

Ecological approaches to human nutrition

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Abstract

Background. Malnutrition affects a large number of people throughout the developing world. Approaches to reducing malnutrition rarely focus on ecology and agriculture to simultaneously improve human nutrition and environmental sustainability. However, evidence suggests that interdisciplinary approaches that combine the knowledge bases of these disciplines can serve as a central strategy in alleviating hidden hunger for the world's poorest.

Objective. To describe the role that ecological knowledge plays in alleviating hidden hunger, considering human nutrition as an overlooked ecosystem service.

Methods. We review existing literature and propose a framework that expands on earlier work on econutrition. We provide novel evidence from case studies conducted by the authors in western Kenya and propose a framework for interdisciplinary collaboration to alleviate hidden hunger, increase agricultural productivity, and improve environmental sustainability.

Results. Our review supports the concept that an integrated approach will impact human nutrition. We provide evidence that increased functional agrobiodiversity can alleviate anemia, and interventions that contribute to environmental sustainability can have both direct and indirect effects on human health and nutritional well-being.

Conclusions. Integrated and interdisciplinary approaches are critical to reaching development goals. Ecologists must begin to consider not only how their field

can contribute to biodiversity conservation, but also, the relationship between biodiversity and provisioning of nontraditional ecosystem services such as human health. Likewise, nutritionists and agronomists must recognize that many of the solutions to increasing human well-being and health can best be achieved by focusing on a healthy environment and the conservation of ecosystem services.

Key words: Anemia, biodiversity, conservation, ecosystem services, Millennium Development Goals, poverty alleviation

Introduction

Adequate nutrition lies at the heart of the fight against hunger and poverty [1]. Great strides in reducing hunger through increases in agricultural productivity have been made worldwide; however, more than 1 billion people remain chronically underfed, i.e., do not have proper access to food to continuously meet dietary requirements [2]. It has long been known that malnutrition undermines economic growth and perpetuates poverty [3]. Healthy individuals contribute to higher individual and country productivity, lower healthcare costs, and greater economic output by improving physical work capacity, cognitive development, school performance, and health [4]. Unrelenting malnutrition is contributing to widespread failure to eradicate extreme poverty and hunger, the first of the eight Millennium Development Goals (MDGs); moreover, if malnutrition is not eradicated, most of the other MDGs—improving maternal health, reducing the child mortality rate, combating HIV/AIDS and other diseases, achieving universal primary education, and promoting gender equality and empowering women—will be difficult to achieve [3]. Yet the international community and most governments in developing countries continue to struggle in tackling malnutrition.

Malnutrition has many dimensions, including not

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only an insufficient amount of food and calories, but also lack of essential nutrients, poor absorption, and excessive loss of nutrients. It is increasingly recognized that the current global crisis in malnutrition has roots in dysfunctional agricultural and food systems that do not deliver enough essential nutrients to meet the dietary requirements of everyone [5, 6]. Agricultural practices are almost always directed at maximizing production while minimizing costs. Recently, preserving the environment has become a more prominent goal of agriculture worldwide; however, maximizing the micronutrient output of farming systems has never been a primary objective in modern agriculture, human health, or public policy.

Increased crop production during the Asian Green Revolution prevented mass starvation in many nations. The focus, however, was primarily on cereal crops (rice, wheat, and maize), which are mainly sources of carbohydrates and contain only modest amounts of protein and a few other nutrients essential to meet human nutritional requirements. The change in agricultural production from diversified cropping systems toward ecologically more simple cereal-based systems may have contributed to poor dietary diversity, significant micronutrient deficiencies, and resulting malnutrition [5].

Malnutrition involves many different nutrient deficiencies. The current global nutrition gaps cannot be corrected by increasing the supply of only one or a couple of foods and nutrients. The role of micronutrients in human health and the synergies in their physiologic functions are recognized and support the concept that nutrient deficiencies rarely occur in isolation [7]. The challenge is to provide the diversity and adequate amount of nutrients required for a complete human diet. This urges a multidimensional approach.

One of the dimensions often not recognized as part of malnutrition is ecology, the study of the interactions between organisms and their environment. Yet the relationship between organisms, in this case humans, and resource acquisition (nutrients) is fundamentally an ecological question. We suggest that human nutrition is one of the most important, but often overlooked, ecosystem services. Ecologists work in multidimensional systems, composed of organisms, energy, and the physical environment interacting at various spatial and temporal scales, which can be described in terms of composition, structure, functions, fluxes, resilience, or other dynamics [8, 9]. Increasingly, ecologists have focused on the impact of communities and their interactions on ecological processes, functions, and ecosystem services. These studies, known as biodiversity and ecosystem function studies, explore the relationship between the numbers and kinds of organisms in a community and the ecosystem services that are derived from them. Though many ecologists have focused on the relationship between biodiversity and ecosystem functioning, there has been little focus on

the role that ecosystems play in providing the essential elements of human diets. How does the combination of environment, communities, and species and human modification of these assemblages impact human nutrition? How can ecological knowledge of species–environment interactions be used as a means of improving human nutritional well-being? What is gained through increased interactions among ecologists, agronomists, and nutritionists?

The environment is a critical determinant of which species occur in an area, and the interactions among species result in a local assemblage of species or communities. As humans modify their environment, they select and protect some species and exclude and eradicate others to achieve management goals and to maximize the provisioning of ecosystem services. The same concept can be applied to managing agroecosystems for the provisioning of human nutrition, particular in areas of extreme poverty. Optimizing for nutrient diversity can be presented schematically as maximizing the various arms of an ecological spider diagram, as illustrated in **figure 1**, where increasing species richness increases the capacity of the agroecosystem to meet the entirety of human nutrition needs.

The notion that nutrition, human and agricultural productivity, and environmental sustainability are interrelated was discussed by Deckelbaum et al. [10] and has been described as “econutrition.” Deckelbaum et al. argued that in tackling malnutrition much can be gained by linking agriculture and ecology to human nutrition and health. Biodiversity hotspots and hunger hotspots almost directly overlap, and although the intellectual paths of agronomists, ecologists, and nutritionists rarely cross, their geographic extensions are the same. The areas where there is hunger, loss of biodiversity, and a need for improved agricultural systems are largely identical. Cyclical feedback between declining soil fertility, loss of biodiversity, decreased food production, and malnutrition can be identified and needs to be turned around through an interdisciplinary approach [1, 10]. Indeed, these disciplines share a common concern, notably the rapid loss of biodiversity that typically accompanies agricultural intensification. Although ecologists tend to focus on nondomesticated species, agriculturalists on improving yields of a few crops, and nutritionists on the availability and utilization of food crops and specific nutrients, there is no reason to think that lessons learned by ecologists about the functional consequences of species losses [11] should not apply within a nutritional framework.

Food systems and system diversity

In the past, food-based interventions in developing countries have been mostly single-nutrient oriented [7]. This approach may in part be attributed to a lack

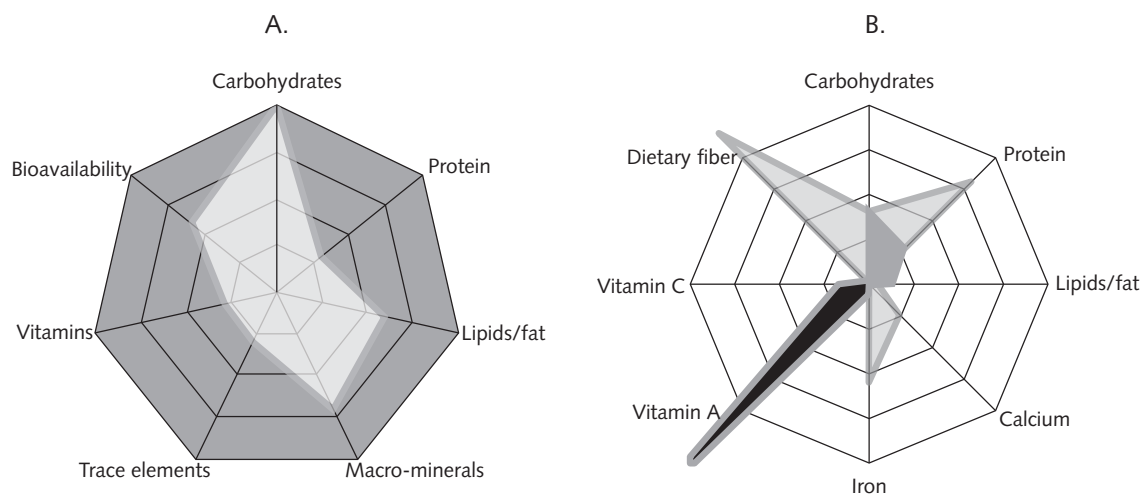


FIG. 1. Ecological spider's web presenting nutrient diversity requirements in a human diet. Nutrient composition of an ideal diet (A) that meets all nutritional needs is shown in dark gray. An example of nutrient composition of a diet that meets carbohydrate demand but lacks protein and micronutrients or trace elements is shown in light gray. Nutrient composition data of three food crops (B) are shown as percentages of daily requirement. The dark gray line represents one cup of white corn (166 g), the light gray line one cup of black beans (194 g), and the black line one cup of pumpkin (116 g) (nutrition facts from www.nutritiondata.com). The spider diagram shows the complementarity among the three food crops for carbohydrates, proteins, dietary fiber, and vitamin A

of knowledge in earlier years of the interactions among nutrients in human physiology and metabolism. From various recommendations for high-protein diets [12] and later for high-carbohydrate diets [13, 14], to more recent efforts directed at the elimination of micronutrient deficiencies [15], attention was generally concentrated on single-nutrient approaches. The introduction of crops focusing on single nutrients serves as an important means to address specific nutrients (macro- or micronutrients), but caution must be exercised, as any single crop, including a fruit or vegetable crop, does not address the complex nutritional needs of humans [5]. The importance of nutrient diversity for human well-being, as discussed above, calls for dietary diversification.

Dietary diversity is often defined as the number of certain food groups consumed by an individual or family. Many studies conducted on people of different age groups show that an increase in individual dietary diversity is related to increased nutrient adequacy of the diet. Dietary diversity has been positively correlated with the micronutrient density of diets of non-breastfed children, adolescents, and adults [16–21]. Research is ongoing by Bioversity International, the Food and Agriculture Organization, the International Food Policy Research Institute, and others to improve the understanding of the association between dietary diversity and micronutrient uptake.

One means of assuring adequate dietary diversity for all would be to manage agroecosystems in ways that will result in a plentiful and diversified nutrient output

of farming systems. Achieving such dietary diversity in agroecosystems is likely to be best achieved through interdisciplinary collaborations among nutritionists, agronomists, ecologists, and local communities, as we demonstrate below.

Agricultural biodiversity and dietary diversity illustrate the nexus of nutrition and ecology. Ecologists have studied the effects of removal or addition of species in ecological communities. For instance, several large-scale grassland studies in the United States and Europe have demonstrated that as the number of species in a grassland area increases, so does the net primary productivity. In addition, increasing species richness has increased the stability of the community; as indicated during drought years, species-rich communities exhibited less reduction in biomass produced than species-poor communities [22].

The mechanisms that drive these relationships between species richness and enhanced ecological performance are still heavily debated but are largely due to two processes. The first is known as the sampling effect, and argues that as you increase the number of species in a plot, the probability of including a highly productive species is greater. From a nutritional point of view, this is analogous to considering that as you increase the number of crops produced on a farm or in a region, the probability that one of those crops will be high in a particular nutrient, for example, vitamin A, also increases. Thus, simply by chance, if we increase the number of crops available to local communities, we increase the probability that the communities will obtain the

nutrients needed for healthy, productive lives.

The second mechanism is known as the complementary effect, in which interactions between species result in a yield or function greater than that expected by chance, also called overyielding. There are numerous possible interactions that can lead to complementarity; these interactions range from resource partitioning, in which different organisms use resources differently, thus reducing competition, to symbiotic and mutual interactions, in which a species facilitates the presence or success of another.

Probably one of the best-known examples of such ecological complementarity that also results in net nutritional benefit comes from the Mesoamerican “three sisters.” The combination of corn (a grass), beans (a nitrogen-fixing legume), and squash (a low-lying creeper) maximizes trait differences for growth and resource use efficiency between species [23], resulting in higher yields than those obtained from three monocultures of these crops. The corn is a grass species that is particularly efficient at maximizing photosynthesis in warm environments. In structure, the corn grows straight and tall, adding a vertical dimension to the system. The vine-like bean takes advantage of the growth form of the corn for structural support, which also enables it to reach more sunlight. The beans are also unique in their capacity to bring atmospheric nitrogen into the system by symbiotic nitrogen fixation, and this nitrogen becomes available to the corn in subsequent cropping seasons. The interaction between corn and beans is an example of complementarity, in which the overyielding is due to a positive interaction between the species. The third member of this assemblage, squash, does not perform as well as corn in direct sunlight and thus occupies the remaining space near the ground where light is somewhat reduced and humidity is increased, thus reducing photorespiration [24]. The addition of squash can decrease the amount of soil lost to erosion as a result of its low-lying form and broad leaves, which ensure greater soil coverage. The added productivity from the squash comes not so much from positive interactions with the beans and corn, but rather from the capacity of squash to use a resource (light) that is not captured by the corn and beans, an example of resource partitioning.

It is notable that these crops are complementary not only ecologically but also nutritionally. Corn is an important source of carbohydrates and some amino acids. The addition of beans completes the set of essential amino acids for a human diet and makes important contributions of carbohydrates, dietary fiber, vitamins B₂ and B₆, zinc, iron, manganese, iodine, potassium, magnesium, and phosphorus. Squash can be an important source of vitamin A, depending on the variety. It is important to note that each of these crops can make an important contribution to the human diet, but none of these crops alone provides total nutrition.

Ecological and nutritional functions of compounds in the plant world

Why is there an association between crop diversity and human nutrition? The question can be rephrased as why is there such a great diversity of nutritional compounds within the plant world? The evolution of nutritional traits by plants is purely a function of rewarding us or other animals for dispersing their seeds, as in the case of almost every piece of fruit we consume, a defense against plant pests, as in the case of chili peppers and mint, or ensuring that their seeds are best prepared for the ultracompetitive world of seedlings, as in the case of beans. The point is that ecological interactions are at the heart of the nutritional content of most species we consume.

Members of the genus *Capsicum*, more commonly known as chili peppers, are frequently consumed in the tropics and enjoyed by many in either their sweet or their spicy form. Why are these chili peppers so pungent? Birds consume the fruit and facilitate the dispersal of chili seeds, apparently unaffected by the spiciness, unlike mammals. However, recent research [25] has shown that plants with greater rates of insect piercing on the fruit have higher levels of the phytochemical capsaicin, and that the plant uses this chemical primarily as a defense against fungi that enter the fruit on the backs of insects to consume the seed. From a nutritional point of view, *Capsicum* has among the highest levels of vitamin A, vitamin C, and β -carotene of crops commonly consumed in poverty hotspots. Capsaicin has been shown to have an antibacterial function [26–28], and some researchers propose that the prevalence of spicy foods in tropical regions is no coincidence but rather a means of preserving food or killing off bacteria in food [26, 29].

Another example of ecological application in human nutrition is the use of nitrogen-fixing plants in agricultural systems. Nutritionists, development specialists, and most farmers recognize that legumes, such as common beans, groundnuts, and soybeans, are important sources of protein. This comes as no surprise to agronomists or ecologists, who recognize that all three of these food items come from a unique and third largest plant family, the legumes or Fabaceae. This plant family is also a major player in the nitrogen cycle in terrestrial ecosystems and is recognized as a driver of several ecosystem functions, including primary productivity in natural systems. From a nutritional point of view, legumes contain 5 times more high-quality protein than maize and 18 times more protein content than potatoes and are also superior to cereals as a source of micronutrients [30].

It is worth exploring the ecological foundation of these high protein levels. Manufacturing protein has a high nitrogen demand, and although 80% of our atmosphere is composed of nitrogen (N₂), none of this

is available to plants. To further exacerbate the problem, most soils are nitrogen-limited. Many species in the legume family have developed a unique symbiotic association with *Rhizobium*, a soil bacterium found in the roots of most legumes that allows the plant to convert atmospheric dinitrogen gas into ammonium, which the plant then uses to form amino acids, the building blocks of proteins. The plant in return provides the bacterium with photosynthetic sugars. This relationship is energetically expensive to legumes; however, this cost provides unique access to nitrogen, one of the nutrients most limiting to primary production in terrestrial ecosystems. This access to nitrogen allows legumes to colonize soils that are inhospitable to many other plant families or to outcompete other plants in nitrogen-poor environments. The high protein content of legume seeds provides the plants' progeny with a competitive advantage for growth in systems low in nitrogen [31, 32]. Humans have learned to take advantage of this high nitrogen content for our own nutritional well-being, as well as a natural source of organic nitrogen fertilizer.

Legumes are often advocated in diets because of their beneficial effects and because they are a low-cost source of protein [33]. However, compared to other food crops, legumes have high contents of secondary metabolites with antinutritional effects, such as amylase inhibitors, lectins, and trypsin inhibitors, which can cause adverse physiological responses or diminish the availability of certain nutrients [34, 35]. This raises the question of why legumes combine such attractive nutritional characteristics as high protein and mineral contents with relatively high contents of antinutritional factors? Secondary metabolites, including antinutrients, have been shown to provide natural mechanisms of defense for plants against microbes, insects, and herbivores [35, 36]. In many agricultural crops, which have been optimized for yield, their original lines of defense have been selected out because the underlying metabolites are unpalatable or toxic for humans or livestock. But in legumes, the numerous nitrogen-containing metabolites with antinutritional properties appear to function both as chemical defenses and as nitrogen storage compounds that facilitate germination in low-nitrogen systems. Legume genotypes selected for low to no amounts of antinutrients have reduced germination power and thus reduced general selective advantage [35, 37]. During germination, however, these antinutrients are degraded to a lower level by the action of several enzymes, resulting in improved digestibility of bean sprouts for humans, compared to dry beans. This example illustrates how enhanced knowledge of underlying ecological functions can benefit human nutrition.

Although we tend to consider humans outside of natural systems, the examples above demonstrate that interactions between species are literally the spice of

human life. Long-term interactions between plants and animals and the active selection of plants from various families by humans have resulted in a large diversity of nutritional traits. It is proposed that the long-term approach toward diversification of nutrient-rich crops will address the significant deficits in micronutrients among the diets and the particular nutrition needs of communities.

Nutritional diversity

Community ecology has demonstrated that increases in biodiversity can lead to increases in plant community productivity when species complement each other or use resources differently, as discussed above. Though ecologists have increasingly focused on the relationship between biodiversity and ecosystem functioning, there has been very little focus on the capacity or role that ecosystems play in providing the essential elements and nutrients of the human diet. Many studies of biodiversity and ecosystem function have demonstrated that there is much variance that cannot be explained by species richness. This leads to the question of the relationship between the taxonomic identity of a species and its functional identity. For example, does it matter that an ecosystem has five species, or would it be more important that a system has five different functional groups? Is a field with maize, rice, wheat, sorghum, and millet the equivalent of a field with maize, beans, squash, sweet potato, and guava? Both have five species, but the latter contains five functionally distinct species from a nutritional point of view in contrast to the former, where all of the species are from the grass family, which are high in carbohydrates but poor in essential nutrients.

To illustrate, a field survey of 30 farms in western Kenya identified over 146 plant species, including 39 edible species important to the local diet. Edible plant diversity was relatively high in farm fields, with an average of 14 edible plants per field, ranging between 5 and 22 species. Rather than simply looking at the relationship between crop diversity and nutrition, we classified the edible species according to their content of seven important nutrients: protein, carbohydrates, vitamin A, vitamin C, iron, zinc, and folate. In this classification, species high in protein (beans, peanuts, and amaranthus) form a distinct cluster in the dendrogram, species high in vitamin A (sweet potato and chili) form a second important cluster, and species with high carbohydrate content (sugar, sorghum, and maize) also form a unique cluster (**fig. 2**).

Using this same dendrogram, in which functional diversity is measured as branch length (see Petchey and Gaston [38] for details), we regressed functional diversity (FD) against species richness for each of the 30 farms. Several patterns became apparent through

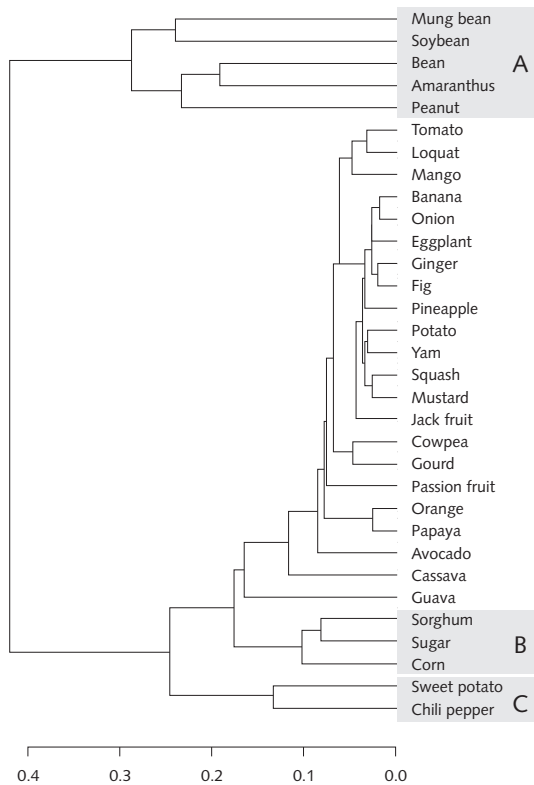


FIG. 2. Agrobiodiversity of 30 farms of a typical western Kenya village. Edible plant diversity was relatively high in farm fields, with an average of 14 edible plants, ranging between 5 and 22 species per field. Here we classify the edible species according to their contents of seven important nutrients: protein, carbohydrate, vitamin A, vitamin C, iron, zinc, and folate, identifying distinct clusters of species high in (A) protein (beans, peanuts, and amaranthus), (B) carbohydrate (sugar, sorghum, and corn), and (C) vitamin A (sweet potato and chili pepper)

this regression. The first is that there is a relatively strong relationship between functional richness and species richness. That is, as the number of edible species increases, the functional richness of the farm also increases. This confirms the notion that increasing farm agrobiodiversity increases the capacity of the farm to provide a multitude of nutritional functions to its owner. The second notable pattern is that although species richness and functional richness are correlated, it is possible for a farm to have many species but low nutritional diversity or for a farm to have fewer species but greater nutritional diversity, in addition to the general trend of increasing nutritional functional diversity with species richness. For example, **figure 3** shows that an important cluster made up of amaranth, soybean, and mung bean is entirely missing from farm A and that the absence of this cluster suggests that an important nutritional function may also be absent from this farm.

Why is there a relationship between species richness

and functional richness and human nutrition? It would be reasonable to expect that nutrients would be normally distributed among the crops grown in this example, with a few species that have low contents of any particular nutrient, many species with moderate nutrient levels, and a few species that have high nutritional values. However, this is not the case, and as with many ecological variables, nutritional content for any particular element is log-normally distributed, with most species containing low levels of any particular nutrient and few containing high levels. The other distinct pattern in nutrient distribution among these species is that there is little redundancy of plants that have the same nutritional content and there is no single species that is capable of providing all the nutrients needed for a human diet. Although a single species may be good at providing a single nutrient, there are no crop species capable of providing all essential nutrients. The importance of a diversified diet increases with the number of nutritional functions we expect agricultural systems to provide.

Correlating agricultural diversity with human nutrition remains difficult for numerous reasons, including ethical constraints on working with human subjects and the complexity of human societies. For example, wealthy landowners may have reduced agricultural diversity but better health because of the ability to purchase a more nutritionally diverse diet and focus their production efforts on cash crops. In contrast, poorer community members may rely more heavily on diversified diets to compensate for lack of purchasing power. However, in the Kenyan village example, the anemia of an individual, as measured by hemoglobin levels, was tested against several measures of crop diversity, including species richness and the functional diversity of crops based on their iron content. Crop species richness was not related to hemoglobin ($r^2 = 0.06$, $p = 0.2932$; **fig. 4**); however, we did find a positive and significant relationship of crop functional diversity with iron content and hemoglobin levels ($r^2 = 0.22$, $p = 0.0353$; **fig. 4**) without taking into consideration external variables. Community members who had low agricultural functional agrobiodiversity had significantly higher levels of anemia, whereas when functional agrobiodiversity increased, anemia became absent. These results support the notion that in poor communities, increased access to crops with greater nutritional diversity can alleviate hidden hunger.

Focusing on those nutritional elements most severely missing in many developing countries—energy, protein, iron, vitamin A, vitamin C, folate, and zinc—and based on the findings from this village survey, corn is the greatest provider of carbohydrates; beans and amaranthus are the greatest providers of iron, protein, and folate; orange-fleshed sweet potato is the greatest provider of vitamin A; guava is the greatest provider of vitamin C; and amaranthus is the greatest provider

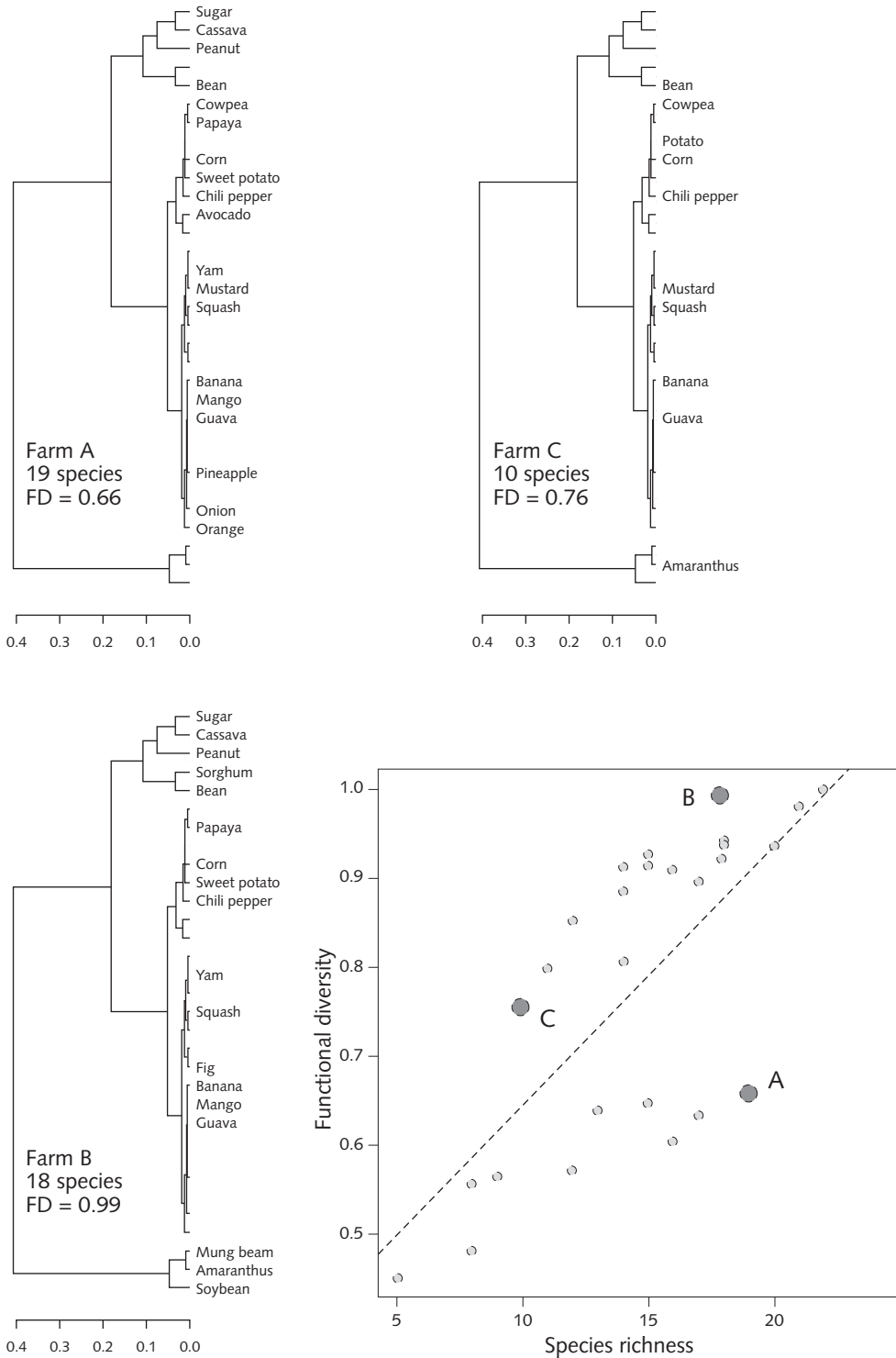


FIG. 3. Comparison of species diversity and functional nutritional diversity of three farms in Kenya, demonstrating the positive relationship between species richness and nutritional diversity. Missing species from the dendrogram indicate those species found in the community, but not in that particular farm. Note, however, that when nutritional functions of the crops are taken into consideration, it is possible to have a field with high nutritional diversity but low species richness, as in farm C. Random assemblages of plants can lead to high species richness but low nutritional diversity, as in farm A

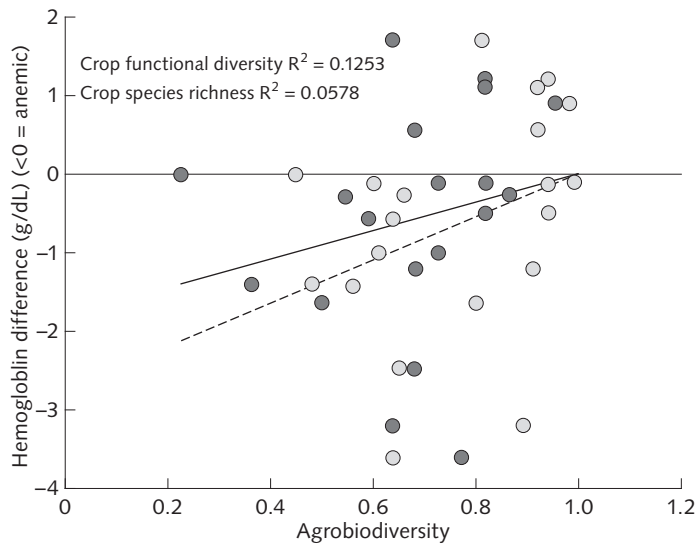


FIG. 4. Comparison of the effect of crop species richness (dark gray circles) measured as a proportion of 22 species, the greatest species richness found in local farms, and crop functional diversity (light gray circles) measured with iron content of the crop as the primary species functional trait using Petchey and Gaston's [38] dendrogram-based measure of functional diversity. Both species richness (dashed line) and crop functional diversity (solid line) were positively correlated with hemoglobin levels; however, the relationship was significant ($p = .0353$) only with crop functional diversity

of zinc. In order to be sufficient in these essential nutrients, a family would have to consume at least five different plant species, but more importantly, not just any five species, but those five species that belong to the different nutritional functional groups that together make a nutritious diet.

Food systems and biogeochemistry

Because plants obtain their nutrients from the soil, soils play a critical role in fueling the entire food chain [39]. Soils are ecosystems unto themselves with numerous ecological interactions of important consequences for the capacity of crop plants to be both productive and nutritious. Management interventions that alter the soil environment have an impact on these ecological interactions and can change the nutritional value of crops. The use of farmyard manure and other forms of organic matter can increase plant-available micronutrients by changing both the physical and the biological characteristics of the soil [40, 41]. These changes improve soil physical structure and water-holding capacity, resulting in more extensive root development and enhanced soil microfloral and faunal activity, all of which can increase available micronutrient levels in soils, which impact plants and then humans [42, 43]. However, the increased provisioning of food from crops and livestock in the past four decades has come

with important tradeoffs that include degradation of soils and loss of many of the regulatory and supporting ecosystem services soils provide, such as the regulation of hydrological and nutrient cycles. These tradeoffs between provisioning and regulatory services can ultimately undermine the ability of the ecosystems to provide the essential nutrients for human diets [44].

Agriculture as practiced in many poor regions without replenishing nutrients soon results in soils that for crop production are deficient in nitrogen, available phosphorus, and to a lesser extent potassium and sulfur. In addition, Sillanpää [45] estimated that of the important agricultural soils of the world, 49% are deficient in zinc for crop production, 31% in boron, 15% in molybdenum, 14% in copper, 10% in manganese, and 3% in iron. These figures may be compared with corresponding figures for the human population that depends on the same soils. Many of those countries, where human micronutrient deficiencies are a problem, are also the countries that have large areas of micronutrient-poor or -deficient soils [5, 46, 47].

Plants are able to supply all the known essential minerals for human diets, even though they may not necessarily require all of them for their own growth. In particular, plants contain selenium, iodine, and cobalt in concentrations high enough to fully satisfy human requirements if the soils on which they grow are not too poor in these same elements. However, probably half of all soils are deficient in one of these

three ultramicro nutrients (with daily requirements about 100 times less than those of iron and zinc), and although plant production is not restricted by this deficiency, human diets based on the crops grown on these soils can be deficient. "Linking unhealthy people and unhealthy soils" was emphasized by Sanchez et al. [1] in reference to integrated approaches to tackling hunger in Africa. The critical point is that crop diversity alone may not be sufficient to meet nutritional needs. The health of the soils in which these crops are grown can play an important role in ensuring human health.

Conclusions

The global health crisis of malnutrition afflicts massive numbers of people and urges changes in global food systems to provide adequate nutrition for all.

In this chapter we argue that ecological knowledge, tools, and models have an important role to play in efforts to direct food systems at improved human nutrition. Malnutrition has many dimensions, and the complex nature of human nutrition calls for dietary

diversification. If agricultural practices are directed at improving the nutritional quality and diversity of their output, they must encompass a holistic system perspective to assure that the intervention will be sustainable. It is here where ecology, through studying interactions between species and their environment, can identify synergies and tradeoffs between agriculture and nutrition and have an important role to play in guiding agricultural interventions for improved human nutrition. Agricultural biodiversity and dietary diversity illustrate the nexus of nutrition and ecology. Examples in community ecology, biogeochemistry, and soil ecology described in this chapter pertain to the linkages among ecology, nutrition, and agriculture and are only a beginning in the use of ecology to improve food systems for human nutrition.

A clear understanding of which species have specific nutritional, as well as ecological, functions shows tremendous promise for managing agricultural systems that provide numerous functions by identifying and combining species assemblages that maximize functions. If we aim toward a truly new Green Revolution in agriculture, we'd better invite ecologists to the table.

References

- Sanchez P, Swaminathan M, Dobie P, Yuksel N, UN Millennium Project Task Force on hunger. Halving hunger: it can be done. New York, NY: Millennium Project, 2005.
- Food and Agriculture Organization. The state of food insecurity in the world. Rome: FAO, 2009.
- World Bank. Repositioning nutrition as central to development. Washington, DC: World Bank, 2006.
- Grosse S, Roy K. Long-term economic effect of early childhood nutrition. *Lancet* 2008;371:365–6.
- Graham R. Micronutrient deficiencies in crops and their global significance. In: Alloway B, ed. *Micronutrient deficiencies in global crop production*. New York, NY: Springer, 2008:41–62.
- Pollan M. Farmer in chief. *New York Times Magazine*, 12 October 2008.
- Frison E, Smith I, Johns T, Cherfas J, Eyzaguirre P. Agricultural biodiversity, nutrition, and health: making a difference to hunger and nutrition in the developing world. *Food Nutr Bull* 2006;25:143–55.
- Pickett S, Cadenasso M. The ecosystem as a multidimensional concept: meaning, model, and metaphor. *Ecosystems* 2002;5:1–10.
- DeClerck F, Ingram J, Rumbaitis del Rio C. The role of ecological theory and practice in poverty alleviation and environmental conservation. *Front Ecol Environ* 2006;10(4):533–540.
- Deckelbaum R, Palm C, Mutuo P, DeClerck F. Econutrition: implementation models from the Millennium Villages Project in Africa. *Food Nutr Bull* 2006;27:335–42.
- Flynn D, Gogol-Prokurat M, Nogeire T, Molinari N, Richers BT, Lin B, Simpson N, Mayfield M, DeClerck F. Loss of functional diversity under land use intensification across multiple taxa. *Ecol Lett* 2009; 12:22–33.
- Brock J, Hansen J, Howe E, Pretorius P, Daval J, Hendricks R. Kwashiorkor and protein malnutrition. A dietary therapeutic trial. *Lancet* 1955;2:355–60.
- McLaren D. A fresh look at protein calorie malnutrition. *Lancet* 1966;2:485–8.
- McLaren D. The great protein fiasco. *Lancet* 1974;2:93–6.
- Ruel M, Levin C. Food based approaches for alleviating micronutrient malnutrition—an overview. *J Crop Prod* 2002;6:31–5.
- Foote J, Murphy S, Wilkens L, Basiotis P, Carlson A. Dietary variety increases the probability of nutrient adequacy among adults. *J Nutr* 2004;134:1779–85.
- Hatloy A, Hallund J, Diarra M, Oshaug A. Food variety, socioeconomic status and nutritional status in urban and rural areas in Koutiala (Mali). *Public Health Nutr* 2000;3:57–65.
- Kennedy G, Pedro M, Seghieri C, Nantel G, Brouwer I. Dietary diversity score is a useful indicator of micronutrient intake in non breast-feeding Filipino children. *J Nutr* 2007;137:1–6.
- Mirmiran P, Azadbakht L, Esmailzadeh A, Azizi F. Dietary diversity score in adolescents—a good indicator of the nutritional adequacy of diets: Tehran lipid and glucose study. *Asia Pac J Clin Nutr* 2004;13:56–60.
- Ruel M, Graham J, Murphy S, Allen L. Validating simple indicators of dietary diversity and animal source food intake that accurately reflect nutrient adequacy in developing countries. *J Nutr* 2004; 140(11):20705–207085.
- Steyn N, Nel J, Nantel G, Kennedy G, Labadarios D. Food variety and dietary diversity scores in children: are

- they good indicators of dietary adequacy? *Public Health Nutr* 2006;9:644–50.
22. Rees M, Condit R, Crawley M, Pacala S, Tilman D. Long-term studies of vegetation dynamics. *Science* 2001;293:650–5.
 23. Risch S, Hansen M. Plant growth, flowering phenologies, and yields of corn, beans and squash grown in pure stands and mixtures in Costa Rica. *J Appl Ecol* 1982;19:901–16.
 24. Gliessman SR. *Agroecology: the ecology of sustainable food systems*. Boca Raton, Fla, USA: CRC Press, 2006.
 25. Tewksbury J, Reagan K, Machnicki N, Carlo T, Haak D, Peñaloza AC, Levey D. Evolutionary ecology of pungency in wild chilies. *Proc Natl Acad Sci U S A* 2008;105:11808–11.
 26. Billing J, Sherman P. Antimicrobial functions of spices: why some like it hot. *Q Rev Biol* 1998;73:3–49.
 27. Molina-Torres J, García-Chávez A, Ramírez-Chávez E. Antimicrobial properties of alkalimides present in flavouring plants traditionally used in Mesoamerica: Affinin and capsaicin. *J Ethnopharmacol* 1999;64:241–8.
 28. Xing FB, Cheng GX, Yi, K. Study on the antimicrobial activities of the capsaicin microcapsules. *J Appl Polym Sci* 2006;102:1318–21.
 29. Sherman P, Billing J. Darwinian gastronomy: why we use spices. *Bioscience* 1999;49:453–63.
 30. Broughton W, Hernández G, Blair M, Beebe S, Gepts P, Vanderleyden J. Beans (*Phaseolus* spp.)—model food legumes. *Plant Soil* 2003;252:55–128.
 31. Andersen M. Competition and complementarity between intercropped barley, rape and fieldpea in ecological cropping systems—the role of plant available nitrogen and sulphur as well as cropping design. Thesis, The Royal Veterinary and Agricultural University, Copenhagen, Denmark, Department of Soil Science. 116 pp. 2005.
 32. Andersen M, Hauggaard-Nielsen H, Ambus P, Jensen E. Biomass production, symbiotic nitrogen fixation and inorganic N use in dual and tri-component annual intercrops. *Plant Soil* 2004;266:273–87.
 33. Graham P, Vance CP. Legumes: importance and constraints to greater use. *Plant Physiol* 2003;131:872–7.
 34. Muzquiz M. Recent advances of research in antinutritional factors in legume seeds and oilseeds. Weimar, Texas, USA: CHIPS Books, 2004.
 35. Wink M. Evolution of toxins and anti-nutritional factors in plants with special reference to Leguminosae. In: Acamovic T, Stewart C, Pennycott T, eds. *Poisonous plants and related toxins*. Wallingford, UK: CABI Publishing, 2004:1–15.
 36. Wink M. Resistance of grain legumes towards insects and other pests: role of plant secondary metabolites. *Grain Legumes* 1997;15:16–8.
 37. Savelkoul FH, van der Poel AF, Tamminga S. The presence and inactivation of trypsin inhibitors, tannins, lectins and amylase inhibitors in legume seeds during germination. A review. *Plant Foods Hum Nutr* 1992;42:71–85.
 38. Petchey O, Gaston K. Functional diversity (FD), species richness, and community composition. *Ecol Lett* 2002;5:402–11.
 39. Daily G. *Nature's services: societal dependence on natural ecosystems*. Washington, DC: Island Press, 1997.
 40. Allaway W. The effects of soils and fertilizers on human and animal nutrition. In: US Department of Agriculture. *Agriculture Information Bulletin No. 378*. Washington, DC: US Government Printing Office, 1975:61 pp.
 41. Allaway W. Soil-plant-animal and human interrelationships in trace element nutrition. In: Mertz W, ed. *Trace elements in human and animal nutrition*, 5th ed. New York, NY: Academic Press, 1986:465–88.
 42. Stevenson F. *Humus chemistry*, 2nd ed. New York: John Wiley and Sons, 1994.
 43. Stevenson F. Organic matter-micronutrient reactions in soil. In: Mortvedt JJ, F.R. Cox, L.M. Shumman and R.M. Welch. eds. *Micronutrients in agriculture*, 2nd ed. Madison, Wisc, USA: Soil Science Society of America, 1991:145–186.
 44. Palm C, Sanchez P, Ahamed S, Awiti A. Soils: A contemporary perspective. *Annu Rev Environ Res* 2007;32:99–121.
 45. Sillanpää M. *Micronutrient assessment at the country level: an international study*. Rome: Food and Agriculture Organization/Finnish International Development Agency, 1990.
 46. Welch R. Linkages between trace elements in food crops and human health. In: Alloway B, ed. *Micronutrient deficiencies in global crop production*. New York: Springer, 2008:287–310.
 47. White J, Zasoski R. Mapping soil micronutrients. *Field Crops Res* 1999;60:11–26.