7 Linking biodiversity and nutrition

Research methodologies

Roseline Remans and Sean Smukler

Introduction

- How do species, varieties and species compositions differ in nutritional function?
- What is the relationship between biodiversity and nutrition in various settings? Does this relationship change over time? How and why?
- How can we manage biodiversity and the ecosystem services it provides for human nutrition, while also managing for other components of human well-being?

In this chapter, a step is taken to explore research methodologies that can help address these questions as well as introduce how tools mostly used in ecology and agricultural sciences can be applied to integrate nutrition.

Although there have been important exceptions, much of the agricultural research conducted over the last decades has been focused on increasing productivity through improvements in crop genetics and the efficacy of inputs. Maximizing nutritional output of farming systems has never been a primary objective in modern agriculture, human health or public policy. Food-based interventions to tackle undernutrition in the past have been mostly single-nutrient oriented. From various recommendations for high-protein diets (Brock et al., 1955) and later for high-energy diets (McLaren, 1966, 1974), to more recent efforts directed at the elimination of micronutrient deficiencies (Ruel and Levin, 2002), the attention was generally concentrated on one single nutrient to improve nutritional outcomes. Literature reviews (Penafiel et al., 2011; Masset et al., 2011) further underline that although biodiversity could contribute to dietary diversification and quality, current research approaches are falling short to provide strong evidence.

Understanding and strengthening the link between biodiversity and nutrition requires a different approach (Figure 7.1; Fanzo et al., 2011). First, it calls for a dynamic systems approach in which the diversity of organisms and nutrients from production to consumption plays a central role. The first part of this chapter focuses on research frameworks and methodologies that allow such a systems approach at different spatial and time scales to link biodiversity

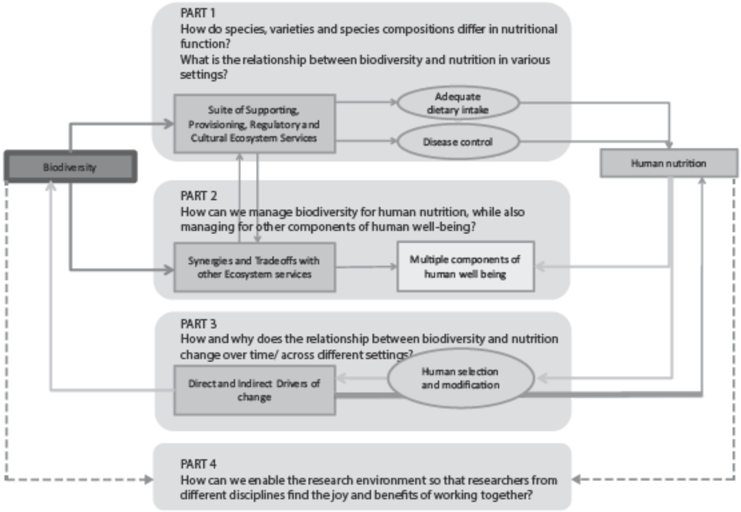

Figure 7.1 Schematic overview of the structure of the chapter. In this chapter, a step is taken to explore methodologies to address four sets of research questions linking biodiversity and nutrition: 1) How do species, varieties and species compositions differ in nutritional function? What is the relationship between biodiversity and nutrition in various settings? 2) How can we manage biodiversity for human nutrition, while also managing for other components of human well-being? 3) How and why does the relationship between biodiversity and nutrition change over time/ across different settings? 4) How can we enable the research environment so that researchers from different disciplines find the joy and benefits of working together?

with nutritional functions and outcomes. We provide an overview of existing methodologies and explore potential future paths.

Second, a basic challenge in investigating and describing the contributions that biodiversity can make to improving nutrition over the next few decades is one of relevance and realism. While there are many possible ways in which biodiversity can improve nutrition, they may not all be feasible in production systems or they may come with negative consequences for other ecosystem services (e.g. reduce fuelwood provisioning or water quality regulation) and components of human well-being (e.g. prove uneconomic or too labour intensive for adoption by farmers). Successful approaches are likely to bring together positive aspects of sustainable intensification and multi-functional agriculture, to reflect the realities and choices of farmers and ultimately improve not just human nutrition but also other components that contribute to human well-being. It is therefore important to investigate the linkages between nutrition and other functions of agro-ecological systems that influence human well-being and to adopt research approaches that can explore trade-offs and synergies in complex systems. Such methodologies are described and illustrated in the second part of the chapter.

Third, considering change over time, a strategy is explored that can help identify drivers of change, and unravel if, why and how the relationship between biodiversity and nutrition outcomes changes (or does not change) over time. Identifying what works in practice over time (see also other chapters), taking into account regional differences and different scales of farming, will be essential if diversity is to be used to improve nutrition in a sustainable way.

Finally, in order to efficiently link biodiversity and nutrition research, researchers from different disciplines must find the joy and benefits of working together. The chapter briefly introduces some tools that can facilitate cross-disciplinary communication (see also Chapter 10).

As new interest on the link between biodiversity and nutrition is emerging in the environment, agriculture and nutrition communities (e.g. the new cross-cutting initiative on biodiversity and nutrition of the Convention of Biological Diversity), this chapter will allow the reader to further enable holistic, cross-sectoral research approaches and help pave the way in developing tools that can guide sustainable decision-making on the ground.

Taking a systems approach to link biodiversity with nutritional functions and outcomes

This section explores approaches that address the questions: "How do species, varieties and species compositions differ in nutritional function?" and "What is the relationship between biodiversity and nutrition in various settings?"

The Millennium Ecosystem Assessment (MEA) provides a widely used framework that links biodiversity to human well-being through ecosystem functions and services (MEA, 2005). Ecosystem functions are the characteristic processes within an ecosystem that include energy and nutrient exchanges, as well as decomposition and production of biomass. The specific ecosystem functions that are apparently beneficial to human civilization are considered ecosystem services. Here, the MEA framework is applied to the relationship between biodiversity and human nutrition and identifies a suite of research methodologies or tools that provide ways to further unravel pieces of this framework (Figure 7.2). An overview of tools based on existing literature is provided in Table 7.1. While many tools are important, there will be a focus on a selection of methodologies highlighted in Figure 7.2 that are considered most relevant for this chapter. To illustrate these tools, data and examples are used from the literature and the Millennium Villages Project, a rural development project with research and implementation sites across all major agro-ecological zones in sub-Saharan Africa (Sanchez et al., 2007).

How do species, varieties and species compositions differ in nutritional function?

A human diet requires at least 51 nutrients in adequate amounts consistently (Graham et al., 2007). In food sciences, several methods have been developed to analyse the composition of food items for this diversity of nutrients and standardized nutrition indicators for biodiversity have been suggested (Kennedy and Burlingame, 2003; FAO, 2007, 2010a). While for many of the minor crops

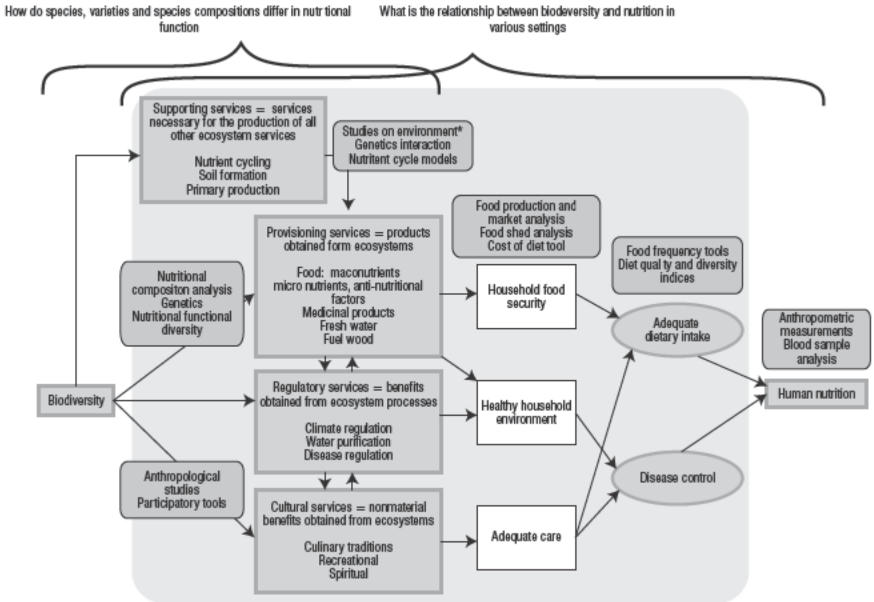

Figure 7.2 Application of the Millennium Ecosystem Framework in combination with the UNICEF Child and Maternal Nutrition Framework on the relationship between biodiversity and nutrition. Research methodologies and tools to investigate specific pieces of the framework are highlighted and a selection of these are further described in the text

the nutritional differences and possible advantages of one variety over another are not yet known, great progress is being made in extending food composition tables (e.g. the International Network of Food Data Systems, INFOODS; Stadlmayr et al., 2010) and in identifying the advantage of several minor crops in securing a healthy supply of specific nutrients (Penafiel et al., 2011; Golden et al., 2011; other chapters in this book). For example, nutritional composition analysis of African green leafy vegetables has clearly shown that these leafy greens (e.g. African spiderweed, black nightshade) provide higher levels of iron and vitamin A than several imported species (e.g. Chinese cabbage, Chweya and Eyzaguirre 1999; see also other chapters). This has helped promotion and adoption in local to regional markets (Shackleton et al., 2009).

Further, progress in genetics and genomics, for example the use of more advanced molecular markers such as microsatellites and the genome-wide screening of different varieties, now allow for more efficient identification of quantitative trait loci (QTL) and genes on the genome that contribute to specific nutritional functions (Galeano et al., 2011). For example, QTL explaining the higher iron and zinc variability in common bean varieties were recently identified (Blair et al., 2010). These tools thereby not only help to unravel the genetic base for differences in nutritional composition of varieties, but also provide means to improve the nutritional value of locally adopted varieties through cross-breeding.

Table 7.1 Overview of assessments and tools in the biodiversity–nutrition research framework

Assessment	*Tools*	*References to examples/reviews/guidelines*
Farming systems	Farming systems model	Dixon et al. 2001; Fanzo et al. 2011
Local biodiversity	Interviews (local names) and literature (scientific names) Observations / field and plant/animal identification	Penafiel et al. 2011; Fanzo et al. 2011
Genetics of nutritional traits	Quantitative Trait Loci (QTL) analysis Gene characterization and isolation	Vijay et al. 2009; Blair et al. 2010; Paine et al. 2005
Nutritional composition of food items	Chemical analysis Food composition tables and literature	FAO 2007; FAO-INFOODS; Engleberger et al. 2010; Penafiel et al. 2011; Kennedy and Burlingame 2003
Nutritional composition of agro-ecological systems	Nutritional functional diversity metric	Remans et al. 2011a; DeClerck et al. 2011
Impact of environment and agronomic practices on nutritional composition	Agronomic/environmental field trials combined with nutritional composition analysis Digital soil maps and GPS	Graham 2008; Graham et al. 2007; Bourn and Prescott 2002; Sanchez et al. 2009
Nutrient cycles, biodiversity and nutrition	Food web pathways Indicators: soil fertility and fauna indicators, diversity and cover of plants at the plot level, diversity of land use types in mosaics at landscape level	Elser and Urabe 1999; MEA 2005, Chapter 12

Assessment	*Tools*	*References to examples/reviews/guidelines*
Food consumption patterns and dietary intake	Food frequency questionnaires Dietary diversity scores 24-hour recalls Dietary reference intake tables Mean probability of adequacy (MPA) for macro and micronutrients	Willett 1998; Penafiel et al. 2011; FAO-FANTA 2008; FAO 2010a; Arimond and Ruel 2004; Arimond et al. 2010; Fanzo et al. 2011
Sources of food	Food shed analysis	Peters et al. 2008; Conard et al. 2011
Access to nutritious food	Cost of the diet tool Food security questionnaires Market analysis Value chain analysis	Perry 2008; Bilinsky and Swindale 2007; Coates et al. 2007; Remans et al. 2011a; Hawkes and Ruel 2011
Human nutrition outcomes	Anthropometric measurements Serum analysis	Cogill 2001; Massett et al. 2011; Golden et al. 2011; Fanzo et al. 2011
Trade-offs between multiple ecosystem services	Trade-off models: InVest, ARIES, EcoMetrix Life cycle analysis	Nelson and Daily 2010; Villa et al. 2009; Parametrix 2010; Bentrup et al. 2004

Recognizing the exciting progress made in methodologies to develop food composition tables and to identify the genetic base of nutritional differences between species and varieties (FAO, 2010b), there are still a couple of major gaps in current research approaches in order to address the question as to how do species, varieties and species compositions differ in nutritional function, in a more holistic way.

First, not much is known about the interaction between the nutritional composition of crop species or varieties, the agricultural management practices and environmental conditions. Food composition tables, for example, mostly do not include information about the management practices applied (e.g. fertilizer, irrigation) nor the environmental conditions in which a specific food item is grown. A number of studies (e.g. Remans et al., 2008; Graham et al., 2007; Graham, 2008; Weil et al., unpublished), however, clearly show that the nutritional composition, including protein, sulfur, iron, zinc content, of crops can vary significantly among different management and environmental conditions. For example, addition of zinc fertilizer to the soil can increase the concentration of trace elements in edible parts of common bean (Graham et al., 2007; Graham, 2008). Also, the concentration of sulfur containing amino acids in the grain of common bean increased as higher levels of sulfate were detected in the soil, while this was not the case for maize (Weil et al., unpublished).

To enhance our understanding as to how the nutritional function of species and varieties differ, there is a critical need to link food composition analyses to agricultural management, soil and environmental studies. There currently exist several opportunities that can strengthen this link in a systematic way. The African Soil Information Service (AfSIS) project is developing a digital soil map of Africa, collecting information not only on soil but also on vegetation, climate and the effects of agricultural management practices on soil fertility and crop productivity throughout the African sub-continent. Linking nutritional composition analyses to such Global Digital Soil Map initiatives could help unravel the interaction between management, environment and nutritional composition. In addition, methodologies such as infrared spectroscopy offer promising potential to analyse the nutritional composition of plant varieties in a relatively quick and cost-effective way in the field as compared with wet-lab analysis (Foley et al., 1998; Brown et al., 2006). These tools provide a way not only to speed up the analyses of plant nutritional composition, but also to directly link such results to soil characteristics if measured simultaneously in the field.

Further, Global Positioning Systems (GPS) tools provide a way to easily record the location where food items used for nutritional composition analysis are collected. This can enable integration of food composition data with spatially explicit environmental data, including soil, climate, land use/cover and water availability characteristics, and enable investigators to address questions such as "Can we identify 'nutritional deserts' where nutritional value of crops is lower than in other regions?" Or "Is the difference in nutritional value between certain varieties larger in conditions of optimal rainfall as compared with droughts?"

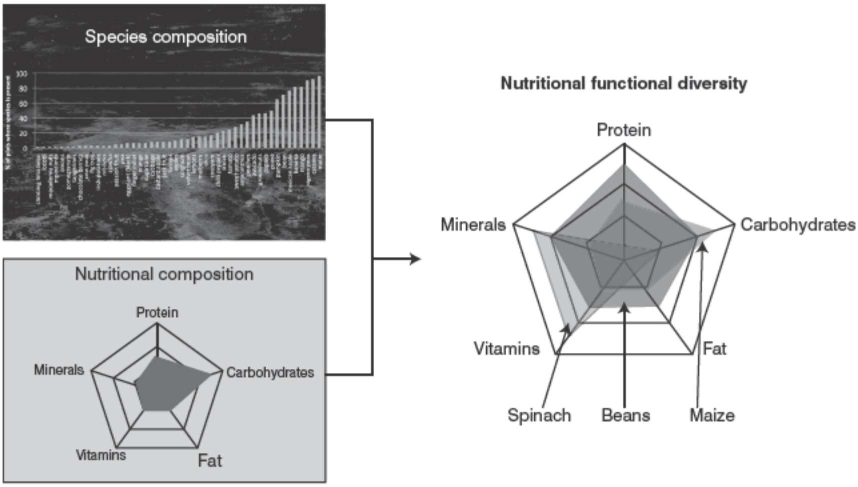

Figure 7.3 Schematic representation of the nutritional functional diversity metric, based on 1) species composition in a given farm or landscape and 2) nutritional composition of these species. Thereby the nutritional FD metric provides a way to assess complementarity between species for their nutritional function

In addition to enhancing our understanding of the interaction between environment and nutritional composition of species and varieties, there is need for research that enables greater consideration of the large diversity of species and varieties available in the system as a whole together with their nutritional composition. This brings us to the question, "How do different species *compositions* differ in nutritional function?" By using examples of rural villages in sub-Saharan Africa, this chapter illustrates how an ecological concept, the Functional Diversity (FD) metric, has potential to address this question.

FD is a metric used in ecology that reflects the trait distinctiveness of species in a community and the degree of complementarity in traits of species within a community. 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 nutrients of human diets.

Applying the FD metric to the nutritional traits of plants (and potentially animals) provides a novel metric, called nutritional functional diversity (nutritional FD, Figure 7.3, Remans et al., 2011a) that bridges agriculture, ecology and nutrition studies. The nutritional FD metric is based on plant species composition at the farm (or landscape scale) and the nutritional composition of these plants for a suite of nutrients (e.g., 17 different nutrients in the study by Remans et al., 2011a) that are key in human diets and for which reliable plant composition data are available. The nutritional FD value increases when a species or variety with a unique combination of nutrients is added to a community, and decreases when such a species is lost. The nutritional FD metric thereby reflects the diversity of nutrients provided by the farm and the complementarity

Box 7.1 Assessing nutritional diversity of cropping systems in African villages

Data on edible plant species diversity were collected for 170 farms in three Millennium Villages in sub-Saharan Africa. Nutritional FD metrics took into account 17 essential nutrients that were calculated for each of the 170 farms, based on farm species composition and species nutritional composition.

Figure 7.4 plots FD values against species richness for each of the 170 farms. Regression of FD against species richness reveals several patterns. First, there is a strong positive correlation ($p < 0.001$; $r^2 = 0.68$) between FD and species richness, independent of village. Thus, as the number of edible species increases, the diversity of nutritional functions that farm provides also increases. Second, at a level of around 25 species per farm, the relationship between FD and species richness starts levelling off, meaning that adding species to a farm with around 25 or more species, increases nutritional diversity very little. Third, although species richness and FD_{total} are correlated, farms with the same number of species can have very different nutritional FD scores. For example, two farms in Mwandama (indicated by arrows on Figure 7.4) both with 10 species show an FD of 23 and 64, respectively. The difference in FD is linked to a few differences in species nutritional traits. Both of these example farms grow maize, cassava, beans, banana, papaya, pigeon pea and mango. In addition, the farm with the higher FD score grows pumpkin, mulberry, and groundnut, while the farm with the lower FD score has avocado, peaches and black jack (*Bidens pilosa*). Trait analysis shows that pumpkin (including pumpkin leaves, fruits and seeds, which are all eaten) adds diversity to the system by its relatively high nutritional content in vitamin A, Zn, and S-containing amino acids (methionine and cysteine) compared with other species; mulberry by its levels of vitamin B complexes (thiamin, riboflavin) and groundnut by its nutritional content for fat, Mn, and S. The black jack, avocado and peaches found in the lower FD farm add less nutritional diversity to the system than pumpkin, mulberry, and groundnut since they do not contain the vitamin B or S complexes, and thus are less complementary to the other plants in the system for their nutritional content.

This example illustrates that by applying the FD metric on nutritional diversity, it is possible to identify differences in nutritional diversity as well as species that are critical for ensuring the provision of certain nutrients by the system (e.g., mulberry for vitamin B complexes). The results also emphasize that the species nutritional composition available in the system determine whether introduction or removal of certain species will contribute to the nutritional diversity of the farming or ecosystem. The quality and sensitivity of this type of metric will be enhanced if more data are available on the nutritional composition of species and varieties grown under different environmental and agronomic practices (see above).

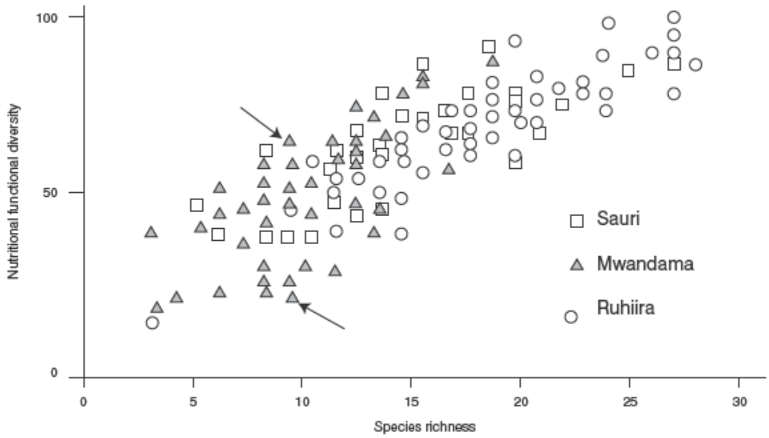

Figure 7.4 Nutritional functional diversity plotted against species richness for 170 farms in three Millennium Village project sites, Sauri in Kenya, Ruhiira in Uganda and Mwandama in Malawi

in nutrients among species on a farm or community. A concrete example of the application and interpretation of this metric is illustrated in Box 7.1 and Figure 7.4. One of the shortcomings of the metric is that it does not include a dimension of food consumption or food habits, e.g. ways in which foods are usually eaten locally. In addition, the current tool does not include abundance data, e.g. data on quantity of food produced or consumed. Current on-going research is exploring how these two dimensions can be incorporated in this tool.

While in the past, food-based interventions have focused mostly on single nutrients, the approach described by this metric can help guide agricultural interventions to provide a diversity of nutrients as well as to enhance nutrient redundancy or resilience of the system. In particular, this tool provides means to identify potential crops, varieties or groups of plants that add nutritional value (diversity or redundancy) to the system if introduced, promoted, or conserved.

What is the relationship between biodiversity and nutrition in various settings?

The methodologies described above provide ways to investigate and describe the nutritional function of species, varieties and species compositions. A suite of additional instruments is needed to unravel how biodiversity and ecosystem services relate to human nutrition outcomes (Figure 7.2; FAO, 2010a; Penafiel et al., 2011; Masset et al., 2011).

According to the UNICEF framework (UNICEF, 1990) that outlines the various direct and indirect determinants of child and maternal nutrition, biodiversity is in general considered part of the natural capital, which can have an impact on the level of poverty, household food security, dietary diversity and food habits (see also Chapter 6), child and maternal caring practices and access to a healthy (or unhealthy) household environment. These factors are determinants for dietary intake and disease control, the two direct determinants of nutrition health outcomes. The UNICEF framework illustrates the complexity of the pathway between biodiversity and nutritional outcomes as well as the many potential confounding factors, e.g. income, access to health services, and adequate care practices (e.g. breastfeeding), that can influence this pathway.

In the MEA framework, four types of ecosystem services provided by biodiversity are distinguished and can be linked to the UNICEF nutrition impact pathway (Figure 7.2): provisioning services (e.g. macro- and micronutrients, fresh water) that contribute to food security; regulatory services (e.g. disease regulation, climate regulation) that contribute to a healthy household environment; cultural services (e.g. culinary traditions, utilization of medicinal plants) that contribute to adequate care; and, as also mentioned above, supporting services (e.g. soil formation) that are critical to enable the other services.

Starting from this combined MEA and UNICEF framework, methodologies will be explored to investigate how biodiversity, food security, diet diversity and nutrition health outcomes are linked. This chapter will not go into depth on assessments of dietary diversity and food habits, but will emphasize that human selection, marketing and consumption habits are key drivers for biodiversity selection and promotion (feedback loop indicated by arrows in Figure 7.1). Critical for linking biodiversity and nutrition is the co-location of data in different scientific disciplines, i.e. ecology, agriculture, economics (e.g. food market prices and functioning, income data), nutrition (e.g. consumption, anthropometric measurements) and health, and a strong research design in order to push toward a firmer grasp of causal mechanisms to guide interventions (Barrett et al., 2011; Masset et al., 2011; Penafiel et al., 2011; Sachs et al., 2010; Golden et al., 2011). Most often, biodiversity studies do not include measurements of human well-being, such as food security, consumption and anthropometric measurements and operate at different time and spatial scales than agriculture or human health studies (e.g. at the landscape level versus at the individual or clinic level). Similarly, human health studies mostly do not include environmental or agricultural indicators. In order to better understand the relationship between biodiversity and nutrition, it is essential that future studies are designed for cross-sectoral hypothesis testing and for stronger integration of different datasets.

An example of co-location of data can be found in the Millennium Villages Project. In addition to the information on biodiversity described in Box 7.1, data were collected on the agro-ecological zones, the three pillars of food security including food availability, access and consumption, as well as anthropometric measurements of children under five years in age and blood samples of adult women and children (Remans et al., 2011a, 2011b).

Through multivariable regression functions, the integrated dataset allows exploring relationships between biodiversity and nutrition outcomes at different scales, i.e. at the household and village scale, as well as over time (MVP is a ten-year project), while controlling for a set of demographic and socio-economic variables. Preliminary findings show that no significant correlations at the household level could be found between species richness or nutritional FD and household food security or consumption indicators. However, certain trends between species richness, nutritional FD and human nutrition indicators are observed at the village or landscape level. For example, villages where biodiversity provides less mineral diversity as compared with other villages, face higher prevalence of iron deficiency among adult women. Also, higher species richness and nutritional FD at the village level corresponds with higher average levels of dietary diversity and food security (i.e. fewer months with inadequate food supply). These findings generate interesting hypotheses on the link between nutritional diversity and nutrition outcomes at the village or landscape level. Importantly, more research is needed to analyse the causal relationships and the role of markets and access to food (e.g. using the cost of the diet tool described by Perry, 2008). While most households in the studied villages are considered subsistence farmers, farm households are not closed systems. Food consumption and expenditure data show that the average proportion of food consumed that comes from own production is around 50 per cent. Also, a significant correlation was found between the number and value of food items bought and sold on local markets and the household food indicators at each of the three sites (Food Insecurity Score (FIS), Household Dietary Diversity Score (HHDDS), Months of Household Inadequate Food Supply (MHIFS)) (Lambrecht, 2009). These findings emphasize the importance of local markets and support the notion that these farm households are not closed systems. Therefore, the most appropriate scale to link nutritional FD metrics to food consumption and nutrition indicators would be the "foodshed", defined as the geographic area that supplies a population centre with food (Peters et al., 2008; Niles and Roff, 2008). Village level data show that for the Ruhiira Millennium Village site in Uganda, 82 per cent of food consumed is derived from production within the village. This indicates that in the case of this village, the foodshed currently largely overlaps with the village (Remans et al. 2011a). While the concept of foodshed seems most straightforward for settings where most of the food is from own production, the concept can and has also been applied at larger geographic scales, such as urban areas, and regional foodsheds, as well as for the global foodshed. For additional reading on this topic, please refer to Peters et al. (2008) and Conard et al. (2011) who describe foodshed analysis for urban areas. To further unravel the role of markets in the biodiversity–nutrition nexus and the dynamics of stocks and flows of nutrients in foodshed analysis, market and value chain analyses offer potential for future investigation (e.g. Hawkes and Ruel, 2011).

Trade-offs and synergies with other ecosystem services and components of human well-being

In addition to providing ecosystem services that directly contribute to human nutrition, biodiversity indirectly supports human nutrition by ensuring the availability of ecosystem services that contribute to other aspects of human well-being (MEA, 2005; Figure 7.1). This section explores methodologies that can help address the question as to how biodiversity and the ecosystem services it provides can be managed for improved nutrition, while also managing for other components of human well-being.

Improving human well-being necessitates managing agriculture for multiple services across geographic extents and through time

In an analysis of the state of the planet and its people, the MEA concluded that in order to address many of the threats to human well-being it is essential to learn to manage for multiple ecosystem services (MEA, 2005). Since the MEA came out much work has been done to develop strategies to assess multiple outcomes, including nutrition, related to biodiversity at various spatial and time scales. This has elucidated numerous challenges of such analysis, important to briefly outline here.

While ecosystem services are not all equally required to ensure human well-being some *combinations* of them are. Without an adequate supply of drinking water, caloric intake ensured by the provisioning of food cannot secure well-being. But the provisioning of drinking water does not suffice if it results in disease that compromises the ability to absorb nutrients, thus ecosystem services that regulate water quality are also required to improve nutrition. In addition, without the ability to cook food, using fuel from the provisioning of wood or fossil fuels, the nutrients might not be bio-available for human consumption. Beyond the need for multiple provisioning services (e.g. food, water, fuel) and regulating services (e.g. disease), well-being also requires a combination of cultural services. Having enough food, water and nutrients to be physically healthy does not ensure that one is mentally healthy.

It is clear that ensuring human well-being requires managing for multiple services but how much of which service is not clear. A clear understanding of how to manage for multiple services is currently elusive for a number of reasons. First, many ecosystem services are difficult to quantify (e.g. religious fulfilment), making it challenging to determine the *amount of each service* that is required to ensure well-being. When thinking about one service at a time, it may be fairly straightforward (as least for some services), to accurately quantify how much is needed to fulfil basic requirements to maintain human well-being. It is possible to see these amounts as thresholds for which, if the amount of the service falls below, a reduction in human well-being would be expected. For example, determining a threshold for food or water provisioning services can be based on our knowledge that humans require a basic amount of daily nutrient intake to prevent undernutrition or a certain number of litres of water to prevent dehydration. Determining thresholds for other services however, is much more difficult. For example, it may be possible to quantify how much one feels a sense of community but the amount required to maintain well-being may vary substantially from person to person. Or determining thresholds for supporting and regulating services that help ensure provisioning services is complicated because the relationship

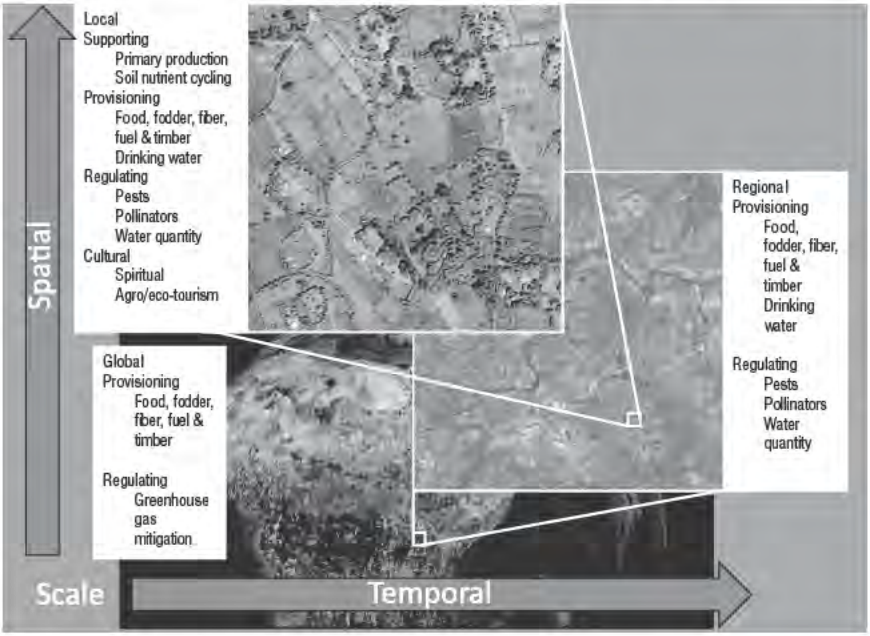

Figure 7.5 The availability of ecosystem services can vary by spatial and temporal scales, illustrated here for the local, regional, and global scales through time. How farmers manage their agrobiodiversity at the local scale not only impacts on quantities of multiple ecosystem services available to them; it can also impact the availability of a different suite of services for people in distant places or even people in the distant future

is indirect. How much soil regulation is required to ensure that crops can produce that daily intake of calories?

Further, there are inherently numerous *interactions among ecosystem services.* These interactions may be close dependencies, or loose associations. In some cases this means a number of ecosystem services will respond to the same driver of change similarly but in other cases they will not. If a storm causes severe soil erosion and reduces soil nutrient regulation, fuelwood and food provisioning are both likely to be negatively impacted. The provisioning of one service might actually be at a cost to the provisioning of another service. Growing enough food on a limited piece of land (food provisioning) may mean that there is no room to grow fuelwood trees (fuel provisioning). Being able to accurately quantify and/or predict changes in the availability of these services is key to understanding these trade-offs and managing for multiple ecosystem services. Equally as important, is the need to identify and understand possible synergies among ecosystem services, i.e. situations where multiple services are enhanced simultaneously by exogenous drivers such as particular management practices.

Beyond trade-offs and synergies among multiple services it is important to recognize that there may also be *trade-offs and synergies among locations and time* *periods* (Figure 7.5). The ecosystem services that humans rely on are often produced far from where they are consumed. Those that consume these services may have little or no relationship to those who manage the biodiversity that mediates their availability and there may be serious trade-offs between the types of services that are available to those that consume vs. those that manage the services. This holds true for those people who will consume services in the near future (i.e. future generations). There are likely large trade-offs in the availability of ecosystem services for the current generation as opposed to future generations. For example, while all humans need clean water very few people actually manage the areas of the landscape that regulate water quality. Watersheds are areas of a landscape that delineate the collection of water (e.g. rain, snow) and drainage, to streams, rivers and aquifers. Management of these watersheds can largely determine the fate of the quality of water that can be supplied far from the source. Managers of a watershed such as farmers, ranchers or foresters, can thus impact the availability and quality of the water for downstream users. This inherent disconnect between beneficiaries and managers for many ecosystem services poses one of the most important challenges to human well-being and illustrates a clear need for policy based on scientific guidance.

The more the trade-offs and synergies can be understood and predicted among ecosystem services in agricultural landscapes that dominate our terrestrial world, the more effective it will be to manage for improved human well-being (MEA, 2005).

Evaluating multiple services requires trade-off analysis

Methods to measure multiple ecosystem service outcomes and relate them to changes in human well-being have until recently been largely theoretical because of the challenges outlined above (Daily, 1997; Foley et al., 2005; Raudsepp-Hearne et al., 2010a, 2010b). Few studies have simultaneously measured ecosystem services (Chan et al., 2011; Nelson and Daily, 2010; Smukler et al., 2010) and fewer still have been able to also measure changes in well-being or nutrition (Raudsepp-Hearne et al., 2010b; Said et al., 2007). Some studies utilize spatially explicit ecosystem process models to predict future outcomes of particular management scenarios, while others have taken the approach of measuring and mapping actual outcomes (Figure 7.1). The evaluation of the trade-offs and synergies in the analyses in most of these studies is limited to graphically illustrating the multiple outcomes and how they have or might change based on different management practices (Figure 7.6).

Recent progress has been made in two key areas that will help with these types of efforts: the development of tools that can effectively model multiple outcomes and the collection of data that can be used to parameterize and validate these models (Nelson, 2011). What is noticeably missing from current analyses is an assessment of trade-offs and synergies of ecosystem services with nutritional outcomes as indicators of human well-being. In what follows, the

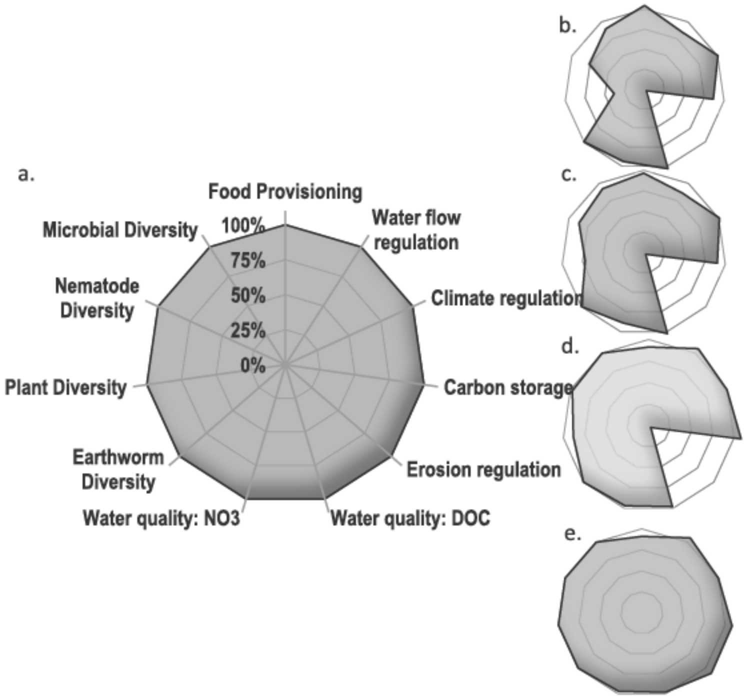

Figure 7.6 An example of how biodiversity and multiple ecosystem services may be graphically illustrated to assess potential trade-offs and synergies. In this case the quantities of six ecosystem services associated with four indicators of agricultural biodiversity are compared for different management scenarios in a case study of a tomato farm in California, USA (Smukler et al., 2010). The quantities of biodiversity and ecosystem services were considered to be 100 per cent for the measured baseline analysis of the current system (a.) and the values in modelled alternative scenarios are reported as percentages relative to this baseline. The scenarios include: (b.) tomato production only, (c.) tomatoes with native shrub hedgerows that provide habitat, (d.) tomatoes with native shrub hedgerows and riparian tree planting that also store carbon, (e.) tomatoes with native shrub hedgerows, riparian tree planting and a detention pond that purifies irrigation runoff

chapter describes these methodologies and discusses how key biodiversity–nutrition questions can be integrated to them.

There are numerous ecosystem process models, economic models, and bio-economic models that can simulate outcomes for one or two ecosystem services and a few outcomes of human well-being (Raudsepp-Hearne et al., 2010a). The MEA utilized a number of these individual models to predict outcomes for living space, food and energy for various land use / land cover change scenarios (MEA, 2005). There are however only a few integrated process models that can predict multiple outcomes simultaneously, yet these do not necessarily link services with well-being but rather predict associated changes in particular indicators.

Of the models currently employed for multiple ecosystem service analysis there are three examples that have recently demonstrated their capabilities and potential to model trade-offs and synergies. Two of these models are open source, the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) (Nelson and Daily, 2010) and Artificial Intelligence for Ecosystem Services (ARIES) (Villa et al., 2009), and one is a proprietary model, EcoMetrix (Parametrix, 2010). Although these models, and others like them, all attempt to quantify and valuate multiple ecosystem services and some aspects of human well-being their methodologies vary greatly (Nelson and Daily, 2010).

Both InVEST and ARIES were designed to provide a tool to assess ecosystem service trade-offs for various landscape management options to a wide range of stakeholders including international conservation organizations, government agencies, and businesses. EcoMetrix is a multi-resource tool designed for quantifying ecosystem services at a much smaller scale and is targeted at stakeholders who need to do site-specific evaluations to measure project impacts and benefits. InVEST and ARIES run a series of modules that simultaneously produce outcomes for ecosystem services ranging from carbon sequestration to water regulation and include analysis for biodiversity and economics. The EcoMetrix model is a compilation of over 50 biotic and abiotic (physical process) functions that are scored based on the percentage of optimal performance for the given site that allows the user to assess changes in the functional performance for a variety of ecosystem services such as water provisioning, water regulation, climate regulation and various cultural services. Using a percentage of optimal performance helps address the challenge of dealing with the various units of each ecosystem service and enables "stacking" of services into a single score. Because the value of ecosystem services depends on stakeholders preferences or site-specific conditions the model also allows for the "weighting of factors" and enables policy goals to be changed and tracked. Each of these models has been utilized in a number of environments and socio-economic situations including Tanzania, Oregon and China (Daily et al., 2009; Tallis and Polasky, 2009) but the number of studies remains small. Furthermore the extent that these models can demonstrate the relationship between ecosystem services and human well-being is limited mainly to economics and, to our knowledge, thus far neglects nutrition entirely.

What we need to do to effectively use trade-off analysis with biodiversity and nutrition questions

Although there is a strong theoretical framework for the relationship between various ecosystem services and nutritional outcomes, as described above, current ecosystem process models don't address this outcome. Developing modelling components that can integrate the various ecosystem services that are directly related to agro-biodiversity and nutrition (e.g. water regulation) is particularly critical for assessing various land management options in agricultural landscapes in impoverished regions, where substitution of services (e.g. buying bottled water) is not an option. Thus far modelling efforts have been largely focused on developing conservation strategies, which do not necessarily equate to sustainable development. It is argued that there is a critical need to modify such models so they can be used in agricultural landscapes to address near-term human well-being concerns such as nutrition and understand how agro-biodiversity may contribute to this goal. What is needed is to start measuring nutritional outcomes in the same locations as biodiversity and ecosystem services are measured. Using these data it is possible to then start to build additional modules into existing models and begin to assess correlations between these ecosystem services and nutrition outcomes.

Identifying drivers of change

In order to guide decision-making on future management of biodiversity for nutrition and other components of human well-being, it is not sufficient to understand the situation at this moment of time. Society and ecosystems change so fast that research methodologies that help to identify drivers of change are critical to enable forward-looking research and adaption to change. This section takes a step in exploring options to address the questions "How and why does the relationship between biodiversity and nutrition change over time? What are the major drivers of change?"

Several hypotheses already exist on these drivers of change. For example, it has been argued that changes in agricultural production systems from diversified cropping systems towards large-scale, industrial agriculture have contributed to ecologically more simple cereal based systems, poor diet diversity, micronutrient deficiencies and resulting malnutrition in the developed as well as the developing world (Welch and Graham, 1999; Frison et al., 2006; Graham et al., 2007). Historically, success of agricultural systems has been evaluated on and driven by metrics of crop yields, economic output and cost-benefit ratios (IAASTD, 2009).

There is, however, no systematic approach to identify trends and drivers of change for the relationship between biodiversity and nutrition. Identification of drivers of change is very complex because of the multiple interactions and feedback loops between factors (resulting in non-linear relationships) (Barrett et al., 2011), but lessons from other scientific disciplines, e.g. climate science, economics and anthropology, can help to pave the way.

Here we discuss a two-step approach as a minimum strategy. First, long-term time series of observational data on biodiversity, ecosystem services, and human well-being outcomes (including nutrition and other components) at different spatial scales need to be collected to enable the identification of trends and generate hypotheses on relationships. A global agricultural monitoring network as suggested by Sachs et al. (2010) could provide such data on biodiversity and nutrition. The network aims to collect data on the multiple dimensions (including biodiversity and nutrition) of agricultural landscapes across agro-ecological, climatic and anthropogenic gradients and over time (Sachs et al., 2012). In addition, already existing time-series and geo-referenced data can be mobilized better to be integrated in cross-sectoral data-analysis and models; for example nutrition time series data are abundant (on anthropometry), as well as agricultural and environmental data (food production, food availability in FAOSTAT, land cover databases etc.).

Second, cross-disciplinary social and experimental research is needed to draw causal relationships on these interactions between social and ecological systems. For example anthropological studies, of which there are now a large number, help to understand why a community conserves certain species or varieties while ignoring others. Experimental research including randomized control trials can help unravel if and why certain species are more tolerant to changing environmental conditions.

It is beyond the scope of this chapter to extend on these approaches. But we do want to emphasize the importance and potential of research on drivers of change. Our science cannot afford to stand still at the snapshot of time that we currently live in. A better understanding of the scope of drivers of change will enable forward-looking research that can provide tools to enhance decision-making at the right time and the right place.

Tools for enhancing interdisciplinary communication

To address the complexity of the relationship between biodiversity and nutrition, it is widely recognized that collaboration between researchers and practitioners from different disciplines is needed. However, the barriers to

Box 7.2 Tools for enhancing interdisciplinary communication (Winowiecki et al., 2011)

- Interdisciplinary Toolbox – undertake structured dialogue about research assumptions.
- Integrated Timeline – brainstorm with all participants and disciplines about historic events that led to the current food-insecurity situation.
- Mind Mapping and Mini-Mind Mapping – brainstorm factors and drivers that influence food security.
- Cross-Impact Analysis – explore the relationships between each major theme identified in the mind-mapping exercises.
- Imagining the Ideal – create and share visions about the ideal outcome or solution to the research problem.
- Backcasting – undertake a scenario-building exercise that works backward from imagining the problem is solved (the world is food secure) and explores the paths to get there.
- Joint fieldwork and visits – undertake joint visits to the field to identify specific problems and related solutions.

efficient communication between different disciplines and enjoyment of the process are often underestimated. There are an increasing number of tools that can help enhance interdisciplinary thinking and communication and this topic is the focus of Chapter 10 of this book. To introduce the concept, we list a few examples in Box 7.2 of methods that we explored and found useful in the context of the research described in this chapter.

Conclusion

Addressing questions on the interaction between biodiversity and nutrition isn't easy. To provide effective science-based decision-making tools to improve human nutrition will require innovative research that utilizes a systems-approach and new thinking that begins to bridge the gaps between disciplines.

In this chapter, we have explored various frameworks and methodologies that can help address some of the key questions about the link between biodiversity and nutrition. We have also emphasized the importance of understanding possible synergies and trade-offs with other ecosystem services and components of human well-being as well as to identify drivers of change. Our objective was not to provide an exhaustive list of options but to trigger new thinking and to contribute to creating an enabling research environment for exploring this intriguing and critical interaction between biodiversity and human nutrition.

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