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Production and supply of high-quality food protein for human consumption: sustainability, challenges, and innovations

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The Food and Agriculture Organization of the United Nations estimates that 843 million people worldwide are hungry and a greater number suffer from nutrient deficiencies. Approximately one billion people have inadequate protein intake. The challenge of preventing hunger and malnutrition will become even greater as the global population grows from the current 7.2 billion people to 9.6 billion by 2050. With increases in income, population, and demand for more nutrient-dense foods, global meat production is projected to increase by 206 million tons per year during the next 35 years. These changes in population and dietary practices have led to a tremendous rise in the demand for food protein, especially animal-source protein. Consuming the required amounts of protein is fundamental to human growth and health. Protein needs can be met through intakes of animal and plant-source foods. Increased consumption of food proteins is associated with increased greenhouse gas emissions and overutilization of water. Consequently, concerns exist regarding impacts of agricultural production, processing and distribution of food protein on the environment, ecosystem, and sustainability. To address these challenging issues, the New York Academy of Sciences organized the conference "Frontiers in Agricultural Sustainability: Studying the Protein Supply Chain to Improve Dietary Quality" to explore sustainable innovations in food science and programming aimed at producing the required quality and quantity of protein through improved supply chains worldwide. This report provides an extensive discussion of these issues and summaries of the presentations from the conference.

Keywords: agriculture; livestock; plant; protein; production; sustainability; undernutrition; stunting; food science

Introduction

The Food and Agriculture Organization (FAO) of the United Nations recently estimated that 843 million people, nearly a seventh of the world's population, are chronically hungry and a greater number suffer from nutrient deficiencies.[1] In central Africa and South Asia, 10% to 30% of children have protein malnutrition.[2,3] Approximately one billion people worldwide have inadequate protein intake, contributing to impaired growth and suboptimal health.[1–3] For example, globally 165 million children under five years of age are stunted.[1] These numbers could increase substantially, as the United Nations projected in June 2013 that the world population will reach from the current 7.2 billion to 8.2 billion by 2025 and to 9.6 billion by 2050.[4] These nutritional deficiencies highlight an urgent need to find sustainable solutions to food insecurity, particularly the availability of high-quality food proteins for human consumption. Towards this goal, on December 12, 2013, the New York Academy of

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Sciences convened the conference “Frontiers in Agricultural Sustainability: Studying the Protein Supply Chain to Improve Dietary Quality” featuring expert discussions on the science of protein nutrition, challenges and obstacles in achieving a sustainable protein supply; new technologies for the production of protein-rich foods; and dietary interventions at the levels of the farm, community, nation, and globe.

Mandana Arabi (executive director, the Sackler Institute for Nutrition Science) introduced the conference by highlighting the importance of integrating scientific, agricultural, health, and environmental sectors to build better systems for food-protein production. Speakers were Barbara Burlingame (Food and Agriculture Organization of the United Nations), Jessica Fanzo (Columbia University), Gabor Forgacs (University of Missouri–Columbia), Geoffrey von Maltzahn (Flagship Ventures), Dennis Miller (Cornell University), Prabhu Pingali (Cornell University), Mark Post (Maastricht University, the Netherlands), Charles Schasteen (DuPont Nutrition & Health Protein Solutions), Josip Simunovic (North Carolina State University), Jean Steiner (U.S. Department of Agriculture), Anna E. Thalacker-Mercer (Cornell University), Irvin Widders (Michigan State University), and Guoyao Wu (Texas A&M University). Topics presented at the meeting included (1) the role of agriculture in providing dietary protein for human consumption; (2) protein foods as sources of amino acids and micronutrients; (3) the function of dietary protein in human health; (4) challenges to the sustainability of protein production by animal agriculture; (5) approaches to solving sustainability problems; and (6) innovations in the protein supply chain. These topics are discussed in the following sections.

The role of agriculture in providing dietary protein for human consumption

Agriculture dates back thousands of years. The primary role of agriculture is to grow crops and raise livestock and poultry to provide food for human populations. Plant production takes advantage of the natural sunlight as the sole energy source while requiring fertilization and water. In contrast, domestic animals (e.g., ruminants, pigs and poultry) are raised in both extensive (e.g., grassland-based) and intensive (e.g., housing) systems, with foods of plant origin as their primary energy sources.[5] Agricultural production is key to supplying food protein and, therefore, to developing and sustaining human civilization.[6]

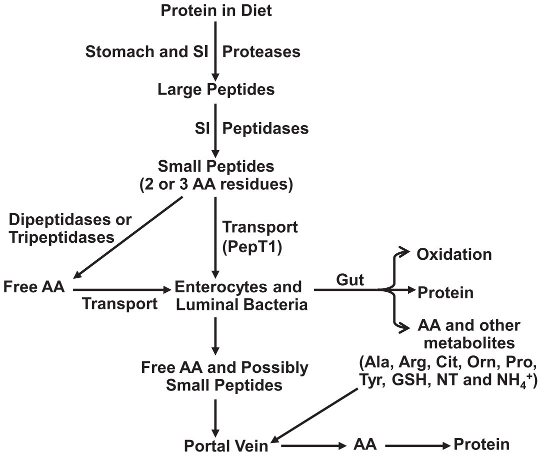


Figure 1. Digestion of dietary protein in the gastrointestinal tract of humans and animals. Proteases in the stomach and the small intestine hydrolyze dietary protein into large peptides and then to small peptides and free amino acids. Products of protein digestion in the lumen of the small intestine consist of approximately 20% free amino acids and 80% of dipeptides plus tripeptides. In the lumen of the small intestine, all dietary amino acids undergo various degrees of catabolism by luminal bacteria and some of them are oxidized by enterocytes. Uptake of ~60% and ~40% of free amino acids from the lumen of the small intestine into enterocytes is performed by Na^+-dependent and Na^+-independent amino acid transport systems, respectively. AA = amino acids; GSH = glutathione; NT = nucleotides; PepT1 = H^+ gradient-driven peptide transporter 1; SI = small intestine.

Needs for protein in human diets

There is a myth among lay individuals that humans can make proteins (e.g., insulin and growth hormone) without a need to consume dietary protein. Guoyao Wu explained that without the provision of dietary protein, which is the ultimate source of amino acids in the blood and cells, proteins cannot be synthesized in the body.[7] This myth likely resulted from a lack of understanding of protein nutrition in mammals. It should be borne in mind that utilization of dietary proteins by the body requires their digestion in the gastrointestinal tract; the absorption of digestion products (amino acids, dipeptides, and tripeptides) through enterocytes (absorptive epithelial cells of the small intestine) into the portal vein; metabolic transformation of amino acids and small peptides in a cell- and tissue-specific manner; and synthesis of tissue proteins from amino acids in the blood and cells (Fig. 1). Currently, it is very expensive to produce large amounts of crystalline amino acids, and yet humans need food proteins as major sources of these nitrogenous nutrients to support growth, development, reproduction, lactation, and health. Thus, plant and animal agriculture is crucial to providing dietary protein for human consumption.[8–15]

Plant- and animal-source foods for protein provision

Humans consume proteins in foods consisting of animal- (e.g., dairy products, eggs, fish, and meats) and plant- (e.g., cereals, beans, potatoes, cassava, vegetables, and fruits) based agricultural products.[6] Dennis Miller indicated that plant-based foods (primarily cereals and legumes) have been a major source of protein for humans for millennia. Currently, plant- and animal-based foods contribute ~65% and ~35%, respectively, of protein in human diets on a worldwide basis. In contrast, in North America, plant and animal foods provide ~32% and ~68% of total protein, respectively. With increases in population and per capita income, demand for animal-source foods is expected to increase substantially. This is particularly evident given that the population of the world is projected to reach 9.6 billion in 2050, as noted previously. As people become wealthier, average meat consumption per capita is expected to increase by 29% from 40.0 kg in 2013 to 51.5 kg in 2050.[5] Accordingly, global meat production will need to increase from 288 million tons in 2013 to 494 million tons in 2050. Because animal diets may include grains (e.g., corn and soybean) whose global supply is estimated to be relatively stagnant over the next 40 years,[5] animal production is perceived to compete with humans for food. However, it should be recognized that ruminants can consume human inedible plants (e.g., pasture grasses, alfalfa, and hay) and/or their byproducts (e.g., soybean hulls, beet pulp, brewers dried grains, and distillers dried grains), thereby converting low-quality materials to high-quality animal products (Fig. 2). Most of these ingredients are also fed to pigs. Guoyao Wu emphasized that this is indeed a unique advantage of livestock production to society.

Food insecurity and protein deficiencies

The need to substantially increase agricultural production of protein also lies in the current status of food insecurity. In October 2013, the FAO reported that 843 million people worldwide (including children and adults) suffered from hunger, nearly all of whom reside in low- and middle-income countries.[1] Deficiencies of protein and micronutrients (including vitamin A, iron, zinc, and folate) remain major nutritional problems in poor regions of the world.[1,2] Of note, deficiencies of vitamin A, iron, zinc, and other micronutrients can result from deficiencies of dietary proteins.[3] Approximately one billion people worldwide have chronically inadequate protein intake or protein-energy malnutrition.[1–3] Partly due to protein deficiencies, vitamin and mineral deficiencies (also known as hidden hunger) affect an estimated 2 billion people worldwide with the highest prevalence being in sub-Saharan Africa and South Asia.[16] Protein deficiencies also occur in subpopulations in developed nations. For example, Dasgupta *et al.*[17] have reported that 51% of home-bound elderly subjects receiving home-delivered meals in the United States have protein intakes below the recommended dietary allowance (RDA) of 0.8 g protein/kg body weight/day.

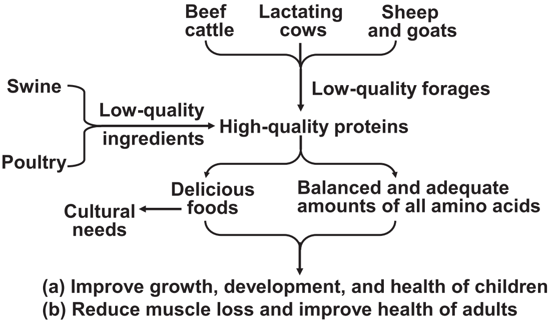


Figure 2. Nutritional perspectives of land-based production of animal proteins. Livestock and poultry convert low-quality forages or ingredients into high-quality proteins for human consumption.

United Nations Secretary-General Ban Ki-moon's Zero Hunger Challenge, announced in 2013, presents his vision for global food security: 100% access to adequate food throughout the year, 100% growth in smallholder productivity and income, 0% stunted children under age 2, and 0% food loss or waste.[8] Barbara Burlingame, deputy director of the FAO's Nutrition Division, explained that these goals are arrayed around a central aim: sustainable food systems.

Additionally, Jessica Fanzo suggested that besides agricultural sustainability, biodiversity is essential to the prevention of human hunger and the improvement of food's nutritional quality. However, the sole cultivation of plant species with a high content of specific nutrients has caused a tremendous erosion of biodiversity.[6] The recognition of varietal differences in nutrient content prompted the International Rice Commission to recommend in 2013 that rice biodiversity and nutritional composition be analyzed before genetic modification is begun. Accordingly, Burlingame discussed notable recommendations made in 2013 by the Commission on Genetic Resources for Food and Agriculture to the FAO, which are intended to promote collaboration among government sectors focused on biodiversity and environment and among academic departments and nonprofits focused on human nutrition. She pointed out that African nutrition experts have long argued that agrobiodiversity determines dietary quality and is, therefore, central to food security; but this idea is only now finding broader acceptance.

Protein foods as sources of amino acids and micronutrients

Amino acids are building blocks of protein in both plants and animals. Protein foods consist of eggs, meat, dairy products, poultry, seafood, beans, peas, processed soy products, nuts, and seeds. All of these foods contain relatively high levels of protein (e.g., $> 40\%$ on dry matter basis). In contrast, most staple foods of plant origin (except for legumes) have protein content $< 15\%$ (dry matter basis). Minerals (e.g., iron and zinc) and vitamins (e.g., vitamins B6 and B12, and vitamin A) are essential nutrients for animals and humans, and must be present in the diet. With the exception of vitamin C, animal tissues are good sources of most micronutrients. In contrast to animals, plants can synthesize all vitamins and/or vitamin precursors (β-carotene, a precursor of vitamin A) with the exception of vitamin B12, which is present in only animal-source foods. While protein is relatively stable during post-harvest storage, processing of plant- and animal-source foods can reduce their vitamin content to various degrees, depending on storage conditions, the stability of the vitamin, and time.

Plant- and animal-source foods for provision of amino acids

The quantity and quality of protein are both determinants of the adequacy of diets for meeting protein requirements.[7] Protein content in most plants is relatively low. Additionally, most plant proteins are "incomplete" in that they are deficient in one or more of the nutritionally indispensable (essential) amino acids.[7] However, proper combinations of different plant protein sources may be complementary, with one source providing the amino acid that is limiting in another source and vice versa, thereby possibly making the mixture of plant proteins "complete" sources of amino acids. In many societies, traditional diets contain both cereals (e.g., maize and wheat) and legumes (e.g., peas and beans), which are complementary for most but not all amino acids and, therefore, may meet protein requirements for adults but not for optimal growth in children.[9]

In his presentation, Irvin Widders reported that the protein quality and crop yield of legume varieties have been improved in rural Guatemala, along with their enhanced consumption by humans. Although some plant-based foods contain inhibitors that reduce protein digestibility, these inhibitors can be inactivated by adequate heat processing prior to consumption. In addition, cereals and legumes contain phytates and other factors that may inhibit the absorption of trace minerals such as iron and zinc. Diets high in these foods may increase the risk for certain micronutrient deficiencies. Guoyao Wu added that animal proteins contain adequate and balanced amounts of all amino acids for human consumption to promote optimal growth, development, and health. For example, meat and white rice contain 2.98 and 0.27 g sulfur amino acids (methionine plus cysteine) per 100 g dry matter, respectively (Table 1). To meet the Institute of Medicine–recommended dietary allowance of these two amino acids by the 70-kg adult human,[10] daily intakes of meat and white rice would be 45 and 493 g dry matter, respectively. Thus, consumption of meat can substantially reduce the need for plant-based foods to meet adequate protein requirements of humans, particularly children. While there is a common belief that there are virtually no nutrients in animal-based foods that are not better provided by plants, it is animal-source, but not plant-source, products that supply taurine (a sulfur-containing amino acid) that is essential for protecting the eyes, heart, skeletal muscle, and other tissues of humans from oxidative damage and degeneration.[11] Furthermore, animal-source, but not plant-source, foods are dietary sources of carnosine (a key

Table 1. **Composition of amino acids in meat and plant-source foods**[a]

Food	Protein and amino acid content (%, g/100 g DM)				
	Protein	Lysine	SAA	Threonine	Tryptophan
Meat[b]	66.7	4.89	2.98	3.56	0.93
Soybean[c]	42.0	2.69	1.05	1.60	0.50
Wheat[c]	11.8	0.34	0.47	0.34	0.11
Corn[c]	10.8	0.28	0.44	0.35	0.08
White rice[c]	8.2	0.19	0.27	0.18	0.07

[a] Adopted from Li *et al.*[49] and Young and Pellett.[50]
[b] Dry matter (DM) content = 30%
[c] DM content = 87%
SAA = sulfur-containing amino acids (methionine + cysteine)

antioxidative dipeptide) for humans to maintain neurological and muscular functions.[7] These facts highlight the importance of animal agriculture for the benefit of humankind.

Plant- and animal-source foods for provision of vitamins and minerals

Foods of plant origin are excellent sources of many vitamins (particularly vitamins of the B complex except for vitamin B12 that is biosynthesized only by microorganisms), but have low contents of trace minerals (Table 2). In contrast, meats, egg and milk are excellent sources of most of these micronutrients. Of note, iron in animal-source foods is absorbed by the human small intestine more efficiently than iron in plant-source foods.[12] Milk is an abundant source of calcium for bone growth. Moreover, animal-source foods are the only reliable source of vitamin B12, a nutrient that is deficient in the diets for up to 86% of children in some developing countries.[12] This presents a dilemma. Namely, low intakes of animal-source foods increase risks for protein and micronutrient deficiencies, especially in children and the elderly, but these foods are expensive and their production at a low efficiency may be environmentally unsustainable.

In her presentation, Barbara Burlingame indicated that fortified foods, as well as the supplements and therapeutic products that consist of either single nutrients or a combination of nutrients, are not the only solutions to malnutrition and that improving whole dietary patterns should be seriously considered. This further underscores important roles for protein foods (particularly foods of animal origin) as excellent sources of amino acids and micronutrients for humans.

There are metabolic interactions among proteins, vitamins, and minerals. Thus, efficient utilization of dietary protein depends on the availability of not only water- and lipid-soluble vitamins but also trace elements, and vice versa. However, as noted previously, most of trace elements and many of the lipid-soluble vitamins are deficient in plant-source foods. Thus, micronutrient fortification of staple foods has been successfully used to prevent micronutrient deficiencies in populations. Food fortification began in the 1920s with the production of iodized salt. This was followed by fortification of milk with vitamin D in the 1930s, the enrichment of flour and other cereal products with iron, niacin, riboflavin, and thiamin in the 1940s, fortification of margarines and low fat milk with vitamin A in the 1950s, fortification of infant cereals and infant formulas in the 1960s, and enrichment of flour with folic acid in the 1990s. Food fortification interventions in the United States and other industrialized countries have been credited with dramatically reducing the prevalences of goiter (iodine deficiency), rickets (vitamin D deficiency), pellagra (niacin deficiency), and iron deficiency. These deficiencies were widespread in the United States and elsewhere in the early part of the 20th century and continue to be major problems in many developing countries around the world.

Miller described his own work undertaken with HarvestPlus,[18] a global alliance of research institutions that uses plant breeding to enhance the concentrations of iron, zinc, and/or beta-carotene in staple food crops. One of his projects aimed to determine whether iron in a newly developed

Table 2. **Micronutrients from plant- and animal-source foods**

Micronutrient	Plant-source foods	Animal-source foods
Thiamin (vitamin B1)	Peas and other legumes, nuts, whole grains, and wheat germ	Meat, liver, milk, eggs, and other animal products
Riboflavin (vitamin B2)	Wheat germ, whole grains, nuts, legumes, and green vegetables	Meat, liver, milk, eggs, and other animal products
Niacin (vitamin B3)	Whole grains, wheat germ, nuts, legumes, and vegetables	Meat, liver, milk, eggs, and other animal products
Vitamin B6	Nuts, legumes, whole grains, vegetables, and bananas	Meat, liver, milk, eggs, and other animal products
Pantothenic acid	Whole grains, legumes, nuts, and vegetables	Meat, liver, milk, eggs, and other animal products
Biotin	Whole grains, legumes, nuts, and vegetables	Meat, liver, milk, eggs, and other animal products
Folic acid	Peas and other legumes, nuts, juice, whole grains, and leafy vegetables	Liver, milk, eggs, meat, and other animal products
Vitamin B12	Absent from plants	Meat, liver, milk, eggs, and other animal products
Vitamin C	Abundant in fresh vegetables, juice, tomatoes, green tea, and potatoes, but virtually absent from whole grains	Liver, milk, eggs, meat, and other animal products contain some vitamin C
Vitamin A	Absent from plants; however, dark, green, orange, or yellow vegetables are good sources of provitamin A	Liver, milk, eggs, meat, and butter are good sources of vitamin A
Vitamin D	Absent from plants; however, sun-dried vegetables contain vitamin D2	Milk, eggs, and liver are good sources of vitamin D3
Vitamin E	Vegetable oils and wheat germ oil	Meat, liver, milk, eggs, fat, and other animal products
Vitamin K	Alfalfa, pepper, whole grains and vegetables	Meat, liver, milk, eggs, and other animal products
Iron	Limited in plants, but beans and dark green leafy vegetables provide some	Meat, liver, blood, milk, and other animal products
Zinc	Limited in plants, but legumes, nuts, wheat germ, and seeds provide some	Meat, liver, blood, milk, and other animal products
Copper	Whole grains, legumes, nuts, green leafy vegetables, wheat germ, and seeds	Meat, liver, blood, milk, and other animal products
Selenium	Whole grains, legumes, nuts, green leafy vegetables, wheat germ, seeds; very limited in certain regions	Meat, liver, blood, milk, and other animal products
Molybdenum	Whole grains, legumes, nuts, green leafy vegetables, wheat germ, and seeds	Meat, liver, blood, milk, and other animal products

biofortified variant of the common bean is bioavailable for hemoglobin synthesis in animals. In one study, pigs fed diets containing beans biofortified in iron had a significantly increased total body hemoglobin iron content over those fed a diet containing a conventional variety of the common bean, suggesting that biofortified beans could increase the intake of bioavailable iron in human populations that consume beans as a dietary staple.[19] While acknowledging that micronutrient biofortification might not be a silver bullet, Miller argued for its promise as an approach to prevent micronutrient deficiencies in populations in developing countries.[20]

The function of dietary protein in human health

As noted previously, dietary protein is the ultimate source of the amino acids used to make protein in humans. In the body, proteins play important roles in (1) cell and extracellular structures; (2) enzyme-catalyzed reactions; (3) gene expression; (4) hormone-mediated actions; (5) muscle contraction; (6) osmotic regulation; (7) protection against oxidative stress, infection, and bleeding; (8) regulation of metabolism; and (9) storage and transport of nutrients (including long-chain fatty acids, iron, vitamin A, and zinc) and oxygen.[7] Therefore, dietary protein intake has an important influence on the status of other nutrients in the body and adequate protein nutrition is essential for optimal human growth and health.

Protein nutrition and children: growth and health

Deposition of protein in tissues, particularly skeletal muscle, is required for the growth of children. They are more sensitive to protein malnutrition than adults. Available evidence shows that protein deficiency is a major factor causing impaired growth in millions of children worldwide.[1–3] Using results from previously published studies, Wu reiterated that isocaloric supplementation (1050 – 1255 kJ/day) with meat to basal diets (7300 kJ/day) consisting almost exclusively of staple crops (corn and beans) could increase upper arm muscle area by 80% in 7-year-old children in Kenya, compared with the control group.[9] These findings indicate that plant proteins alone may not be adequate to support maximal growth in humans. Furthermore, infants and children with a deficiency of dietary protein exhibit impaired immune function and increased susceptibility to infectious disease.[7]

Protein nutrition and aging

Dietary requirements of protein by humans differ throughout the life span. While it was previously thought that adults need less dietary protein as they age, results of recent studies indicate that increased intake of high-quality protein can alleviate muscle loss in elderly subjects.

Indeed, Anna E. Thalacker-Mercer reported that some populations, such as older adults, are particularly vulnerable to the adverse effects of inadequate dietary protein. Her research has focused on protein metabolism in skeletal muscle, which accounts for 40–45% of body weight in healthy nonobese individuals and is the major reservoir of protein in humans.[7] When dietary protein intake is reduced, as it often is in the elderly, the body breaks down skeletal muscle protein to generate the amino acids it needs for the provision of energy, immune response and other physiological processes. Under conditions of protein malnutrition, skeletal muscle also becomes less able to synthesize protein, leading to muscle atrophy. Using advanced molecular-biology techniques, Thalacker-Mercer has further identified a crucial clue to the impact of aging on muscle metabolism from her studies of transciptome (gene expression) profiles.

Protein nutrition is a major factor affecting healthy aging in humans.[13] Globally, the aging population is growing, and in most countries life expectancy is increasing. However, this could mean additional years of impaired living from chronic disease and disability. The mass and function of skeletal muscle is a significant factor affecting the quality of life in the elderly, and this tissue is impacted by nutrition, particularly dietary protein.[21] Acute studies demonstrate that old (compared to young) adult skeletal muscle has impaired anabolic responses when the quantity of amino acids available for protein synthesis is low; responses improved with higher quantities.[14] The skeletal muscle transcriptome further supports the view that older adults have an impaired anabolic response to habitual protein consumption between 0.75–1.00 g/kg body mass per day and an augmented catabolic response when protein intakes are below the RDA values (Fig. 3).[15] Recent studies demonstrate enhanced mixed muscle protein synthesis in adults consuming ∼30 g of dietary protein at each meal throughout the day compared to a skewed dietary protein intake (i.e. the majority of protein is consumed at the evening meal).[22] Further research is necessary to determine the benefits of balancing the composition and amounts of amino acids in dietary protein throughout the day for older adults. Defining an optimum amount of dietary protein that is appropriate to maintain the availability of amino acids for biological needs is necessary, but has not been achieved in older individuals.

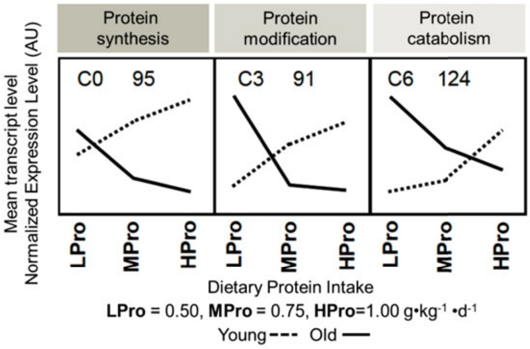


Figure 3. Representative clusters (C0, C3, and C6) from a self-organizing map showing the patterns of differentially expressed transcripts resulting from the diet-by-age interaction. Each point within a cluster is equal to the mean transcript level for the younger (dashed line) or older (solid line) males at each of three dietary protein intakes (indicated at the bottom of the graph; LPro (lower protein, 0.50 g/kg body weight per day), MPro (medium protein, 0.75 g/kg body weight per day), and HPro (higher protein, 1.00 g/kg body weight per day)). Numbers in the top center within each cluster are the number of transcripts that had the specified expression pattern. Functional categorization for differentially expressed genes within a cluster are indicated on top of the cluster. Adapted from Thalacker-Mercer *et al.*[15]

Amino acids and insulin sensitivity in humans

Aside from the biological use of dietary amino acids for protein metabolism in skeletal muscle, recent research suggests a role for amino acids in insulin sensitivity. With the emergence of metabolomics, elevated concentrations of branched chain amino acids (BCAA) have been identified as possibly an early predictor for the future development of diabetes in adults,[23] children and adolescents.[24] These findings are supported by earlier studies that demonstrated higher levels of BCAA, primarily leucine, in the plasma of obese and insulin-resistant individuals.[25] Leucine and other amino acids are also prognostic for improved insulin sensitivity following lifestyle interventions and bariatric surgery.[26] In addition to leucine, Thalacker-Mercer *et al.*[27] recently identified the amino acid glycine as being tightly correlated with insulin action; leucine/isoleucine and glycine were the strongest predictors for insulin action in nonobese individuals, while glycine alone is the only predictor of insulin action in obese individuals.[27] Intriguingly, they found that the relationship between leucine and insulin action was influenced by the body's preference for fat utilization. Together with data from Newgard *et al.*,[28] there is evidence that insulin sensitivity, particularly that of the skeletal muscle, is related to BCAA under conditions of high fat feeding. It is unclear whether amino acids play a causal role in metabolic dysfunction or are just a biomarker, but future studies are warranted.

There are many unanswered questions about the biological need and role of dietary protein for overall human health. Much research is still needed to address whether the RDA for dietary protein is adequate for older adults. Establishing an optimum protein intake for older adults, to improve muscle maintenance while aging, may address some of the problems/concerns identified with the RDA. Additionally, changes in meal patterns for older adults might improve protein and/or amino acid efficiency for stimulating skeletal muscle anabolism. While only briefly discussed, increasing physical activity and exercise might be the best stimulation for improving the nutritional efficiency of dietary protein and and overall skeletal muscle health. Physical activity and exercise patterns could also underlie the relationships between BCAA and insulin sensitivity.

Challenges to the sustainability of protein production by animal agriculture

Globally, natural resources for feedstuff provision are becoming increasingly limited. The conversion of dietary proteins to tissue proteins in animals, which requires complex physiological and biochemical processes, occurs at suboptimal rates. This necessitates the development of effective means to improve the efficiency of livestock and poultry production. Specifically, microbial fermentation of protein in the rumen of ruminants (e.g., cows, goats, buffalo, and sheep) produces ammonia and small peptides, with some of them being utilized for synthesis of amino acids and polypeptides in bacteria. Digestibility of dietary protein in post-weaning non-ruminants (e.g., pigs and chickens) is at best 75 to 92%, depending on ingredients. Irreversible catabolism of amino acids generates CO_2, ammonia, H_2S, methane, urea and uric acid, further resulting in suboptimal efficiency of animal production and potentially adverse effects on the environment. Thus, there are sustainability challenges for the production of high-quality protein by farm animals.

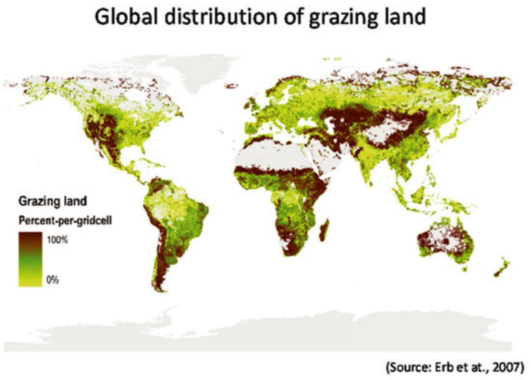
Suboptimal efficiency of protein production by animals

An important concept emerging from the presentations is that efficiencies in the conversion of dietary proteins into tissue or milk proteins in livestock species and poultry remain suboptimal (e.g., 23.3% for pigs during a 25-week period of growth and 6.7% for grazing beef cattle during a 76-week period of growth). Major reasons may be (a) the historic lack of consideration of so-called nutritionally nonessential amino acids (NEAA; e.g., arginine, glutamate, glutamine, glycine, and proline) in dietary formulations; (b) high rates of amino acid catabolism by bacteria in the small-intestinal lumen; (c) high rates of amino acid catabolism by intestinal mucosa; (d) high rates of protein degradation in the intestinal mucosa; and (e) low rates of protein synthesis in skeletal muscle.[7] Promising means to ameliorate these problems include dietary supplementation with amino acids (e.g., glutamate, glutamine, glycine, and arginine) to inhibit intestinal amino acid catabolism, thereby enhancing the entry of dietary amino acids into the blood circulation; activating cell signaling pathways (e.g., the mTOR pathway) through genetic and dietary means to promote synthesis of amino acids and proteins in animals; and formulation of low-protein diets by considering the needs for all amino acids, particularly those with regulatory functions (namely, functional amino acids), to optimize the proportion and amounts of dietary amino acids.[29]

Impacts of animal production on the environment

As alluded to previously, animal production can have potential impacts on the environment. These impacts include (a) use of water, (b) contribution (14.5%) to human-caused greenhouse gas (GHG) emissions (carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)) and thus global warming, and (c) generation of NH_3 and urea as sources of environmental pollution, and (d) overgrazing causing soil erosion.

These impacts were also highlighted by Jean L. Steiner, who explained that a major goal of her project is to reduce the environmental footprint of beef-grazing systems by reducing the emissions of potent GHGs, such as nitrous oxide and methane. N_2O is increased by the application of nitrogen fertilizer to crops on forage land. Steiner is building a database to improve our knowledge of how to manage agroecosystem fertilization and reduce N_2O emissions. Her team is analyzing fertilizer management practices to find ways to minimize N_2O emissions through appropriate rate, timing, and type of fertilization and collecting information about background emissions from unfertilized prairie land. In addition, methane emissions from cattle depend on the quality of forage (including the types of species consumed) and the type of livestock (e.g., cow, calf, heifer, steer). The team is using grazing lands as open laboratories, tagging cattle with GPS collars to identify their grazing patterns and preferences to develop emissions-reducing steps in the production cycle. Efforts are also underway to improve the quality of vegetation, increase soil carbon sequestration, and understand how agronomic management strategies impact water quantity and quality, which is particularly important in regions prone to drought.


Global distribution of grazing land

(Source: Erb et at., 2007)

Figure 4. Global distribution of grazing land in the year 2000. Adapted from Erb *et al.*[29]

Rearing of ruminants on grasslands for protein production

Steiner explained that improving the sustainability of forage-based animal productivity systems and reducing their environmental footprint can increase resilience to vagaries of climate, market, and government policy. An example is to build a robust cattle production system in grasslands to withstand climate, resource, and market variability. The grasslands constitute the largest global land use and are an important part of agricultural and ecological systems across a wide range of potential productivity conditions on every continent (Fig. 4).[30] Ruminant livestock grazing is often the only viable form of agricultural production on these lands.[31] In most regions of the world, lands suited to some level of grazing (grasslands, woodlands, forestlands, and sparsely vegetated or barren lands) constitute the majority of the land use. In the world's lower income countries, grassland and woodland that support ruminant grazing are proportionally more important than other land uses, compared to middle- and high-income countries. Grazing lands provide a wide range of ecosystem services, including provision of food, livelihoods, biodiversity, habitat, carbon storage, and water filtration.[32–34] The role of grassland ecosystems as net sinks or sources of GHGs is poorly understood, limited by sparse data regarding management impacts on the flux of nitrous oxide and methane. In grazing lands, soil quality and integrity of the vegetative and faunal communities are intrinsically intertwined and both are impacted by grazing systems.[33]

In the southern Great Plains of the United States, beef cattle production is a dominant part of the agricultural sector. Beef cattle production is based on mixed annual and perennial land uses, including native prairie, a variety of introduced pastures and hays, and grazing of winter wheat during the winter. Agriculture in this region is subject to a highly dynamic climate with extremes of heat and cold as well as drought and flooding.[35] Because of the portion of land in this region that supports beef-grazing systems, it has a large impact on carbon, nitrogen, and water budgets of the system. Management practices are critical to ensure efficient use of these resources to produce animal protein, but quantitative understanding of environmental effects of beef grazing systems is sparse.

Multidisciplinary efforts to reduce gaseous emissions from livestock

Beef cattle enterprises include cow-calf production, weaned stocker grazing, and finishing operations. Animal science research has focused predominantly on the finishing phases of beef production. However, addressing the system as a whole requires integrated, multidisciplinary research and extension involving soil and plant sciences, ecology, animal science, climatology, hydrology, sociology, economics, and other disciplines. Steiner described a multi-institutional, collaborative project "Resilience and Vulnerability of Beef Cattle Production in the Southern Great Plains Under Changing Climate, Land Use and Markets." This "Grazing CAP" was established to better understand vulnerability and enhance resilience of beef-grazing systems through diversified forages, improved management, strategic drought planning, and improved decision support systems for evaluation of alternative options and to safeguard and strengthen production and ecosystem services while mitigating GHG emissions.

The research addresses how different management practices and systems affect the environmental footprint of beef-grazing systems, particularly how rate, form, and timing of fertilization of wheat and perennial pastures affect soil nitrous oxide emissions; how forage and feed quality affect enteric methane emissions for various livestock classes (cow, calf, stocker, heifer); and how agronomic management of crops and pastures (tillage, rotation, fertilization, stocking density, duration, and timing) affect soil organic carbon, species diversity of pastures, water quality and water quantity.

Steiner shared with the audience that her collaborative team includes 34 coinvestigators and numerous students and postdoctoral research associates located at Oklahoma State University, Kansas State University, University of Oklahoma, Tarleton State University, and the Samuel Roberts Noble Foundation; and Agricultural Research Service researchers from El Reno, Oklahoma, and Bushland, Texas. Their research is structured around ongoing long-term research at the partner institutions to quantify seasonal and annual productivity and C, N, H_2O, and energy budgets, along with new intensive field campaigns conducted to develop improved understanding of interactive processes (Fig. 5). Research and extension efforts include on-farm research. A modeling team is developing a framework for linking models to develop regional maps of the environmental footprint and life cycle analysis of beef-grazing systems (Fig. 6). Extension teams are developing improved climate content for extension programs, decision support tools for beef cattle producers, and delivery of science-based information, including best management practices and technology for producers as well as for consumers.

Steiner's project was developed to increase resilience and sustained productivity of beef cattle systems, including mitigation of GHG emissions, through improved grazing management,

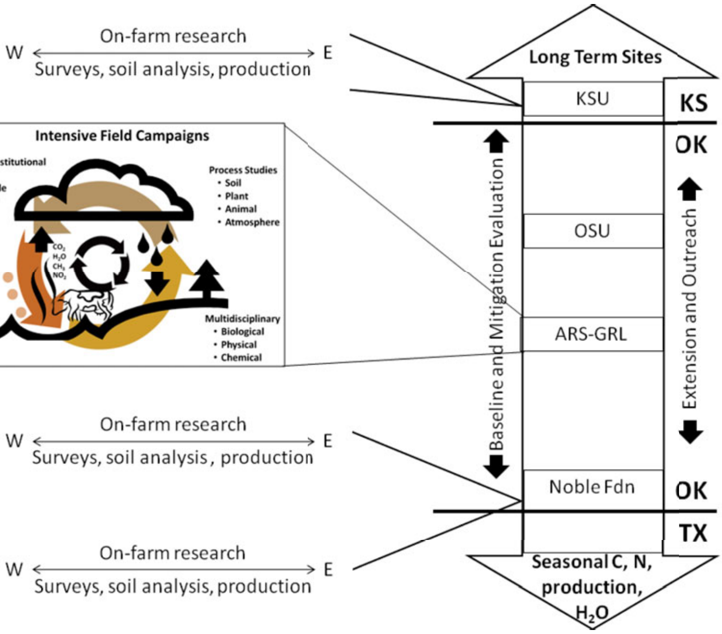


Figure 5. Grazing CAP research framework addressing multiple, interactive processes that interact at multiple scales to affect beef-grazing impacts on the environmental footprints of C, N, H_2O, and energy.

increased water use efficiency, diversified forage sources, multiple marketing options, strategic drought planning, and improved decision support. As the project progresses from its first year through the five-year plan, success will contribute to sustainable rural economies under variable and changing climate, market, and policy environments.

Approaches to solving sustainability problems

Enhancing biodiversity

There is strong evidence linking biodiversity and nutritional quality.[6] Fanzo explained that biodiversity in the ecosystem is an attractive way to sustain protein production to improve nutritional quality of food. Redirecting the global agricultural system as the supplier of the world's food to ensure better nutrition is crucial. Now more than ever, we need to better define new and sustainable approaches to improving the quality and variety of food produced and consumed around the world to meet critical nutrient gaps, such as protein, essential fatty acids and micronutrients. One area that requires further understanding is the role of biodiversity in improving dietary diversity and quality. Biodiversity is potentially important to food systems because it provides the basis of sustaining life. The diverse traits exhibited among crops, animals and other organisms used for food and agriculture, as well as the web of relationships that bind these forms of life at ecosystem, species, and genetic levels all directly or indirectly affect the nutritional quality of foods. Agricultural biodiversity is the basis of the food and nutrient value chain. The sustainable conservation and use of biodiversity could be an important contributor to food security.

Varietal and species differences, which can be exploited within more biodiverse environments, have different protein content and quality. For example, animal source foods, mainly meat, milk and eggs, provide concentrated, high-quality sources of essential nutrients for optimal protein, energy and micronutrient nutrition (especially iron, zinc, and vitamin B12). The diversity of breeds is closely related to the diversity of production systems and cultures. Local breeds in regions are usually used in grassland-based pastoral and small-scale mixed crop–livestock systems with low to medium use of external inputs. However, only about 40 of the almost 50,000 known avian and mammalian species have been domesticated. On a global scale, cattle, sheep, chickens, goats and pigs are the major

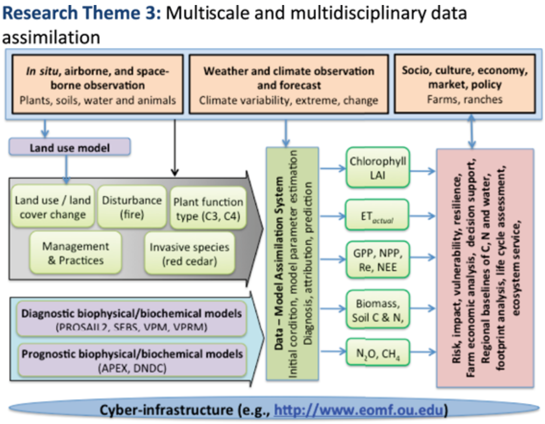


Figure 6. A linked observation-modeling framework to assess vulnerability, risks, and resilience of beef grazing systems.

animals raised and consumed. Therefore, the majority of products of animal origin are based on quite narrow species variability. There are also ethical considerations about the equitable distribution and access to these valuable sources of food across countries. Other sources, such as insects, can make significant contributions to dietary protein quality.

A question remains of how to best promote the use of biodiversity within food production systems that provide nutritionally rich protein sources, contribute to dietary diversity and quality and, potentially, promote better nutrition and health. There are also challenges on how to balance tradeoffs and avoid poverty traps while using and conserving biodiversity. More research is needed on how biodiversity of animal, plant and forest species and varieties contributes to dietary quality. There is a need for more guidance on what conservation and use of biodiversity would mean economically for all food value chain actors. Last, we need more implementation research to better understand how to measure, assess and evaluate the impact of biodiversity on diets, health and nutrition in the context of climate variability and environmental degradation in low- and middle-income countries.

Aseptic methods for food processing and storage

Josip Simunovic proposed that improving technologies for industrial muscle-food preservation is another approach to sustaining a protein supply. One challenge faced by the industry that processes so-called muscle foods (i.e., hot dogs, salami, and hams) is the limited shelf life and the potential for spoilage during distribution and storage of raw frozen and thermally processed "fully cooked" meats. Canned and sterilized muscle foods are shelf stable at ambient temperatures but are rapidly losing market share because of their low sensory quality: they "smell and taste bad."

The sterilization process for canned solid food, namely, the time/temperature regimes required to kill pathogens, such as *Salmonella* and *Escherichia coli*, in the whole product results in over-processing of everything surrounding the so-called cold spot at the center of the canned product. Overcooking results in loss of sensory quality, destroys valuable nutrients, wastes energy, and limits the maximum package size (i.e., products in large cans are most susceptible to damage). To mitigate these problems, Simunovic has developed a new aseptic processing technique to more rapidly and uniformly heat meat products than conventional approaches. In contrast to canning in which products are sterilized within the package, his method sterilizes food products under continuous flow (as a continuously flowing liquid substance as opposed to a solid lump) and then combines rapidly cooled products with separately sterilized packaging under aseptic conditions. The thermal technology used for food sterilization relies on a focused microwave energy that creates uniform heat distribution. This technology has been refined in the last decade and can now be used on large, industrial volumes and nonhomogeneous products, yielding different textures and consistent results.

Development and implementation of sustainable agricultural policies

Changes in agricultural technologies and government policies are also needed to sustain production of high-quality protein. On the basis of his observations in rural India, Prabhu Pingali argued that an opportunity exists for an agricultural renaissance, based on government investment in agricultural infrastructure, innovations in genomics and biofortification, ease of information dissemination through cellular technologies, and increased enrollment in safety-net programs to improve the nutrition and health of women of childbearing age. He stated that the past fifty years has been a period of extraordinary growth in food crop productivity, despite increasing land scarcity and rising land values.[36] In India, productivity gains and food supply expansion through the Green Revolution have provided tremendous opportunities for tackling nutrition and economic development challenges.[37,38] Despite these promising developments, India has remained an epicenter for childhood stunting and malnutrition.[39] Approximately 40% of the country's children are stunted.[40] In addition to reduced labor productivity and reduced physical development, stunting (the result of chronic malnutrition), causes lifelong reductions in cognitive potential and ability. Identification of policies and programs that can ensure that all households are able to access and afford sufficient dietary diversity, including access to iron and protein-rich foods, like milk, meat, and legumes, remains a challenge.

The Tata-Cornell Agriculture and Nutrition Initiative (TCi) is a long-term research initiative focused on solving problems of poverty, malnutrition, and rural development in India, with a particular emphasis on reducing childhood stunting and improving the diets of women in their childbearing years. Along with core TCi research and administrative staff, the program comprises student scholars (Cornell graduate students), Cornell faculty and external faculty fellows, and visiting researchers from universities in India and around the globe. Together, the TCi team works alongside partner institutions in India and worldwide to address the agriculture–nutrition nexus.

TCi research focuses on four pathways that link agriculture to nutrition. The first area considers food affordability, which includes household income and the impact of farm-level profitability and productivity for expanding food budgets and cultivating food for home consumption. TCi research in this area focuses on agriculture-led growth strategies, including a current research effort to understand how changing cropping patterns are affecting women's empowerment, women's iron-deficiency prevalences, and various anthropometric indicators of childhood growth. The TCi's second area of research looks at the availability of micronutrient-rich foods, as well as the effectiveness of food and micronutrient intervention programs. TCi scholars and researchers in this area are currently engaged in work that is evaluating new methods of delivering and fortifying the mid-day meals for Indian schoolchildren and testing for impacts in child nutritional status and cognitive ability.

The third and fourth areas of TCi research go deeper than evaluating a household's ability to access food. Even if a household is able to access food, the distribution of food and micronutrients within the household may not be equitable. TCi research in this area highlights how behavior change can positively influence the distribution of food so that women, girls, and young children not only get the quantity of food they need, but also the diversity of food they require. TCi research underway in Orissa is analyzing what types of iron-rich foods are traditionally fed to infants and how campaigns aiming to bolster consumption of these foods can be delivered in contextually appropriate ways. Similarly, a fourth TCi research area evaluates the linkages between nutrition and the rural health environment, including household and individual access to clean water, sanitation and toilets. TCi is partnering with AguaClara, a Cornell University–based engineering firm that has designed and developed clean water pumps and filtration systems specifically designed for the Indian context. TCi research is evaluating how the time saved by women (who would otherwise spend hours fetching water) might translate to greater nutritional impacts, including infant breastfeeding and early childhood care. A fifth area of research has focused TCi researchers evaluating the metrics currently used and needed for linking agriculture to nutritional outcomes.

Collectively, increasing protein and micronutrient consumption requires research and developments of the policies and practices that can ensure that these foods are affordable and available—and consumed in a healthy environment—at both the household and individual levels. The TCi program is an effort to focus researchers from multiple disciples on addressing the ever-complex and changing issues around maternal and child malnutrition, by honing in on the agricultural factors that determine relative food affordability, availability of high-quality protein and micronutrients, as well as intra-household distribution of food and resources.

Optimizing dietary formulation for animals

Livestock and poultry convert low-quality forages or ingredients into high-quality proteins (Fig. 2). Nutritional means can be developed to enhance the efficiency of animal growth and development. For example, Wu and coworkers have formulated an optimal protein diet that contains adequate proportions and amounts of all amino acids to increase milk production by 17%–26% in lactating sows.[7] Thus, it is imperative to modify the long-standing ideal protein concept, which ignored NEAA in the diet, to now include these amino acids in dietary formulation, thereby improving the efficiency of livestock production. In addition, dietary arginine supplementation can increase litter size by two in gestating sows. Besides nutritional approaches, animal breeding should also play an important role in increasing protein deposition in skeletal muscle. Improvements in farm animal productivity will not only reduce the contamination of soils, groundwater, and air by excessive excretion of animal wastes, but will also help sustain animal agriculture to produce high-quality proteins for the growing population in the face of declining resources worldwide.

Improving plant breeding to enhance crop yield and protein quality

Plant physiologist Widders told the audience that the productivity of legume crops in many areas in the developing world is pitifully low. This indicates a need to close the yield gap—the difference between the genetic yield potential of the crop and the actual yield on farms. The Widders team studies many aspects of crop yield, from molecular genetics to crop management strategies that aim to improve nutritional quality and marketing approaches. Through the United States Agency for International Development's Feed the Future program, Widders is working to reduce undernutrition in Guatemala, where 80% of children in rural areas are stunted and a majority of the population live in poverty. Collaborating with the country's Ministries of Agriculture and Health, Widders aims to increase bean production on farms and consumption of beans by children and women of childbearing age. Interventions aim to improve access to quality seeds of bean varieties with enhanced yield potential; to improve integrated crop management practices, such as crop rotation; to implement simple steps, such as disseminating sacks for long-term, non-wasteful storage; to promote seed exchanges; and to improve local understanding and appreciation of beans as a nutritious, ancestral crop. Another project is looking at the impact on child health of regular consumption of pulses by examining gut microbial flora, intestinal nutrient absorption, and immune function. It also examines whether the benefits of pulse consumption extend to better child growth and reduced incidence of diarrheal disease.

Innovations in the protein supply chain

The end of the conference featured discussions of new methods for producing protein, which are intended to create sustainable alternatives to animal protein in response to a scarcity of natural resources required for its production.

Reclaiming healthy, sustainable products from soy protein waste streams

Charles Schasteen explained that the production of soybeans is an energy-efficient process. He also indicated that soy protein is an accessible form of plant-based protein with relatively high quality and will play an important role in regions with huge projected population growth and limited infrastructure to produce animal protein. When soybeans are processed to create protein ingredients, the starting material used by the food industry to make commercial products is a form known as defatted soy flake. However, the process of producing isolated soy protein is wasteful and generates products that contain only 46% of the protein in the starting soy flake. Schasteen's team has developed a new process to mitigate this waste. The feed material, raw soy whey, is formulated to contain 2% solids and 98% water. The technology concentrates and separates this starting material into individual components (e.g., soy whey protein, soy whey sugars, soy whey minerals, and water), each of which is usable at the end of the process. Soy whey protein has several traits (e.g., unprecedented solubility across a range of pH, low viscosity, and high emulsification capacity) that make it a viable replacement for dairy proteins. Furthermore, soy whey protein forms a more stable foam than egg white and is a healthier alternative to chemical-based emulsifiers. These new protein products for use as food ingredients and in beauty and personal care products are targeted for prototype availability later in 2014.

Launching companies for innovation across the nutrient supply chain

New technologies, combined with genome, proteome, and microbiome research, are catalyzing startup companies focused on global problems in nutrition and health. In this regard, Geoffrey von Maltzahn presented innovative ideas and technologies that have driven the launch of companies focused on nutrition and health. In his view, agriculture practiced in its current form is a wasteful endeavor, using over 40% and 75%, respectively, of arable land and fresh water while producing up to 30% of GHG emissions, degrading land, depleting ground water, and leading to habitat destruction and loss of biodiversity.

The startup company Essentient aims to streamline food production by eliminating the need for arable land and wasteful intermediary steps in cultivation, harvesting, storage, and transportation, turning instead to single-celled photosynthetic organisms that are engineered to produce and secrete nutrients (including protein and amino acids) currently derived from agriculture at supra-agricultural efficiencies. Notably, early-stage nutrient factories, whose yield has far outstripped that of traditional agriculture, are being pilot tested in nonarable regions. Another company, Pronutria, has built a proprietary library of more than a billion protein polymers (amino acid chains) found in the typical Western diet. By comparing clinically proven amino acid combinations to the library, the company has designed proteins with desired characteristics to treat disease. These proteins can be delivered orally as prodrugs, which are digested in the gastrointestinal tract to release a specific combination of amino acids with unique functions. Some protein candidates are in clinical trials to prevent or ameliorate the loss of skeletal muscle in humans. Other candidates are scheduled to begin trials in 2014 for treating metabolic disease. Von Maltzahn also described efforts to pioneer a new type of medical treatment involving the human microbiome at a startup called Seres Health. The company designs Ecobiotics to therapeutically adjust microbial ecology for medical benefits. A new startup, Symbiota, is exploiting new knowledge of plant microbiota to improve crop yield, pathogen resistance, and stress resilience.

Laboratory-made animal protein to replace livestock meat

An alternative to current non-sustainable protein production practices is to produce beef meat in the laboratory from stem cells via regenerative techniques. Conventional beef production in animal agriculture at a low efficiency is unlikely to be sustainable. Beef cattle have a poor bioconversion rate—about 15%—from feed or grass input to edible protein output and may be a huge environmental burden. Nonetheless, meat production falls short of demand in many regions of the world. Mark Post (a pioneer in tissue engineering using the stem cell technology) and Gabor Forgacs made the case for laboratory-derived meat products as an alternative to livestock meat.

At the beginning of his talk, Post introduced tissue engineering for food as the next challenge in large-scale cell production. He stated that building the world's first hamburger from bovine skeletal muscle stem cells required 3 billion cells. The three main reasons why this endeavor was undertaken are insufficient capacity of traditional livestock meat production to supply the projected doubling of demand in the coming decades, the need to mitigate climate effects from livestock as a result of GHG emissions, and improving animal welfare.[41] In order to succeed, a tissue engineering alternative to livestock beef production should be resource efficient and sustainable, and the result should sufficiently mimic beef. The application of tissue engineering for food shares technological challenges with medical applications but is different in scale, physiological requirements and behavioral/ethical implications.[42,43]

After harvesting a small piece of skeletal muscle from a cow through biopsy and simultaneously extracting skeletal muscle stem cells, also known as satellite cells (SATs), and adipose tissue–derived stem cells (ADSCs), cells are expanded separately through standard cell-culturing techniques. For the proof of concept hamburger, Post and coworkers used 10-layer cell factories; but in the near future they will move to micro-carrier or cell aggregate–based production. To sustainably produce the large number of cells needed for production of consumption meat, a serum-free medium is an absolute requirement. From hundreds of serum-free culture conditions, Post's group has identified some that are promising for SATs and ADSCs. Further optimization of medium conditions for SATs is necessary, as these cells require unusually high serum addition and therefore specialized serum replacement. The origin (e.g., algae lysates) and production of non-serum components of the medium also require attention to the development of a resource-efficient cell culture. Recycling of media will be an integral part of the process.

Differentiation of SATs is performed by a combination of serum starvation and the supply of a provisional matrix that allows self-organization of the cells into muscle fibers.[44] For the fibers to fully and stably mature, they need to develop tension between anchor points. By laying down the cell-matrix gel in a donut shape encircling a centrally positioned column, the cells anchor to themselves in an elastic fashion that also allows scaling and easy harvesting of tissues. With this technique, the Post team is able to reach more than 95% success in muscle fiber formation. Part of the production process is conducted under low oxygen conditions that enhance muscle differentiation and increase myoglobin expression 5-fold. The latter contributes to color, taste, and nutritional value of cultured beef.

Cultured beef will only be a solution for problems with livestock meat production if the public is willing to accept and consume it. The association with other artificial or modified foods has been translated by investigators and media as the "yuck factor."[42,43] However, a survey among a cross-section of the Dutch population indicates that 63% of the 7700 respondents are in favor of the cultured beef development.[45] Of the respondents who had heard about cultured beef and know what it is, approximately 71% are willing, 14% are not sure, and 16% are not willing to try cultured beef. Similarly, a web-based poll issued by the United Kingdom newspaper, *The Guardian*, immediately following the public presentation of the proof-of-concept stem cell hamburger, indicated that 68% of the participants had a positive attitude towards cultured beef. Considering the seriousness of the problems faced by livestock meat production and the promising developments in culturing meat, forward efforts to bring cultured beef into larger scale practice are warranted.

Like Post, Gabor Forgacs is keen to overcome the challenges of pursuing sustainable sources of protein for human consumption. To produce meat that reflects the geometry and composition of an animal tissue, Forgacs is using a bioprinting technology, which lays down bio-ink units—a preparation of multicellular aggregates—with support materials along an architectural template. Structural formation, or "magic," as he called it, occurs post-printing, in a process similar to embryonic development of animals. When the bioprinted material has reached the desired thickness and shape, cells assemble, fuse, and undergo morphogenetic changes to produce a tissue that largely resembles animal meat. Several challenges remain to improve this tissue engineering technology, most notably scaling up the process, reducing cost, and achieving consumer acceptance. Nonetheless, both Post and Forgacs believed that because of dwindling natural resources and global population growth, alternative protein sources, such as those derived from their laboratories, might not be a choice, but rather a necessity in the future.

Conclusion and perspectives

Human health depends on consumption of dietary protein with adequate amounts and proper ratios of all amino acids. High nutritional quality of animal protein and the sole sources of physiologically important amino acids (e.g., taurine) and dipeptides (e.g., carnosine) from animal products necessitate the continuation and extension of animal agriculture. Production of animal-source foods is more expensive and generates more GHG emissions than production of plant-based foods. Therefore, there is increasing pressure to reduce consumption of animal-source foods in global populations. However, as noted previously, animal-source foods are excellent sources of high-quality protein and micronutrients that are often deficient in the diets (primarily based on plant-source foods) of populations in developing countries. Low intakes of animal-source foods increase risks for protein and micronutrient deficiencies, especially in children. At present, there is concern that animal production at a low efficiency is environmentally unsustainable.[46] So, what strategies can we use to enhance the nutritional quality of plant-based foods? Several approaches have promise:

1. Select plants that have enhanced concentrations of limiting essential amino acids. Considerable progress has been achieved in increasing the levels of lysine in maize. For example, quality protein maize (QPM) has nearly double the concentration of lysine as conventional maize.[47] So far, however, QPM seeds are not available to farmers, in part, due to poorer yields and undesirable changes in the phenotype of the seeds.
2. Biofortify staple food crops with vitamins and minerals. Biofortification is the application of plant breeding and agronomic practices to increase the concentrations of essential nutrients in staple food crops.[46] HarvestPlus is leading a global effort to develop and distribute biofortified seeds to farmers in resource-poor areas around the world.[18] When farmers plant

these biofortified seeds and later harvest the crops for consumption by their families and community members, they will be helping to increase the intakes of essential nutrients in these communities. To date, HarvestPlus has released beans and millet biofortified with iron; cassava, maize, and sweet potato biofortified with vitamin A; and wheat biofortified with zinc.
3. Commercially fortify foods. Commercial food fortification is the addition of vitamins and minerals to foods during processing. It dates to the 1920s when iodine was added to salt in the United States and Europe to prevent iodine deficiency. Fortification of milk with vitamin D began in the 1930s, and iron, thiamin, riboflavin, and niacin were added to cereal flours in the 1940s. Fortification has been a successful strategy for reducing micronutrient malnutrition in developed countries, but only recently has it been implemented in many developing countries. Likewise, addition of one or more limiting or functional amino acids (e.g., lysine, arginine, glycine, and taurine) to food can improve human health and growth.
4. Balance the proportions of all amino acids in human diets by consumption of animal products (e.g., meats, egg, and milk) containing high-quality protein.[48–50]

Recommendations:

1. Make enhancing nutritional quality of food crops an explicit goal for plant breeding programs across the globe.[47] The focus should be on those nutrients that are limiting in the diets of people in resource-poor areas. These nutrients include nutritionally essential amino acids (especially lysine and the sulfur amino acids), iron, zinc, and beta-carotene (pro-vitamin A).
2. Conserve and use sustainably agrobiodiversity to ensure sufficient production of food proteins at low costs, particularly for smallholder farmers.
3. Promote and support agricultural research that will help to develop food crops with enhanced nutritional quality. Approaches should include both conventional plant breeding and genetic engineering.
4. Expand commercial fortification and home fortification of foods to regions where protein and micronutrient malnutrition is prevalent.
5. Encourage dietary diversity and consumption of animal-source foods in regions where protein and micronutrient malnutrition is prevalent until nutritionally enhanced plant-based foods are more widely available.
6. Enhance the efficiency of livestock and poultry production through mechanism-based means (e.g., optimizing the proportion and amounts of both nutritionally essential and "nonessential" amino acids in diets) to stimulate protein synthesis and inhibit protein degradation in tissues.
7. Promote sustainable practices for ruminant grazing on grasslands and rangelands. Extensive grazing is often the only viable agricultural system for regions that have climate and soil limitations that preclude cropping. Properly managed grazing lands can sustain biodiversity and provide nutritious foods to the growing global population, including the world's poorest population.
8. Continue to explore radical innovations in the production of animal proteins (e.g., insect protein and cultured meat).

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Conflicts of interest

The authors declare no conflicts of interest.

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