varied diet is a key part of healthy nutrition and provides environmental as well as public health benefits, but access to those diets is limited in specific areas. Consumption diversity will also provide greater flexibility in production systems and thus enable responsive shifts to a changing climate.

2. Consensus on a healthier aspiration

Emerging scientific consensus links the affluent-country (animal-rich) diet to reduced overall health, increased risk of chronic disease and reduced intestinal microbial diversity. Despite the clear downsides to this diet, it is being adopted across the globe; increasing GDP is closely correlated to increasing meat consumption. When the starting point is over-consumption of animal protein, a shift back to a more balanced animal-plant consumption ratio is expected to reduce the overall prevalence of chronic disease. Still, specific groups like the elderly, pregnant women, and children can be at risk of protein deficiency. For example, with age, the body's ability to digest and utilize proteins decreases, and elderly consumers tend to struggle to consume an appropriate volume of food. Care must be taken not to harm at-risk groups when defining a protein-specific nutrition narrative.

> *"I believe that milk will be one of the solutions to combat any food shortages that may occur. Milk is a primary food staple for the world's population of more than 7 billion people. Scores of malnourished and food-insecure children across the world receive crucial nutrients from milk."*
> *Ban Ki Moon, former UN secretary*

(In comparison, encouraging increased consumption of fruits and vegetables is beneficial for all target groups.) Furthermore, as new proteins are introduced, it is important to evaluate the risk of allergy development by studying immune responses for early markers. In developing nations, where protein-related malnutrition is prevalent, increased access to animal protein sources will be beneficial. By delivering a complete amino acid source and valuable micronutrients animal-based proteins have the potential to address deficiencies.

3. Improved plant-based alternatives

In OECD countries, annual market growth in plant-based foods of 12-18% suggests that plant-based alternatives are attractive to certain segments of consumers. Long term, it remains debatable whether plant-based alternatives which resemble meat are required. These products may be most beneficial as transitional products which address the needs of specific meat- and dairy-centric consumers. While a shift to plant-based is desirable, there are ways in which the

current generation of plant-based alternatives is sub-optimal. Many are produced from highly-refined, highly-processed ingredients. This high degree of processing may have detrimental health effects; a better understanding of the impact of processing on human physiological responses to protein consumption, for example inflammation (an early marker for allergenic reaction), is needed. The high degree of purity and high energy inputs to processing these foods also severely reduce their potential gains on environmental impact. Furthermore, consumers report dissatisfaction with the currently available options for both their hedonic value as well as their perceived 'artificial' nature. Less-processed, better-tasting alternatives could potentially entice more traditional eaters to shift toward more-plant based products. Increased consumption of minimally-processed plants remains the long-term goal.

4. Attracting consumers to healthy & sustainable choices

Related to protein transition, efforts so far have focused on persuading consumers to change behaviour through education/information campaigns. Consumption, however, is often not the result of an individual, deliberate decision-making process. Dietary behaviour is strongly routinized and habitual. Social, physical, and cultural contexts combine to make consumption patterns change-resistant. This resistance is even greater with meat, which is used as an expression of status and identity. To prevent a drastic increase in global meat consumption in the coming decades, it is essential to first understand the complex nature of the association between meat and identity. Communication about the protein transition should also be carefully considered in order to prevent reflective backlashes in population subgroups. For example, if plant-based alternatives to animal-sourced foods become associated with high-educated, urban populations, adoption of these alternatives may remain limited to a dedicated consumer niche. Contextual clues like portions, price, available, and accessibility have been shown effective in influencing a single choice setting, however the total impact of these single-choice interventions must be examined within a broader context. Research related to the green energy transition clearly showed a tendency toward compensation behaviour. Protein transition research will have the greatest impact by seeking to identify the total impact of interventions; meatless Mondays will not contribute positively if they lead to consumption of double portions on Fridays. Creating a significant dietary shift likely requires a mixture of coordinated instruments including communication, nutrition education in schools, food policy, choice architectures, and economic measures.

4 bad excuses for inaction

1. We only need to work on demand; supply will follow

Systems change requires that we work on both.

Efforts to motivate rich-world consumers to adopt a plant-rich diet and to create a healthier aspiration are certainly worthy, but ineffective in isolation. Demand and supply must evolve hand-in-hand. In parallel to consumer-focused interventions, we can work to ensure technology and supply-chain readiness. Many actors have significant capital investments in the established system and only a total-chain approach can overcome the vested interests.

2. We can change the whole system by adapting pricing.

Price adjustments may be part of the solution but not the whole solution.

Marginal increases in pricing toward the true environmental cost of agricultural production may have a small beneficial effect on both consumers and providers.

However, studies investigating pricing and behaviour in related areas show that the magnitude of this change is not large enough to address the currently-needed change. Increasing the price of less-sustainable options like meat, which is already expensive, may even be counterproductive in regions and subpopulations where meat is consumed to signal status and wealth. Pricing strategies that reduce the price of healthier and more sustainable options may be more promising. However, price-related strategies should be implemented very carefully to avoid potential inequitable outcomes, with disproportionate impact on lower-income consumers.

3. We require quantitative, authoritative between-source comparisons and international databases to proceed.

We cannot let the ideal situation stand in the way of a better situation.

In an ideal world, each actor in our protein systems would have direct access to quantitative footprint analyses for every source, under every set of growing conditions and use scenarios, to guide their decision-making. Still, qualitative directions are already clear: the OECD countries need to reduce animal protein consumption; waste should be reduced; feed should be based as much as possible on products not suitable for human consumption; and climate-fragile areas require robust protein supply chains.

4. We have time.

To avoid increasing undernourishment and inequity we must act now.

Climate change is a reality, and action is needed sooner than we thought. Agriculture represents a significant piece of global GHG emissions, and a new agricultural system must be part of the solution. The current moment presents an opportunity to create a new global protein system for a sustainable, nutritious, and equitable food supply.

Priority actions

4 research agendas

1. Plant breeding for nutrition and total use

The focus of plant breeding in the last century has been mostly on increasing yield of edible parts of the crop and disease resistance. Limited efforts have been made to develop crops adapted to abiotic constraints, such as drought, heat and salinity. The non-edible organs on the plant have remained untouched by breeding programs, partly due to their limited economic value. This means that we are not making efficient use of plant-produced biomass, where valuable components such as proteins are part. The limited economic value and use of this biomass is mostly due to the fact that this biomass is difficult to process for access to useful compounds. To resolve this bottleneck a concerted action of plant breeders (to develop more amenable crops) and process technologists (to develop more efficient technologies) is needed. The animal (-protein) production chain has been effectively optimized for total use and valorization of all side streams into co-products, and this knowledge could be used to improve the efficiency of plant production. We call for a major European initiative to reorient plant breeding programs in alignment with the demands of downstream food processing.

2. Animal production in a circular food system

While our research clearly indicates substantial benefits of animals in a circular food system, further modelling is required to envision the optimal scales of circularity, and to detail recommended land use changes per region. Trade-offs in land use, GHG emissions, and biodiversity must be addressed. Furthermore, the circularity narrative must be placed in societal and social context. For example, insects may form a powerful part of the circularity narrative, but their limits to adoption are dependent on changing consumer attitudes. Rearing animals under a circular paradigm requires a supply chain transition from linear to circular. Future research should be undertaken jointly by an ecosystem of actors, in collaboration between government, public sector, industry, investors, and academics. Circular-by-design systems should be prioritized in climate-fragile, regions with currently-underdeveloped supply chains.

3. Mild processing

There are many reasons to explore alternative routes to food production. A high level of food processing clearly contributes to a high environmental impact by requiring energy and water inputs. Each processing step also reduces yield and each refining step reduces the crop valorization case. Emerging research also points to a potential contribution to inflammation reactions, which contribute to chronic disease and may be early indicators for allergy development. The nutritional quality of proteins may also be reduced by loss of (free) amino acids during processing. In practice, application of less refined ingredients requires new technology platforms as well as knowledge development. Technology platform development for ingredient processing should focus on avoiding or improving drying, the most energy intense unit operation in most protein ingredient production. In food conversion, sterilization is typically the most energy intense process, so alternative preservation strategies have the greatest potential benefit. When moving to less refined ingredients, a higher level of scientific understanding of the interaction of various food components is required. Formulations based on highly purified ingredients are predictable, and thus more easily controlled than formulations based on more intact crop fractions in which proteins are often bound to fibres, starches, fats, and other minor components. The most effective instrument to develop these technology and knowledge platforms are public-private partnerships, which stimulate industry investment in longer-term developments.

"In the future, we will make use of the natural structure of our foods instead of using highly-refined additives. By mildly processing, we will retain more fibre and micronutrients, make better use of our harvested crops, and spend less water and energy."
Prof. Dr. Remko Boom, Wageningen University

4. Shifting consumption

Prior to implementing any communication or intervention strategies, it is essential to establish an understanding of the complex drivers resulting in current consumption patterns. The nature of the interlinkage between meat consumption and social status should be understood. Potential backlashes should be elucidated and preventative strategies developed. Consumer communication campaigns should be tested carefully to identify any inadvertent negative consequences for at-risk groups like elderly consumers. Intervention strategies should not be studied in a single-decision setting, but placed in a sufficiently broad context to measure potential compensation behaviour. Incremental approaches for the broad population, such as a gradual addition of plant-based protein to traditional animal-source products, should be considered alongside the less-familiar alternatives targeted to the highly-motivated population. A European ecosystem approach to develop, pilot, and share best practices in consumption shifts is recommended.

4 governmental initiatives

1. Provide a regulatory fast-track for new protein sources and new production circles. A possible quick-win can be achieved by creating room for permitted exceptions to regulation for companies and institutions to pilot test innovative solutions.
2. Level the playing field: eliminate subsidies which contribute to the low price of animal proteins.
3. Empower regional governments to experiment with outreach and interventions to encourage sustainable consumption.
4. Create a shared EU-level food policy innovation centre to bring together stakeholders, to test innovative policy directions, and to align local, regional, national, and European initiatives.

4 priorities for the private sector

1. Create supply chain collaborations for new sources.
2. Increase transparency in environmental impact.
3. Invest in a strong knowledge base in proteins' functional properties to enable application of less refined ingredients, milder processing, and protein substitution.
4. Create product offerings to stimulate diversity in consumption, including incremental approaches for the broad population.

4 outreach partners for knowledge institutes

1 Schools and parents to support implementation of nutrition education and school food policies to establish lifelong awareness and healthy habits, including a reduction in animal-source protein consumption and increasing consumption of fruits and vegetables.
2 Health care providers to ensure the needs of fragile populations like elderly, allergen-sufferers, pregnant women, children, and recovering patients by providing up-to-date, science-based information into protein requirements.
3 Retail and out-of-home channels to help make the sustainable choice the easy choice by sharing insights into drivers for consumer choice.
4 Media to increase public engagement with the protein transition. Knowledge institutions are uniquely able to provide accessible information grounded in sound science.

The European Committee on Agriculture and Rural Development states that "The EU is suffering from a major deficit in vegetable proteins, which are used to feed the livestock, and is dependent on imports from third countries." Europe urgently needs an ambitious protein supply plan.
Jean-Paul Denanot, MEP

4 snapshots of European food systems in 2050

1. What do we eat?
European consumers enjoy a diet primarily based on whole foods from a variety of sources. Pulses like fava beans and grains like quinoa are combined to form a solid nutritional basis for most meals. These are complemented by occasional consumption of a variety of new protein sources: water-based plants like duckweed and kelp; plants cultivated on marginal lands like sea buckthorn and cactus; and bacterial and fungal biomass like mycoprotein. Animal protein consumption from a mixture of meat, fish, dairy, eggs, and new species of animals is on average 10kg per person per year or about 28g per day. Local circular greenhouses integrate protein production with fresh fruit and vegetable cultivation, leading to increased access to and consumption of fresh foods.

2. How is our food sourced, processed, and distributed?
Europe maintains a strong global trade position based sustainable innovations in

agriculture. Protein imports and exports are in balance. The total energy footprint of the European agri-food system has been drastically reduced by technological breakthroughs in food processing. A rich variety of new and traditional food products is available, based on minimally-refined plant sources. Food distribution systems are optimized so that no food is wasted; circular production systems upcycle industrial side streams and post-consumer waste through animal protein production. The digital revolution has enabled harmonization of supply and demand.

3. What do we eat from the sea?

Oceanic farms which combine green energy production and protein production can be seen from much of the European coastline. After a period of reduced fishery catch designed to enable oceanic ecosystems to recover, the open sea fish numbers have increased and Europe's oceanic resources again provide a rich source of proteins and omega-3 fatty acids to the population. Supplemental fish protein is produced through sustainable aquaculture based on feed from algae, seaweed, and industrial side streams.

4. How does the land look?

The European landscape includes a more diverse collection of protein-rich crops, based on a flourishing ecosystem of pulse production and a variety of plants growing on lands typically not considered prime farm lands. Food production and recreation co-exist in biodiverse food forests and coastal areas. The total number of ruminant animals is reduced and cattle are grazed on marginal lands planted with deep-rooted perennial plants. Pigs and insects are fed primarily with post-consumer waste streams.

Colofon

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