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Sustainable food protein supply reconciling human and ecosystem health: A Leibniz Position

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A R T I C L E I N F O

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A B S T R A C T

Many global health risks are related to what and how much we eat. At the same time, the production of food, especially from animal origin, contributes to environmental change at a scale that threatens boundaries of a safe operating space for humanity. Here we outline viable solutions how to reconcile healthy protein consumption and sustainable protein production which requires a solid, interdisciplinary evidence base. We review the role of proteins for human and ecosystem health, including physiological effects of dietary proteins, production potentials from agricultural and aquaculture systems, environmental impacts of protein production, and mitigation potentials of transforming current production systems. Various protein sources from plant and animal origin, including insects and fish, are discussed in the light of their health and environmental implications. Integration of available knowledge is essential to move from a dual problem description ("healthy diets versus environment") towards approaches that frame the food challenge of reconciling human and ecosystem health in the context of planetary health. This endeavor requires a shifting focus from metrics at the level of macronutrients to whole diets and a better understanding of the full cascade of health effects caused by dietary proteins, including health risks from food-related environmental degradation.

1. Introduction

Agriculture affects earth system functioning through various impact channels (Foley et al., 2005) and significantly contributes to the transgression of planetary boundaries for biosphere integrity and biogeochemical flows, and to increasing the risk of their exceedance for land-system change and freshwater use (Campbell et al., 2017; Steffen et al., 2015). Owing to population growth, projected dietary transitions and more food waste, the role of agriculture as a driver of environmental change will become even more critical (Bajželj et al., 2014; Bodirsky et al., 2014; Hiç et al., 2016; Popp et al., 2017). These demand-side trends may increase environmental impacts by 50–90% until 2050, if no mitigation measures are taken, which could push the food system beyond environmental limits (Springmann et al., 2018).

However, food consumption is not only crucial in view of ecosystem health. Undernutrition and obesity substantially contribute to the total

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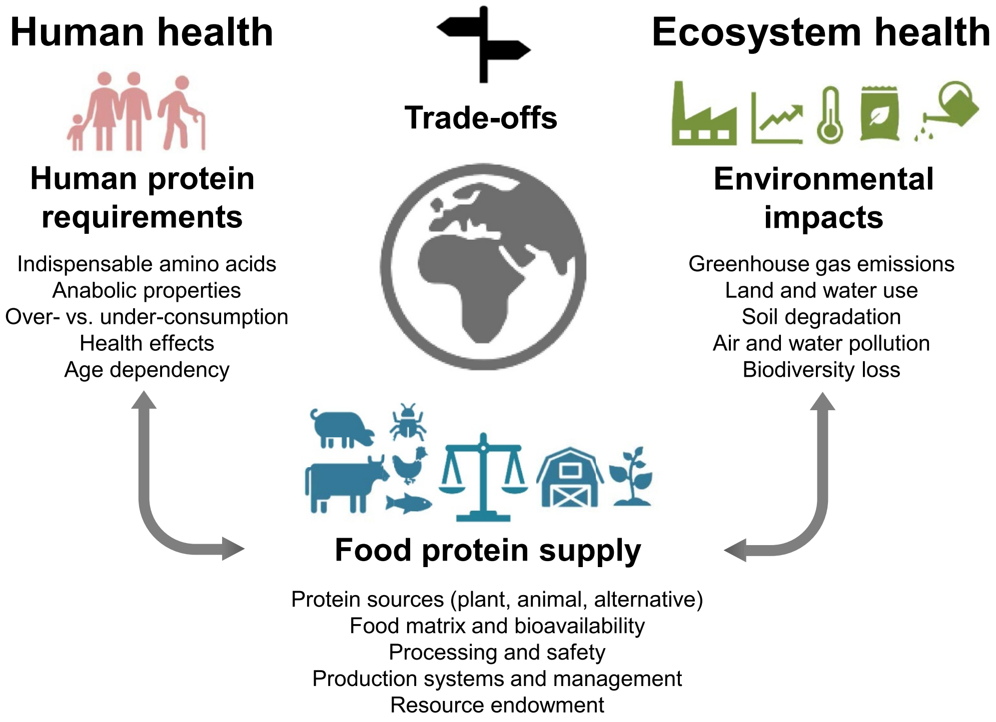

Fig. 1. Sustainable food protein supply at the intersection of human and ecosystem health.

burden of disease (GBD, 2017 DALYs and HALE Collaborators, 2018). Over the past decades, dietary patterns have been shifting considerably, from under-to over-nutrition and away from freshly produced to processed food high in carbohydrates, fat and sugar, and to animal-based protein (Adair et al., 2012; Popkin, 1993). This is mirrored by an increasing importance of health risks related to overnutrition by affluent diets (GBD, 2017 DALYs and HALE Collaborators, 2018).

At the intersection of human and ecosystem health, it will be a major challenge to re-align future protein supply and demand, especially from animal-source food, towards a “safe operating space for food systems” (Willett et al., 2019) that accounts for both human nutritional requirements and environmental implications (Fig. 1). Proteins derived from animals have a higher biological value than those from plants (Smil, 2002), referring to the proportion of absorbed food protein that is incorporated into body proteins, but their environmental footprint is much larger (Clark and Tilman, 2017; Steinfeld et al., 2006). Moreover, there is still uncertainty about the appropriate intake of proteins from different dietary sources and their corresponding health effects (Levine et al., 2014; Smil, 2002).

The development of viable solutions how to reconcile healthy protein consumption and sustainable protein production requires a solid evidence base, grounded in complementary expertise in physiology and pathophysiology of nutrition, agriculture, aquaculture, ecophysiology, and earth system research. During a Leibniz Workshop held in Potsdam on March 22–23, 2018, organized by the interdisciplinary Leibniz Research Alliance “Sustainable Food Production and Healthy Nutrition”, we brought together different perspectives from various scientific disciplines on dietary proteins in the context of human and ecosystem health (neglecting other food components such as fatty acids or vitamins). Within the workshop, consensus statements were formulated giving the positions shared by the participating scientists, which build the basis for this position paper.

The consensus statements cover biological value, bioavailability and nutritional physiological effects of classical and alternative dietary proteins, the potential of agriculture, aquaculture and insect food production to ensure sustainable protein supply, and the environmental footprint of dietary proteins dependent on their origin. Based on this summary of evidence, we identify lessons learned, research gaps and limitations of current approaches for adjusting dietary protein supply both with regard to human and ecosystem health and define cornerstones of an interdisciplinary research agenda that frames the food challenge of reconciling human and ecosystem health in the context of planetary health.

2. Current evidence on proteins, health and the environment

2.1. The biological value of different dietary proteins

Leibniz consensus: The biological value of different proteins depends on the availability of the limiting indispensable (formerly termed essential) amino acid. It is generally highest for dairy and egg protein, followed by meat and other animal proteins. It is lower for plant protein with legumes as one of the best plant protein sources. The biological value of insect derived protein has not yet been systematically assessed, but from the available data it can be considered similar to meat protein. Finally, mixtures from different sources with complementing amino acid composition can overcome a low biological value of individual foods.

Background: Protein as a source of indispensable amino acids is an important macronutrient. There is a continuous turnover of protein in the body depending on various factors such as age, muscle mass, activity level, and health status. Based on nitrogen balance, protein requirements have been set at 0.8 g/kg of body weight as the recommended daily allowance to ensure a sufficient supply of indispensable amino acids for healthy adults (Phillips, 2017). Considering an adult weight range of 50–100 kg, this amounts to a recommended daily consumption of 40–80 g of dietary protein. Optimal dietary protein intake is still a controversial topic of discussion. On one hand, increasing protein intake has an anabolic effect, and diets with a high proportion of protein are effective in the prevention and treatment of obesity and associated disorders. On the other hand, the idea that a reduced energy and reduced protein diet prolongs life is gaining ground, and epidemiological studies showed that a protein-rich diet is associated with a higher risk of disease (Klaus et al., 2018).

Table 1
Protein quality scores (PDCAAS and DIAAS) of selected food sources. *Source*: Phillips (2017).

Food source[a]	Food	PDCAAS	DIAAS	Limiting AA
Animal (dairy)	Milk protein concentrate	1.00	1.18	Met + Cys
Animal (dairy)	Whey protein isolate	1.00	1.09	Val
Animal	Egg (hard boiled)	1.00	1.13	His
Animal (meat)	Chicken breast	1.00	1.08	Trp
Plant (legume)	Soy protein isolate	0.98	0.90	Met + Cys
Plant (legume)	Pea protein concentrate	0.89	0.82	Met + Cys
Plant (legume)	Chickpeas	0.74	0.83	Met + Cys
Plant (legume)	Tofu	0.56	0.52	Met + Cys
Plant	Almonds	0.39	0.40	Lys
Plant	Cooked rice	0.62	0.59	Lys
Plant	Corn-based cereal	0.08	0.01	Lys

Note: AA, amino acid; DIAAS, digestible indispensable amino acid score; PDCAAS, protein digestibility-corrected amino acid score.

[a] No reliable data for insect protein available.

The biological value of proteins is determined by their digestibility and amino acid composition, especially their content of indispensable amino acids that cannot be synthesized endogenously. The optimal intake of indispensable amino acids is determined empirically using feeding experiments mainly in rats. Assessment of dietary protein quality is based on the content of the limiting indispensable amino acid (s). Scoring methods commonly used are the PDCAAS (protein digestibility-corrected amino acid score) and the DIAAS (digestible indispensable amino acid score) which score protein quality based on fecal digestibility (Phillips, 2017) and intestinal uptake (true ileal digestibility), respectively (FAO, 2013).

Animal derived proteins (including insects) have higher nutritional value than plant proteins since the amino acid composition of animal proteins is more similar to human protein composition (Table 1). However, combinations of different plant proteins and/or supplementation with limiting indispensable amino acids can ensure a high dietary protein quality. Among plants, pulses (legumes), especially soybeans, have the highest protein content and best amino acid composition and are therefore an important source of dietary protein (Henchion et al., 2017). Woolf et al. (2011) developed a computational tool (vProtein) to identify optimal food complements to satisfy human protein needs. Their top ranked food parings include obvious examples such as sesame seed flour/soy protein isolates, but also less obvious ones such as sweet corn/tomatoes and apple/coconut.

2.2. Physiological effects of classical and alternative dietary proteins

Leibniz consensus: Anabolic properties (postprandial muscle protein synthesis) are lower for plant proteins compared to animal proteins. It should be studied whether this can be compensated by fortification of food with indispensable amino acids, by consumption of greater amounts of plant-based protein, and/or by the ingestion of multiple plant protein sources (= balanced amino acid profile). Future research regarding insect-based protein and muscle protein synthesis is warranted. Taking into account the age- and health status-related protein demands, there are conflicting data of metabolic and health effects of low vs. high and animal vs. plant protein, which needs further investigation.

Background: Dietary protein is an essential nutrient required to preserve muscle mass as well as vital function and regulates whole-body metabolic health. Besides physical activity, the ingestion of amino acids and/or protein strongly stimulates postprandial muscle protein synthesis (MPS) (Koopman, 2011). The only plant-based protein source that has been extensively studied in humans is soy protein, demonstrating lower MPS rates compared to the ingestion of whey, milk, or beef protein. This may be attributed to differences in protein digestion, amino acid absorption kinetic and/or the indispensable amino acid composition. Various strategies to improve the muscle anabolic response after ingestion of plant-based proteins include the fortification of plant proteins with free amino acids, the blending of various plant protein sources to create a more balanced indispensable amino acid profile and the consumption of greater amounts of plant proteins (van Vliet et al., 2015).

Although epidemiological studies show that dietary protein intake and type 2 diabetes mellitus (T2DM) risks are positively correlated in humans (van Nielen et al., 2014), it has been suggested that protein-specific mechanisms offer novel opportunities for the treatment of metabolic diseases and promoting health span (Morrison and Laeger, 2015). In contrast, intervention studies in subjects with T2DM recently demonstrated that high protein diets based on either plant or animal protein strongly reduced liver fat content, an indicator of metabolic dysfunction (Markova et al., 2017). Furthermore, isocaloric diets high in animal or plant protein allow similar improvements in metabolism and cardiovascular risk factors in patients with T2DM, indicating that the source of protein does not affect the metabolic responses to the interventions (Sucher et al., 2017).

Adequate dietary protein intake combined with continuing exercise is important to limit and/or treat age-related declines in muscle mass, strength and functional abilities (Deutz et al., 2014). Notably, low dietary protein intake can help to prevent cancer and other diseases in middle-aged adults (50–65 years), while in adults aged 65 and older, high protein consumption was found to reduce all-cause (including cancer) mortality which was unaffected by relative energy intake from fat, carbohydrates, or animal protein (Levine et al., 2014). Interestingly, the association between protein intake and mortality in younger adults was either attenuated or abolished if the proteins were plant derived.

2.3. Food-matrix effects on the bioavailability of dietary proteins

Leibniz consensus: The bioavailability of proteins in the food matrix is influenced by several factors including the presence of phenolic compounds. Food matrix-protein-interactions could decrease the amount of available amino acids via oxidation and covalent reactions, e.g. with phenolic compounds, resulting in the formation of protein conjugates.

Background: Major sources of high-quality vegetable protein include leguminous plants, oil plants and pseudocereals (amaranth, quinoa) (Zralý et al., 2006). In addition, fruits and vegetables are also a source of phenolic compounds, for instance pea and kale are rich sources of flavonoids such as kaempferol and quercetin glycosides (Neugart et al., 2015; Schmidt et al., 2010). The intake of these metabolites is associated with anti-cancerogenic and anti-inflammatory effects (Kashyap et al., 2017; Wang et al., 2016). However, food matrix-protein-interactions can be found within plants as well as in compound foods and are influenced by thermal processing. Similar to protein--protein interactions, hydrogen and ionic bonding and hydrophobic and aromatic interactions are possible. Covalent bonds are of special interest, since they are irreversible (Rohn, 2014). There is controversial discussion about how low molecular weight carbohydrates, such as sucrose, possibly inhibit formation of protein-proanthocyanidin aggregates by competition for hydrogen-bonding sites of proanthocyanidins (Ribas-Agustí et al., 2017). The effects depend on the type of protein and phenolic compound involved. Especially complex phenolic compounds with a high number of hydroxyl groups have a comparably high affinity for proteins (Bohn, 2014) and decrease protein bioavailability (Bohn, 2014; Ribas-Agustí et al., 2017).

During thermal processing phenolic compounds are decreased in the food matrix due to leaching or oxidation (Bohn, 2014) and undergo deglycosylation and deacylation along with an increased antioxidant activity (Fiol et al., 2013). This was also shown for leafy vegetables baked into a bread dough matrix (Klopsch et al., 2018). Therefore, the decrease of phenolic compounds during food processing could decrease undesired protein-phenolic compound interactions. Concomitantly, proteins are denatured during thermal food processing, which does not affect their bioavailability. To which extent this affects protein-phenolic compound interactions or the generation of other protein containing compounds needs to be addressed in future investigations.

2.4. The potential of legumes to increase protein supply from fields

Leibniz consensus: Legumes have a large potential to increase protein production sustainably based on their high protein content and their ability to fix nitrogen. Demand for protein-rich crops in Europe is high, which is currently not covered by domestic production. In view of a changing climate and given the heterogeneous environmental conditions in Europe, cultivating a higher variety of better adapted legumes is required to increase protein self-sufficiency and contribute to healthy diets. Policy promotion and field management improvement play an important role for tapping the full potential of legumes.

Background: Grain legumes provide high-protein seeds for food and feed (Kirkegaard et al., 2008). Fodder legumes such as clovers and alfalfa are an important protein source in animal husbandry. Legumes provide various important ecosystem services such as biological nitrogen fixation, pollination, pest control and the yield enhancement of subsequent crops (Watson et al., 2017). The biological nitrogen fixation reduces the use of chemical fertilizer and enables nitrogen supply oriented towards the requirement of the crop (Kimura et al., 2004).

Currently, 71% of the demand for high-protein crops in Europe is imported, of which 87% is met by imported soybean and soybean flour that is mostly used in livestock feed (Bouxin, 2014; Houdijk et al., 2014). Grain legumes are only grown on 1.5% of the arable area in Europe, dominated by soybean, pea, and faba bean (Eurostat, 2016). Legumes became increasingly unattractive to farmers because of lower profits and especially yields staying far behind that of cereals. Moreover, broad-leaved crops (including legumes) have more unstable yields than cereals (Watson et al., 2017). Small investments in breeding and insufficient farmers' knowledge on legume management practices are considered as two underlying causes (de Visser et al., 2014; Magrini et al., 2016; Zimmer et al., 2016).

The diversity richness in species and varieties of legumes provides possibilities to site-specifically select adapted legume species as well as varieties for the cropping system, i.e. timing of seeding, duration of growth, environmental requirements and targeted yield. Improving field management such as pest, disease and weed control, crop rotation design, and intercropping of grain legumes with cereals contributes to yield stability (Bedoussac et al., 2015). To concur challenges and benefits of including legumes into the cropping system, a systems approach must be adopted to evaluate effects on the overall production of a farm, instead of focusing on yields of individual crops. Acknowledging the positive effects of cropping legumes on soil and food quality in agro-environmental measures, especially in future common agricultural policy (CAP), is necessary for increasing the attractiveness of domestically cultivated legumes for consumers and producers and for incentivizing targeted agronomic research. Policy promotion plays an important role for the development of legumes, pulses and cover crops in Europe in order to reach a higher self-sufficiency, in addition to changing dietary habits to lower meat consumption.

2.5. The potential to sustainably produce proteins in marine and freshwater systems

Leibniz consensus: Capture fisheries have largely transgressed sustainable maximum yields, which makes aquaculture the only option to sustainably meet progressively raising fish demand of a growing global population. This development trajectory calls for pathways towards sustainable aquaculture intensification by boosting the culture of non-fed (e.g. shellfish and seaweeds) and lower trophic-level species (e.g. herbivorous fish and invertebrates) and by a transformation towards heterogeneous, multi-trophic and integrated production systems.

Background: Fish is critically important for the global provision of animal protein (Béné et al., 2015). While per capita fish consumption rates differ drastically between countries, ranging from 60.4 (Korea) to 5.2 (India) kg/capita/year (Thilsted et al., 2016), fish and fish products are globally a pivotal protein source, especially in low-income countries. Around 3 billion people source about 20% of their daily animal protein from fish and related aquatic products (Béné et al., 2015; Costa-Pierce, 2016). To meet the expected per capita fish demand in 2030 (200 Mt), aquaculture production needs to increase by 20% (FAO, 2018).

Current aquaculture practices, predominantly monoculture, are widely dependent on supplemental feed, based on wild fish and food-grade crops (e.g. soy), which poses the biggest sustainability challenge (Béné et al., 2015; Duarte et al., 2009; Troell et al., 2014). However, novel feed protein sources including marine invertebrates, microbial protein (Matassa et al., 2016), insect meal (see section 2.6), and hydrolyzed feather meal (Tschirner and Kloas, 2017) represent promising secondary alternatives (not in competition with resources for direct human consumption) for fishmeal and fish oil. Moreover, relative to terrestrial livestock production, the aquaculture sector currently gives more promising circular economy options, e.g. recovery of byproducts and wastes (Hall et al., 2011), and causes less dramatic interferences with the most pressing environmental challenges (e.g. CO_2 emissions and eutrophication), as measured per unit protein produced (Béné et al., 2015). Besides the praises and promises, aquaculture also provokes various environmental concerns, mainly about pollution and disease transmission between farmed and wild organisms as observed for current aquaculture practices.

The vast amount of potential marine aquaculture (mariculture) candidate species, including non-fed and lower trophic-level species from diverse feeding niches, brings mariculture at the forefront of sustainable protein production. In this context, “Integrated Multi-Trophic Aquaculture” (IMTA) promises the largest sustainability gains. IMTA combines the culture of fed species (e.g. fish) with extractive organisms, such as various invertebrate species and algae (Barrington et al., 2009; Chopin et al., 2001). In this way feed residues and excretions from the fed species are recovered and transformed into valuable, food-grade biomass, which in turn enhances feed-use efficiency and product variety, and mitigates environmental impacts. In freshwater aquaculture, the recently developed decoupled aquaponic system (Kloas et al., 2015) combining fish and vegetable production is the most advanced approach. Aquaponics use the nutrient rich fish waste water for irrigation and as fertilizer for plants, providing especially nitrate and also phosphate and further minerals. However, modern aquaponics request some initial technical investment and thus might need more practical proof before large scale facilities will be used. Ultimately, aquaculture needs to close its production cycle to strive for full independence from agricultural resources.

2.6. The potential to use insect protein in food and feed

Leibniz consensus: The potential of using insect protein in food and feed is enormous and insects already contribute to environmentally sustainable protein supply in several regions of the world. However, techno-functional and physiological properties of insect proteins remain a poorly studied field of research. For industrial production, there is high demand for criteria assessing the suitability of rearing and technological processes for establishing safe insect products considering hazard analyses.

Background: Edible insects are characterized by an excellent nutritional profile (Akhtar and Isman, 2018; Payne et al., 2016; Rumpold and Schlüter, 2013) and more than 2000 different insect species are consumed on a regular basis by two billion people worldwide (entomophagy) (Huis and Tomberlin, 2017; Jongema, 2017). Insect larvae are among the future foods that were suggested to provide good-quality alternatives for current animal-source foods (Parodi et al., 2018).

However, insects are rarely used by the European food industry, but they are subject of growing interest as an alternative source in the food and feed sector (Grau et al., 2017; House, 2016; Huis and Tomberlin, 2017; Schlüter et al., 2017). The revised EU Regulation (2015/2283) on novel foods facilitates marketing of insects and their products as novel foods across Europe (Fernandez-Cassi et al., 2018).

The majority of the insects consumed are still gathered in the wild (Schlüter et al., 2017) but mass-rearing on an industrial scale in the Western world is developing (Mlcek et al., 2014; Smetana et al., 2019; Veldkamp et al., 2012). However, risks associated with the use of insects in the production of foods and food ingredients (such as the accumulation of hazardous chemicals) have not yet been sufficiently investigated. Research regarding microbial aspects in selected edible insects showed that they need to be processed and stored properly (Klunder et al., 2012; Stoops et al., 2016, 2017; Vandeweyer et al., 2017). More scientifically based knowledge on insect processing has to be generated to ensure food safety, especially when these processes are carried out on an industrial scale (Rumpold et al., 2017; Schlüter et al., 2017; Vandeweyer et al., 2017; Wynants et al., 2019). Also, there are only limited data available on the sustainability of insect mass rearing. Some existing data suggest lower land use and greenhouse gas (GHG) emissions per edible protein from insect compared to livestock production (Grau et al., 2017) but do not allow to draw general conclusions on the environmental footprint of rearing insects on an industrial scale.

Species-specific safety aspects as well as the impact of processing methods on the nutritional or functional quality of insects and their components in food need to be considered and determined (Bußler et al., 2016); feasibility and economic aspects of processing steps and processing routes need to be further assessed (Pleissner and Smetana, 2020). Consumer acceptance is important and can be increased if insects are invisibly incorporated into conventional food matrices and improved sustainability is shown (Hartmann and Siegrist, 2017).

More research is needed on production and processing methods on an industrial scale including microbial safety and nutritional quality aspects of edible insects. Thus, hazard analyses, identification of critical control points (CCPs), and potentially required preventive programs (Hazard Analysis and CCPs concept) must be developed. Key aspects include the determination of insect and product-specific processing parameters, the clarification of legal aspects in Europe and non-European countries, and the design of specific production and processing equipment.

2.7. *The environmental footprint of different protein sources*

Leibniz consensus: The environmental footprint of different foods shows a consistent ranking across a broad range of indicators and different units (per gram mass, protein or kcal). It is highest for beef, intermediate for seafood, pork, poultry, eggs and milk, and lowest for plant-based foods. Environmental impacts of dietary protein also depend on the production system, agro-ecological conditions and local resource endowment. The assessment of alternative proteins is still at an early stage.

Background: Agriculture is a major cause of environmental degradation through land, nutrient and water use, pollution and biodiversity loss (Campbell et al., 2017). Life cycle assessments (LCAs) are a standardized method (ISO 14040 and 14044) to assess environmental impacts of individual foods and production systems. Many meta-analyses were conducted focusing on GHG emissions (Clune et al., 2017) and animal-based products (de Vries and de Boer, 2010; Nijdam et al., 2012). Irrespective of expression in mass, kcal or protein, they consistently associate plant-based foods with the lowest GHG emission intensity, followed by milk, eggs, poultry, pork and seafood with intermediate impacts, to ruminant meat associated with highest impacts (e.g. Table 2). The bottom-line of these studies is substantiated by water footprint assessments (Mekonnen and Hoekstra, 2012) and recent meta-analyses (Clark and Tilman, 2017; Poore and Nemecek, 2018), that include several indicators such as GHG emissions, land use, acidification and eutrophication.

Table 2
Land use and carbon footprint per kilogram protein for different foods with high protein content, based on several life cycle assessment (LCA) studies (cradle to retail) analyzed in Nijdam et al. (2012).

Food group[a]	Land use		GHG emissions	
	m^2 kg^{-1} protein		kg CO_2-eq kg^{-1} protein	
	Mean	(Min-Max)	Mean	(Min-Max)
Beef extensive	1132	(164–2100)	192	(58–643)
Beef intensive	98	(75–143)	115	(45–210)
Beef from dairy cows	37	(37-37)	51	(45–62)
Pig meat	55	(40–75)	29	(20–55)
Poultry meat	31	(23–40)	15	(10–30)
Sheep meat			238	(51–750)
Milk	39	(26–54)	34	(28–43)
Eggs	39	(29–52)	27	(15–42)
Seafood from fisheries			68	(4–540)
Seafood from aquaculture	21	(13–30)	28	(4–75)
Vegetal protein[b]	18	(4-43)	7	(4-17)
Other meat substitutes[c]	12	(8-17)	26	(17–34)

GHG: greenhouse gas.
[a] Definition of food groups according to Figs. 1 and 2 in Nijdam et al. (2012).
[b] Vegetal protein covers dry pulses (protein content 20–36%) and meat substitutes on the basis of plant-based protein (protein content 8–20%).
[c] Other meat substitutes contain egg or milk protein and have a protein content of 15–20%.

These results suggest that lower consumption of animal-based products and diet shifts within food groups (e.g. from beef to poultry) reduce environmental degradation. However, dietary changes occur in a certain time frame and induce feedbacks in the food system, precluding a linear upscaling of environmental impacts with consumption. Moreover, the environmental footprint of foods varies considerably depending on local resource endowment, climatic conditions, management and production systems (Herrero et al., 2013; Nijdam et al., 2012), while most LCAs investigate intensive systems under agro-ecological conditions in OECD countries.

Consequently, the wide range of environmental impacts, especially from livestock, is even conservative and less an indicator of uncertainty than of mitigation potentials. Generalization of solutions is however complicated by the multifaceted nature of sustainability. Grassland-based systems with low stocking density can sequester carbon and preserve biodiversity (Soussana and Lemaire, 2014), but land requirements and lifetime methane emissions are high (Clark and Tilman, 2017). Other options include improved feed efficiencies (Smith et al., 2013) and better nutrient cycling by (re-)integrating crop and livestock farming. Here, temporary grassland can improve crop rotations, while animals are often fed with non-food biomass and provide organic fertilizer, sometimes also traction and insurance (Franzluebbers et al., 2014; Herrero et al., 2010). The availability of non-food biomass and the viability of grassland-based systems, or conversely the risk for land expansion, crucially depend on the socio-economic context including market and demand dynamics and teleconnections via trade.

In contrast to LCAs, spatially explicit agro-economic models quantify environmental implications of transformation pathways in the entire agricultural sector. They account for indirect and remote repercussions of demand signals, potentially causing leakage of environmental impacts (Popp et al., 2014). While emphasizing the role of productivity, economic processes and policies for environmental protection, modelling studies support the conclusion from LCAs that a transition from high-impact to low-impact foods increases the sustainability of the food system across a range of indicators (Bajželj et al., 2014; Bodirsky et al., 2014; Weindl et al., 2017). Notably, Springmann et al. (2018) could not only model the environmental benefits of diet

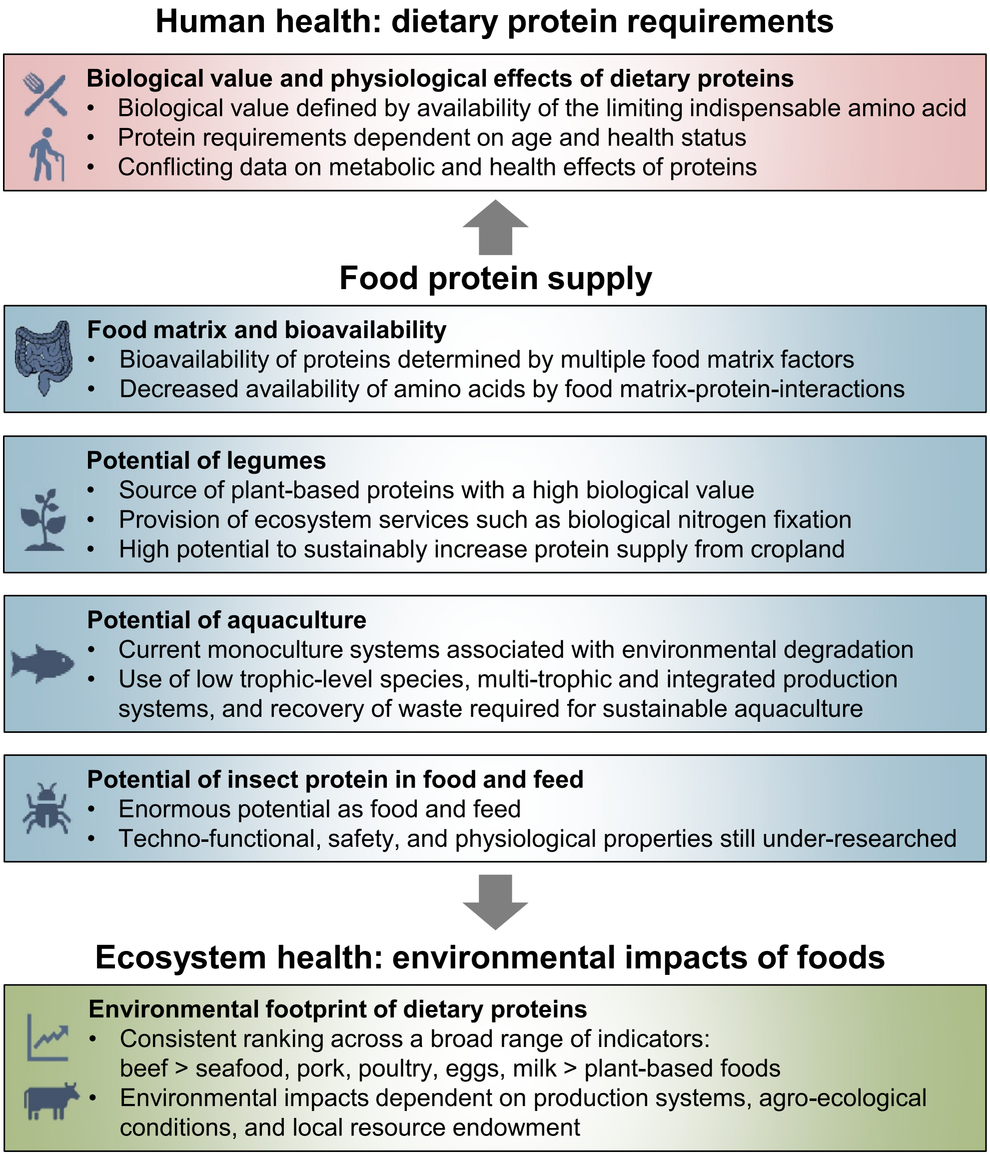

Fig. 2. The Leibniz Position on the role of proteins for human and ecosystem health.

shifts towards dietary guidelines, but also demonstrate that it is impossible to keep the food system within planetary boundaries without dietary changes towards more plant-based, flexitarian diets.

3. Lessons learned

3.1. The trade-off between environmental sustainability and protein quality

At the first glance, the Leibniz Position (Fig. 2) seems to perpetuate the dual narrative of a dilemma where the sufficiency and quality of future protein supply for a growing world population is in an inescapable trade-off constellation with environmental protection: Animal-source food is rich in protein of high nutritional value, but its production requires much more resources and causes severe environmental degradation. These two statements are already two of three powerful ingredients from which the storyline of a *protein trade-off* ("human versus ecosystem health") can be constructed: 1) increasing demand for protein due to population growth and socio-economic development, 2) the higher biological value of animal protein, and 3) the lower environmental footprint of plant protein.

But already on this upper layer of problem description and almost axiomatic interpretation of projected protein demand, the consensus statements offer three pathways to attenuate the trade-off between supply of high-quality protein and environmental sustainability: 1) Switching to more sustainable animal-source food: While variances in protein quality between animal-source foods are small, the range of their environmental footprints is substantial. 2) Increasing the share of plant-based proteins from multiple plant sources: Protein quality refers to the content of the limiting indispensable amino acid. Combining different plant proteins of complementary amino acid composition can overcome the lower biological value of individual plant proteins. 3) Exploring the full portfolio to sustainably produce proteins for food and feed by tapping the potential to provide plant proteins from fields, improve nutrient cycling and resource use efficiency in animal agriculture, transform current monoculture aquaculture to multi-trophic and integrated production systems that recycle nutrients, and use alternative protein sources like insects, which have a favorable amino acid composition, a low environmental burden, and can potentially be used to upcycle agricultural waste. Crucial to these pathways is a societal shift in the ideal of meat being a status symbol for prosperity towards being a dietary protein source with unfavorable ecological foot print which should be eaten in moderation.

On the inner layer of the apparent protein dilemma of an adequate and sustainable diet, a thorough understanding regarding drivers and

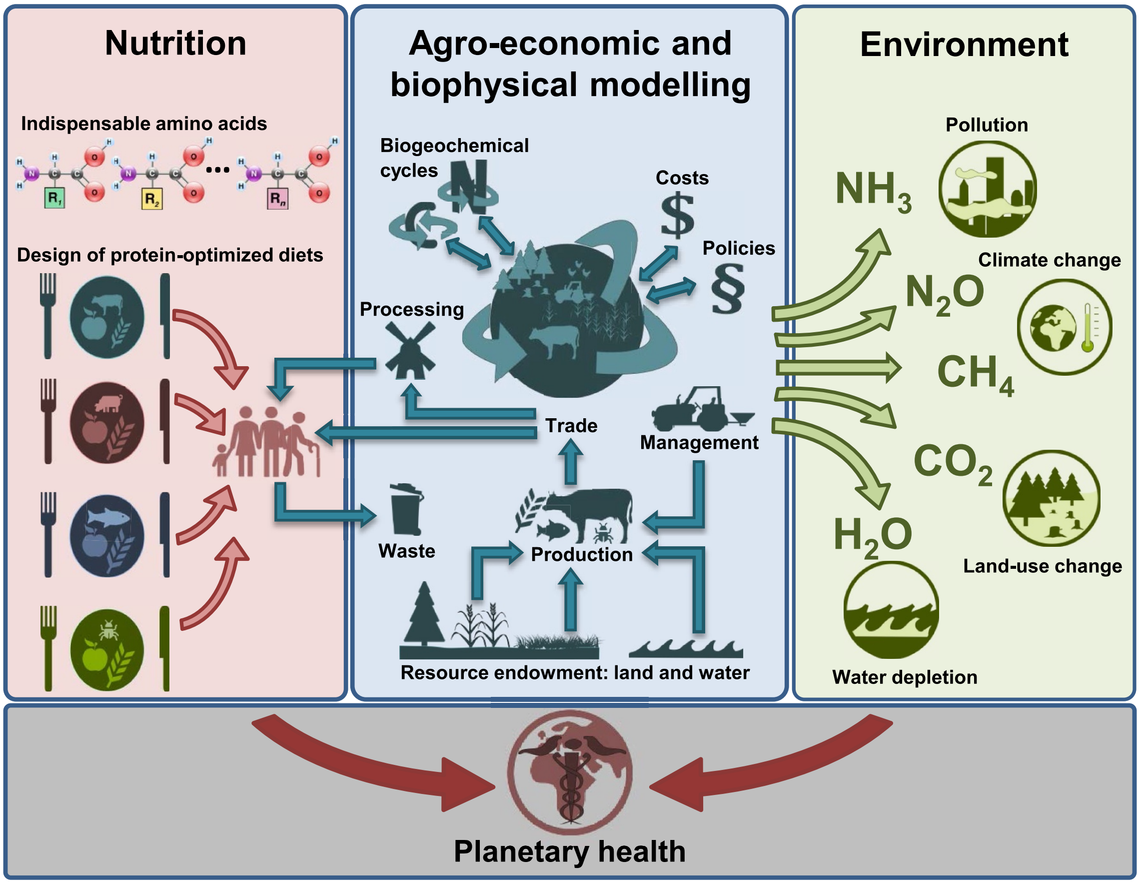

Fig. 3. Towards an interdisciplinary framework in protein research that enlarges the option space for reconciling human protein requirements with environmental protection. Study diets should contain different foods that in combination fulfil human requirements for indispensable amino acids and be evaluated according to their environmental impacts.

health implications of future protein demand, including distributional issues and overall health effects of plant versus animal protein, is crucial for its resolution. There is still uncertainty regarding the optimal intake of dietary proteins for different population sub-groups, which is, however, smaller than differences between protein under- and oversupply in many low- and high-income countries (Smil, 2002). This uncertainty is part of the second storyline of a *protein paradox*.

3.2. The protein paradox in the context of human health

The *protein paradox* refers to the controversial discussion evolving around the health effects of dietary proteins (Klaus et al., 2018), including the level of intake, the protein source and interactions with other macronutrients. As the consensus statements point out, there is clear evidence that increasing protein intake has an anabolic effect which is lower for plant proteins compared to animal proteins. Moreover, high-protein diets applied in intervention studies were effective in treatment and prevention of obesity and related metabolic disorders (Astrup et al., 2015; Markova et al., 2017). However, there is conflicting evidence on the overall health effects of dietary proteins, where especially epidemiological studies demonstrate positive effects of low-protein diets on life expectancy and risk of disease, including cancer and type 2 diabetes mellitus (Levine et al., 2014; van Nielen et al., 2014). Here, the negative effects of dietary proteins were stronger in the case of animal proteins.

This observation from epidemiological studies, which do not collect data on macronutrients but on the intake of all food groups, points to the important role that individual foods and complete diets have. The overall health effect of diets with different levels of animal and plant proteins is mediated by other macronutrients like carbohydrates and fat, and by micronutrients like vitamins and phenolic compounds, which also affect bioavailability of proteins. While plant-based foods often contain high levels of dietary components with favorable health effects, such as dietary fiber and some vitamins, increased red meat intake is associated with an elevated risk of cardiovascular disease, type 2 diabetes and colorectal cancer (Jannasch et al., 2017; Willett et al., 2019). Moreover, the processing of food is of great importance, in the case of red meat additionally increasing risk of disease and mortality (Abete et al., 2014). There is increasing awareness that overall dietary patterns rather than the consumption of specific food components are associated with health outcomes. A recent meta-analysis identified eating patterns characterized by red and processed meat, refined grains, high-fat dairy, eggs, and fried products as being positively associated with diabetes risk, whereas patterns characterized by vegetables, legumes, fruits, poultry, and fish were inversely associated with diabetes risk (Jannasch et al., 2017).

With unsolved puzzles regarding the optimal protein intake for human health, future research should be targeted toward integration of evidence from interventional and epidemiological studies and consolidate different perspectives on healthy nutrition focusing on macronutrients, food groups and diets, possibly leading to an update of dietary guidelines (including alternative protein sources such as insects).

3.3. Broaden the problem to solve it

The Leibniz Position is based on research areas that are traditionally separated into scientific disciplines and communities that all share the overarching aim of finding solutions to the challenge of a sufficient, equitable, healthy and sustainable protein provision for an increasing population. However, a better description of the option space to provide healthy food for everybody within environmental limits requires scientific approaches that acknowledge multiple end-points for sustainable development and the intrinsic connection between human well-being and the state of natural systems on which it relies.

With ongoing environmental change, it will become increasingly important to study health effects of human interventions in nature, especially via food systems, in view of their environmental feedbacks and related long-term consequences for human well-being. This perception motivated the concept of planetary health that transgresses the anthropocentric view in the field of public health (Whitmee et al., 2015).

4. Towards a new interdisciplinary framework in protein research

Inter- and transdisciplinary approaches will be essential to respond to the challenges ahead. Integration can be achieved gradually starting from disciplinary approaches, e.g. by evaluating observed diets not only with regard to protein composition and health effects, but also quantifying their environmental footprint by using static coefficients from LCAs, a workflow from environmental to nutrition science.

A complementary workflow from nutrition to environmental science forms the basis of exploring emerging environmental impacts of a transition from current towards different theoretical diets, which spell out possible realizations of an optimized amino acid supply for human health, by means of biophysical and agro-economic modelling (Fig. 3). Hereby, a broad scope of food production systems and available protein sources including marine and freshwater aquaculture, insects, and other alternative proteins is important, which calls for dedicated research to determine their nutritional and environmental effects.

Ambitious integration could also be achieved by an equitable representation of nutrition, health and environment within integrated assessment models of planetary health. Available models used in climate change studies and the broader sustainable development context with a detailed representation of agriculture (Popp et al., 2017) could be extended by evaluating both simulated diets and resulting environmental impacts in view of their health effects. The successful coupling of a global health model accounting for diet and weight related risks with an agricultural model is a promising example of recent advances in simultaneously modelling health and environmental impacts (Springmann et al., 2018).

The viability of step-wise and ambitious integration depends on a clear definition and communication of the required interfaces: What information does the public health community need from environmental science to understand health risks from diet-related environmental degradation, e.g. risk of cancer and asthma associated with agricultural nitrogen pollution (Erisman et al., 2013; WHO, 2003; Wolfe and Patz, 2002)? What data are required in modelling studies investigating the configuration and feasibility of large-scale transformation pathways, for instance in the context of the UN Sustainable Development Goals (SDGs), to optimize future diets according to human protein requirements not only in terms of quantity but also quality?

Finally, solutions to future protein supply in accordance with planetary health have to be tailored to the region-specific context to exhibit practical relevance. In regions where livelihoods largely depend on agriculture, sustainable and healthy diets are linked to economically resilient agricultural systems and socio-economic factors like access to education, markets and capital. In affluent regions, protein overconsumption has to be conceived in view of its socio-economic and psychological drivers, including consumers' uncertainties and misconceptions regarding healthy protein intake, to enable stakeholders in the areas of public health, policy and food industry to develop strategies for increasing the adoption of healthy and sustainable diets. Of course, besides an adequate protein supply, this also needs to include other food related health and environmental aspects such as micronutrient adequacy and the environmental impacts of dietary oil and sugar supply.

5. Conclusion

A key challenge for sustainable development is to re-direct projected increases in food demand, especially for animal-source food and dietary proteins, towards healthy diets and a safe operating space for food systems. In interdisciplinary collaboration, we assembled current evidence on the role of proteins for human health, the potential to sustainably supply proteins from land and oceans, and the environmental footprint of dietary proteins depending on their origin. The synthesis of disciplinary perspectives allows describing two manifestations of the protein dilemma to satisfy human protein requirements within environmental limits: a protein *paradox*, constituted by conflicting evidence on health effects of dietary proteins, and a protein *trade-off* between the conflicting goals of human well-being and environmental protection.

To resolve the latter, we emphasize the vital need to advance the integration of disciplinary research efforts to describe the full portfolio of solutions on the demand- and supply-side and, no less important, the full cascade of human health effects surrounding nutrition, from dose-response effects of macronutrients, to impacts of complete foods, dishes and diets, towards downstream effects along the food system and on the environment, with repercussions on human health via various channels like air and water pollution. Even without accounting for these knock-on effects, what and how much we eat is currently dominating global risks for human health.

Declaration of competing interest

None.

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