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Agricultural biodiversity, social–ecological systems and sustainable diets

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The stark observation of the co-existence of undernourishment, nutrient deficiencies and overweight and obesity, the triple burden of malnutrition, is inviting us to reconsider health and nutrition as the primary goal and final endpoint of food systems. Agriculture and the food industry have made remarkable advances in the past decades. However, their development has not entirely fulfilled health and nutritional needs, and moreover, they have generated substantial collateral losses in agricultural biodiversity. Simultaneously, several regions are experiencing unprecedented weather events caused by climate change and habitat depletion, in turn putting at risk global food and nutrition security. This coincidence of food crises with increasing environmental degradation suggests an urgent need for novel analyses and new paradigms. The sustainable diets concept proposes a research and policy agenda that strives towards a sustainable use of human and natural resources for food and nutrition security, highlighting the preeminent role of consumers in defining sustainable options and the importance of biodiversity in nutrition. Food systems act as complex social–ecological systems, involving multiple interactions between human and natural components. Nutritional patterns and environment structure are interconnected in a mutual dynamic of changes. The systemic nature of these interactions calls for multidimensional approaches and integrated assessment and simulation tools to guide change. This paper proposes a review and conceptual modelling framework that articulate the synergies and tradeoffs between dietary diversity, widely recognised as key for healthy diets, and agricultural biodiversity and associated ecosystem functions, crucial resilience factors to climate and global changes.

Food security: Sustainable development: Nutrition-sensitive agriculture: Dietary diversity: Food policy: Integrated assessment: Bio-economic modelling

Humanity faces a global nutrition crisis, with the dual problem of hunger and obesity. A total of 842 million people still suffer from undernourishment[1] while obesity has become a significant public health issue with 500 million obese adults[2]. More than 1 billion adults are projected to be obese by 2030 if no major effort is made[3]. Meanwhile, climate change and environmental degradation are massive threats to human development. Indisputable and unprecedented changes in extreme weather and climate events have been observed and will increasingly have detrimental impacts on livelihoods, particularly in combination with other environmental threats[4]. Above all, global biodiversity is constantly declining, with substantial ongoing losses of populations, species and habitats. Vertebrate populations have declined by 30 % on average since 1970, and up to two-thirds of species in some taxa are now threatened with extinction[5]. These global changes have major implications for food and nutrition security.

Abbreviation: GHGE, greenhouse gas emissions.
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There is a bi-directional relationship between the environment and food. Human subjects depend on the goods and services provided by natural and managed ecosystems to meet their food needs. The production of food and its nutrient content are inextricably linked to the environment. Ecological interdependences are key factors for the dietary content of most living species we consume[6]. The observed environmental degradation and biodiversity depletion, in particular, are affecting the food systems, with implications for yield, quality and affordability[7]. At the same time, processes along the food chain, from agricultural production to food consumption, produce other outputs than food that are returned to the natural environment, such as pollution or waste. Human activities impact the diversity of organisms found in ecosystems, and thus influence the provision of ecosystem services.

The links between environmental degradation and food system activities are increasingly recognised and translate into joint negative environmental and nutritional outcomes[8,9]. The sustainable diets' research and policy agenda essentially aim at putting nutrition and health at the core of sustainable development. However, there is not a clear understanding of the interactions between food systems; their production activities and subsequent outputs, ecological processes and human nutrition. This has resulted in a perceived lack of evidence of the benefits of agrobiodiversity on nutritional outcomes from food systems, preventing agrobiodiversity from being a key consideration in food and nutrition policies.

Since the processes underlying nutrition insecurity and diet-related environmental, economic and social unsustainability derive from a shared food system, a recurrent fundamental question is: what types of system shift could create an enabling environment for sustainable diets? Research has a critical role in answering this type of question. System dynamics are widely considered of particular interest to food and nutrition security[10]. Starting from a conception of food systems as social–ecological systems, thus fully tackling the systemic dimension of the food sustainability question, this paper proposes a review and a conceptual modelling framework that articulates biophysical processes with socio-economic dynamics. Within this coupled human–environment framework, taking into account the determinants that influence food consumer behaviours will be key to improving strategies that mitigate negative patterns on health and the environment. It will help frame the agricultural biodiversity's role in nutrition and develop modelling tools for the policy-makers to guide changes towards sustainable diets and food systems.

Sustainable diets: a new concept calling for changes

A nutrition-driven perspective

Gussow and Clancy[11] were the first to suggest the term 'sustainable diet' to describe a diet 'composed of foods chosen for their contribution not only to health but also to the sustainability (the capability of maintenance into the foreseeable future) of the (…) agricultural system'[12]. Literally, the concept of diet in nutrition refers to the sum of foods consumed by a person. Whole diet, or dietary pattern, analysis has emerged as an alternative and complementary approach to the study of individual nutrients or foods, highlighting the dynamic and multiple factors involved in eating practices[13]. It helped better communicate healthy eating messages that emphasise a balance of food and beverages within energy needs[14]. More fundamentally, adopting a whole-diet approach is now seen as necessary to examine the relationships between nutrition and health[15]. It reflects the increasing recognition of the multidimensional nature of diets and diet-related diseases, from nutrient intakes and metabolism to food consumption behaviours and attitudes[16].

Multidimensionality is further enhanced as the impacts of diets not only on health, but also on the environment or the economy, are considered to assess the sustainability of food choices. Participants at the 2010 International Conference jointly organised by the Food and Agriculture Organization and Bioversity International agreed on a common definition of sustainable diets as 'those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimising natural and human resources'[17].

The sustainable diet concept advocates for a more consumer-driven thinking on the sustainability of agriculture, promoting a research and policy agenda that introduce nutrition as one of its core dimensions. It claims that understanding the determinants of consumer choices can improve agricultural and food systems, the environment and the health. More fundamentally, it emphasises the health and food security purpose of food systems, and highlights the need for quality, not just quantity or access. Advocates promote economically, socially and environmentally sustainable food systems that concurrently ensure 'physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life'[18]. This reminds us that food, or more precisely feeding people, is agriculture and food systems' main reason for being[19]. As such, the concept of sustainable diets provides a food and nutrition security-orientated perspective on the question of the sustainability of food systems.

Food security and sustainable development

Food and nutrition security is a major concern today with still 842 million people undernourished[1]. Resulting undernutrition is affecting millions of people, in particular children under 5 years with about 165 million stunted children in developing countries[20]. Sub-Saharan Africa and South Asia, with wide subregional variation, are the most affected regions by stunting. Undernutrition is accompanied by, in some cases linked to, micronutrient malnutrition. Malnutrition involves privation in essential micronutrients with low food diversity. Deficiencies in essential micronutrients have detrimental effects on health; vitamin A is required for multiple physiological processes, ranging from vision to embryonic development; iron is an important component of haemoglobin, the oxygen-carrying component of blood; iron also plays an important role in brain development and iron-deficiency anaemia can impair the cognitive development of children; iodine is essential for healthy thyroid function and growth, etc. Simultaneously, increased prevalences of overweight and obesity are reported in both low- and high-income countries and represent the major health threats. Excessive fat accumulation, measured by the BMI, is acknowledged to be a risk factor for various non-communicable diseases and health problems, including CVD, diabetes, cancers and osteoarthritis[21].

Simultaneously, climate change and environmental degradation are major challenges to sustainable development. The global climate and other life-supporting environmental systems are seriously perturbed and depleted[4]. These changes include higher temperatures, drought-prone and long-term drying conditions in some sub-tropical regions, rising sea levels, acidification of oceans, declining water quality, depleting fish stocks, increasing frequency and severity of floods and other climate-related natural disasters. Biodiversity is also at risk, with 20 930 species and ecological communities known to be threatened[22]. Biodiversity, the basis of ecosystem health and future food security, has been more seriously harmed by human activities in the past 50 years than at any other time in human history[5]. Agriculture and the food sector have historically been major contributors to environmental degradation. For instance, irrigated agriculture globally accounts for 70 % of the consumption of freshwater resources[23]. However, there is a bi-directional relationship between environmental degradation and food system activities. People, particularly those living in developing countries, are vulnerable to environmental changes that result in reduced quantity, quality and affordability of food. Similarly, nutrition transition and food system transformation go together. The current global health crisis of malnutrition, both in developed and developing countries, and the contemporaneous urging environmental degradation present new challenges for food systems and calls for changes. Improved food systems could be a major partner in the environmental solution.

Diets as system outputs

A crucial question is then: can optimal diets be derived that concurrently meet dietary requirements while reducing detrimental environmental impacts? Contrary to conventional wisdom, recent evidence suggests that high nutritional quality products might not be necessarily more environment-friendly. Although plant-based foods have lower greenhouse gas emissions (GHGE) per unit weight, better quality diets were found associated with significantly higher GHGE after adjustment for energy intake[24,25]. So, can consumers lower, for example, their carbon footprint through making changes in the kind of food they buy, and still meet nutritional adequacy recommendations? MacDiarmid *et al.*[26] derived what would look like such an optimal diet for a representative UK consumer for different GHGE reduction targets. Using mathematical linear programming, they conclude that such a diet can be achieved for the GHGE objectives set for 2020 (−25 %); however, meeting the targets for 2050 (−70 %) and dietary recommendations will require a ‘radical shift in food consumed’. *Ad hoc* constraints were added to the model to maintain simulated diets within consumers’ acceptability limits. These results clearly show that demand-side approaches to the problem of environmental unsustainability are desirable and likely to contribute to improvements. However, as highlighted by MacDiarmid *et al.*[26], GHGE reductions should be made to both the demand and supply sides within the food chain, in particular to attain longer-term objectives. If other environmental, economic, social and ethical aspects of sustainability were to be included in the optimisation model, while strengthening the acceptability constraints, one can wonder if feasible solutions can be derived by changes at the sole food basket level. Linear optimisation theory tells us that if there are x decision variables, then a set of x equality constraints needs to be specified for one unique optimal solution and vice versa. Any extra equality constraints will overspecify the problem. If feasible solutions are to be identified, extra decision variables need to be considered. In other words, other levers need to be operated jointly with actions encouraging behaviour changes.

The processes underlying food insecurity and diet-related environmental, economic and social unsustainability derive from a shared food system. For instance, GHGE are not food attributes, but outputs of different activities along the value chain. Food consumption is a heavy contributor to ‘embodied’ or indirect emissions in products that result from activities prior to purchase[27]. In practice, these indirect emissions are very hard to be accurately estimated and attributed to a good or an individual. Modelling exercises of optimal diets have had to use so far averages coming from life-cycle assessment studies on, sometimes, rather aggregated food groups. There might thus be a high degree of variation around these average estimates. For instance, Lindenthal *et al.*[28] report substantial differences in terms of GHGE between organic production methods as compared with conventional farming in Austria (10–21 % lower CO_2-eq/kg product for organic dairy, 25 % for organic wheat bread and 10–35 % for organic vegetable.). Similar studies elsewhere have reported the same results[29,30].

Consumers stand at the top of the food system and diets are outputs of longer and more complex food chains encompassing several activities. Technologies and policies affect the overall environmental performances, food security and health outcomes[31]. To derive optimal sustainable diets, we need to look at all the variables that influence the flow of activities along the food system.

These are the levers to act upon. To assess and enhance food sustainability, focus needs to move beyond the food basket while ultimately bearing in mind that diets and nutrition are the final reason for being of the food system. Burchi *et al.*[32] define a system as 'a set of elements that function together as collective units which have properties greater than the sum of their component parts'. The food system concept describes the required inputs, processes and generated outputs involved in the provision of food and nutrients for sustenance and health, including growing, harvesting, processing, packaging, transporting, marketing, consuming and disposing of food[8,33,34]. The current joint crisis of malnutrition and unsustainability has roots in agricultural and food systems that do not deliver enough essential nutrients to meet dietary requirements for all[35,36]. The solution to sustainable diets lies both in sustainability-orientated food choices and in changes in the food systems. And modern societies depend on complex social–ecological systems to provide food[8,37–39].

A complex human–environment system

Food and nutrition as ecosystem services

Agriculture and the food sector at large have a first-hand touchpoint with nature: crops need soil, water, insects for pollination, etc. The analysis of the relationships between resource acquisition and living organisms, at the heart of the sustainable diet concept in the case of human organisms, is also an ecological question, and can surely benefit from insights from ecology. Ecosystems consist of a community of species, or biodiversity, interacting with each other and with their environment. The product of these interactions, which include competition, predation, reproduction and cooperation, is essential to human wellbeing. Human subjects depend on goods provided by natural and managed ecosystems. These goods and other benefits provided by ecosystems to mankind are collectively referred to as ecosystem services (Ecosystem services were defined in the Millennium Ecosystem Assessment[7] as 'the benefits people obtain from ecosystems', both natural and managed. These services may be categorised as provisional (fibre, food, water and fuel), regulative (climate and disease regulation, water purification), cultural (aesthetics, heritage, education, recreation and spiritual) or supporting services (nutrient cycling, primary production and soil formation)). All are processes through which ecosystem sustain human livelihoods. Food production is an ecosystem service central to human welfare[40]. The capacity of ecosystems to provide us with the energy and nutrition for our daily life fully depends on the foods that agriculture and food systems provide us. Clear from this process-based interpretation, human nutrition should be considered one of the most fundamental ecosystem services, or alternatively as dependent on several ecosystem services, including provisioning, regulating, supporting and cultural services[41].

Agricultural biodiversity, or agrobiodiversity, is the sub-component of biodiversity that refers to the biological variety and variability of living organisms that are involved in food and agriculture. It can be considered at three main levels: ecosystem diversity, species diversity and genetic diversity[42,43]. It includes habitats and species outside of farming systems that benefit agriculture and enhance ecosystem functions such as pollination, soil dynamics and control of GHGE. Agrobiodiversity comprises the constituents of biological diversity important to food and agriculture as well as for the agroecosystem[6,44]. Furthermore, it is the result of the deliberate interaction between human subjects and natural ecosystems. Subsequent agroecosystems are thus the product of not just physical elements of the environment and biological resources, but vary according to cultural and management systems[42]. Agrobiodiversity includes a series of social, cultural and ethical variables.

Reduction in agrobiodiversity and simplification of diets

Modern agriculture and food systems are contributing to the simplification of the structure of the environment, replacing nature's biodiversity with a small number of domesticated plant species and animal breeds[45]. This process has been one of the main factors that allowed much of the human population to enjoy unprecedented levels of development and improved health. However, as efforts have been directed at maximising production and productivity, uniformity has replaced diversity within cultivated systems[46]. Agricultural intensification, which implies specialisation and genetic standardisation, reduction of utilised species, conversion of forests and wild land to anthropogenic habitats, homogenisation of soils through amendments, is certainly the first human-related cause of biodiversity loss[6,47,48]. The increase in food supply has thus come with important trade-offs that include soil degradation and loss of many regulatory and supporting ecosystem services. These trade-offs can impair the ability of the ecosystems to deliver the essential nutrients for human diets[49].

This increased reliance on domesticated species and selected crop varieties can be linked to a significant reduction in dietary diversity. Modern agriculture is genetically dependent on a handful of varieties for its major crops[50]. The world's agricultural landscapes are planted mostly with some twelve species of grain crops, twenty-three vegetable crop species and about thirty-five fruit and nut crop species[51] (as a comparison, one single hectare of tropical rain forest contains on average over 100 species of trees [52]; cited in[53]). This process of simplification of agriculture generated a model where only a small number of crop species dominate our energy and nutritional intakes. Three crops alone (rice, wheat and maize) account for more than 55 % of human energy intake[54].

Although varying in nutrient content, no single crop species is capable of providing all essential nutrients. Nutritional diversity is now widely recognised to be a key factor for adequate diets likely to satisfy the complex human nutritional needs[55–58]. Evidence of the valuable outcomes of diversity in decreasing malnutrition, morbidity and mortality[6,59] is completed by indications of positive correlation with child growth and survival[60,61]. The importance of nutrient diversity for human well-being calls for dietary diversification. However, the quality of nutritional supply and human health is in danger because of a loss in biodiversity. A reduction in the consumption of varied, 'nutritionally-rich' and 'functionally-healthy' plant-based foods is reported in most developed and emerging countries[62]. The pre-eminent simplification of human diets, associated with changing lifestyles, led to nutrient deficiencies and excess energy consumption. However, the elimination of most essential nutrient deficiencies (most important micronutrients usually reported are vitamin A, iodine and iron, zinc; Graham *et al.* [35] provide a list of fifty-one essential nutrients for sustaining human life) requires only small increases in the variety of food items an individual consumes[63]. As a result, balanced nutrition in human diet can depend significantly on the diversity within crops[64].

Ecological interdependences are key factors of the dietary content of most living species. Some lesser-known cultivars and wild varieties have been reported to be micronutrient superior over other more extensively utilised cultivars. For example, recent analyses have shown that provitamin-A carotenoid content of bananas differs by a factor of 8500 between different cultivars[65]. In Micronesia, the local 'karat' banana has been found to contain high levels of provitamin-A carotenoids, which contribute to protection against vitamin A deficiency and chronic diseases, including certain cancers, heart disease and diabetes[66] (cited in[67]). In this regard, the term 'neglected and underutilised species' or 'development opportunity crop' refers to those species whose potential to improve people's livelihood is not being fully exploited (given the current lack of detailed and comprehensive nutritional information about diversity within crops at the cultivar level and the role it plays in nutrition, the Food and Agriculture Organization has launched the INFOODS initiative[64]).[68]. For instance, a local fruit, *Berchemia discolor*, was found to contribute in a low-cost manner to closing nutrient gaps in Kenya[69]. Peach palm (*Bactris gasipaes*) provides, under low soil fertility and extreme rainfall conditions, starchy fruits with high protein density, rich in monounsaturated oleic acids, carotenoids, vitamin E and potassium[70]. Amaranth, as a leafy vegetable, is nutritionally comparable with spinach while showing strong photosynthetic activity and water use efficiency[71,72]. The drumstick tree (*Moringa oleifera*) combines the traits of high yield and high nutrient density in essential micronutrients, vitamins, antioxidants and bioavailable iron, making it a good supplement for children and pregnant and lactating women[72]. All these examples demonstrate how intraspecific biodiversity and the consumption of neglected species and varieties can be essential to nutrition security.

Increasing the number of crops available to local communities, in particular in developing countries, increases the likelihood of obtaining the nutrients needed for healthy and productive lives[36]. Deckelbaum *et al.*[73] showed that biodiversity and hunger hotspots geographically correspond, reminding us of the link that Jared Diamond unravelled about the spatial relationship between biodiversity availability and society development[74]. This evidence, demonstrating the correlation between hunger and biodiversity-losing areas, confirms the need for local biodiverse agricultural systems. DeClerck *et al.*[36] further observed that improving functional agrobiodiversity in Kenya reduces anaemia incidence, and that interventions supporting environmental sustainability, through biodiversity, can have multiple direct and indirect outcomes on human health and nutritional wellbeing. Similarly, in rice-based aquatic production systems, Halwart[75] found that vegetal agrobiodiversity allowed improved biological diversity and diverse nutritional sources for human subjects (calcium, iron, zinc, vitamin A, some fatty acids and limiting amino acids). Moreover, through fish biodiversity, rice yields increase and the presence of several aquatic organisms in rice ecosystems allows a better biological control of vectors and pests. Animal and vegetal agrobiodiversity in rice-based ecosystems increases income through yield growth and lower costs for pesticides through biological control[74]. These issues suggest, for tackling malnutrition, but also other aspects of food insecurity, the need to link ecology and agriculture to human nutrition and health.

Agrobiodiversity and resilience for food security

On top of nutritional issues, agricultural biodiversity is an essential component in the sustainable delivery of a more secure food supply. Agrobiodiversity is the outcome of thousands of years of efforts by farmers, selecting, breeding and developing appropriate production systems and methods. It plays a crucial role in productivity and livelihood of farmers, by providing the wide range of resources they need to increase productivity in favourable settings or to adapt to variable conditions. Biodiversity simplification resulted in an artificial ecosystem that requires constant human intervention, whereas plant biodiversity allows internal regulation of essential functions in natural ecosystems[53]. Several nature- and human-related drivers of change threaten the ability of social–ecological systems to maintain vital functions and processes: climate change, natural resources exploitation, habitat depletion, pollution, etc.

Understanding how agrobiodiversity is likely to impact agricultural and ecosystems is key. Climate change is a potent risk to the world's food supply in coming decades, likely to undermine production and driving up prices[76,77]. Agricultural biodiversity will be absolutely essential to cope with the predicted impacts of climate change. Crop genetic diversity provides partial resistance to diseases, and enables farmers to exploit different soil types and microclimates for a variety of nutritional and other uses[53]. Improved resilience, to climatic shocks among others, is observed in highly biodiverse ecosystems[78,79]. In Malawi, Mozambique and Zambia, between 26 and 50 % of rural households relied on indigenous fruits as a coping strategy during critical seasonal hunger periods[80,81]. Furthermore, biodiversity in agroecosystems accomplishes multiple ecological services beyond the production of food such as: nutrients recycling, hydrological regulation, purification of toxic chemical compounds, etc. For instance, improvement in agroforestry biodiversity reduces nutrient leaching and soil erosion and refurbishes key nutrients from the lower soil layers(82). To assess the role of agricultural biodiversity in sustainable and secure food production, cross-sectoral approaches are necessary as potential benefits can be manifested at different ecological and human scales(6). Farmers also conserve, and modify their use of, agrobiodiversity to better adapt to different environmental conditions, but also to changing market conditions(83). In Indonesia, the conservation of high levels of biodiversity in rubber agro-forests helped secure population livelihood during the 2008 fall of rubber prices by providing an alternative source of income from secondary products(81,84). Agrobiodiversity can thus be seen as a crucial asset to keep multiple options open. As a general rule, increasing the number of species in a community will enhance the number of functions provided by that community, and will reinforce the stability of the provision of those functions(36).

Bio-economic modelling for biodiversity and nutrition

Modelling activities, capturing diversities

In recent years, there has been a significant development of bio-economic models, enhanced by the recognition of the multifunctionality of agriculture and the multiplicity of objectives assigned to the agricultural policies(85). The subsequent increasing demand for integrated assessment called also for more dialogue and co-operation between scientists from various disciplines, and bio-economic models have been advocated as an adequate tool for such a purpose(86). Bio-economic models refer to models that couple both an economic and a biophysical component. Brown(87) more precisely identifies models primarily concerned with 'biological process (...) to which an economic analysis component has been added'. Another kind of model consists of 'economic optimisation models which include various biophysical components as activities among the various choices for optimization'. In between, he suggests a third category that integrates in an interactive manner the biophysical and the economic modules. This last category genuinely deserves to be called 'bio-economic'.

At the heart of most bio-economic models lies the paradigm that, for analysing the relationships and trade-offs between socio-economic systems and biophysical and ecological processes, and to help evaluate how management actions affect different policy objectives, it is necessary to model activities(88). What produces biodiversity depletion or soil erosion is not wheat or maize production *per se*, but the way it is produced. And there are several ways of producing the same product. The degree of pressure on the environment will depend on the crop selected and its combination with other crops, the tillage technique, the type of soil, the production system, the period of harvest, the seasonality and many other technical issues. It is therefore not adequate to associate a final product with a single simple production function. The relationships between a final product and the inputs associated with its production, highly non-linear because of the large set of possible combinations, might be better captured by considering the variety of activities or production processes.

Land, water, seeds (of different species and varieties), labour, energy, machinery, fertilizer, etc. are taken into account as inputs to the agricultural production. Food are outputs, as well as pollution, changes in landscape, depletion of natural resources, soil erosion, loss of underground water, habitat destruction, biodiversity losses, etc. There are numerous possible combinations of inputs to produce several outputs. Using an example from agricultural production, wheat systems do not only produce grain, but also straw and different types of pollution. They are 'joint products'(89,90). Thus each activity can produce several products (e.g. grain, straw and pollution), and in turn each product can be produced by several activities (e.g. several ways of producing grain). As a consequence, modelling the relationships between a final product and the 'externalities' become even more challenging to synthesize.

Bio-economic models represent production activities in an explicit manner. A production activity describes a specific production process. Usually called an engineering production function, it describes explicitly the relationships between factors of production and products expressed in physical quantities (e.g., kg fertilizer/ha, m^3 water for irrigation, etc.). In agriculture, an activity is defined by the technical coefficients that represent the use of inputs needed to produce different outputs(88). These engineering production functions, which use primal variables (physical quantities), constitute the essential link between the biophysical and economic processes. Models based on cost functions, which use dual variables (prices), can hardly analyse the relationships between inputs and outputs in a straightforward and proper manner. The fact that one product is obtained through several production activities, explains in part the complex and non-linear relationships between inputs and outputs observed per product, which are difficult to capture mathematically. On the contrary, the average cost can more realistically be assumed equal to the marginal cost when considered per activity. Relationships between inputs and joint products by activity are thus linear functions of Leontief type. The use of engineering production functions creates a strong information demand, requiring data framed in terms of physical input–output matrices. However, thanks to this representation, positive and negative jointness can be simultaneously taken into account. This more direct approach can help assess the joint interactions between biodiversity and nutrition.

Biodiversity in bio-economic modelling

There are basically four approaches to introduce biodiversity or agrobiodiversity in bio-economic optimisation models. In a normative approach, it is possible to include biodiversity conservation targets directly in a multi-objective function. Multi-objective optimisation models are goal-oriented models, where optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. Holzkämper and Seppelt[91] developed a spatially explicit optimisation model with respect to ecological and economic goals, namely habitat suitability for three target species and profit losses from different land-use options. Results show that optimum agricultural land-use patterns differ between species, as well as between study sites. Groot *et al.*[92] explore the synergies and trade-offs between financial returns, landscape quality, nature conservation and environmental quality in a spatially explicit land-use allocation model, which combines agronomic, economic and environmental indicators with biodiversity and landscape quality indicators. More specifically, their Landscape IMAGES model couples an agroecological model to a multi-objective optimisation algorithm that generates a set of alternative landscape configurations. An agroecological engineering approach was used to design production activities.

Alternatively, impacts on biodiversity of different land-use management options and policy scenario can be assessed through optimisation models. Schönhart *et al.*[93] address the effects of land use intensity and landscape development on biodiversity at farm and landscape levels. Their integrated land use model combines a crop rotation model with a biophysical process model (erosion–productivity impact calculator) and a spatially explicit farm optimisation model. Field- and farm-specific crop yields, crop rotations and environmental outcomes of the biophysical model are inputs to the farm optimisation model, which maximises total farm gross margin subject to resource endowments and several balance equations. Decisions in integrated land use model are assumed to reflect actual producers' choices postulating efficient farm resource utilisation. This structure allows introducing landscape metrics, such as the Shannon's diversity index, to quantify the spatial biodiversity impacts of landscape development scenarios. Scenario analysis is used to assess the cost-effectiveness of different agro-environmental measures to achieve biodiversity targets. One asset of the integrated land use models is the inclusion of spatial modelling of landscape elements. Similarly, Mouysset *et al.*[94] adopt a multi-criteria approach to assess jointly the impacts of public policy options on conservation of biodiversity and farming production. Assuming income-maximising farmers under technical constraints, the authors test different taxation scenarios on economic performances and farmland bird abundance.

As argued by Schönhart *et al.*[93], biodiversity conservation targets can also be introduced in the model as constraints. Van Wenum *et al.*[95] study optimal wildlife management on crop farms using integer programming. They compute a wildlife-cost frontier at the farm level evaluating the optimal trade-off between species richness and total gross margins. Their model derives sets of management activities that maximise farm income under incrementally varying wildlife conservation requirements. Results provide the extent to which stepwise increases in species richness objectives impact negatively farm profits.

A last approach consists of integrating agrobiodiversity at the core of the model in the definition of the agricultural activities. All the earlier examples of models that consider impacts on biodiversity are based, at least partially, on engineering production functions. It implies defining activities such as obtaining constant marginal costs. Combinations of crops and rotation schemes, in interaction with the environment and agronomic technique, on the farm at the field level have to be considered to specify activities. For example, maize, beans and squash (the indigenous 'American three-sisters') planted simultaneously would be modelled as a specific activity, different from an activity involving only one of the three crops or any other combination. The planting techniques used, either just in the same field or in the same hole, would also be distinguished. Conceptually, this approach by activity would allow setting agrobiodiversity at the core of the model, and better match an understanding of the environmental and nutritional outcomes of diets as system outputs. Indeed, specific environment and nutrition impacts can thus be specified by activity and not by product. However, one strong limitation regards data requirements. Given the wide array of possible combinations, a large number of technical coefficients, which enter the model as external variables, need to be available and properly estimated to result in real improvement to existing modelling exercise.

Joint assessment of nutrition and biodiversity

The increasing demand for integrated assessment, including nutrition[10,96–98] calls also for bio-economic models integrating consumer choices and dietary patterns, and subsequent sets of food consumption and nutrition indicators. A nutrition-driven food system, which also ensures that environmental integrity, economic self-reliance and social well-being are maintained and enhanced, places people, as consumers, as one of its central focus[32]. Not only should we be able to determine food and nutrient availability at the farm or food system level, resulting from the use of biodiversity for instance, but we also need to understand and consider how it translates into actual consumption at the household and individual level. To achieve this, models of food consumption patterns and behaviours need to be integrated into the bio-economic models. This type of tool will allow a proper nutritional analysis and evaluation of required changes in the food systems to reach sustainable diets. In the context of developing countries, farm-household models offer the conceptual background to expand existing bio-economic farm models, to capture the interactions between ecological dimensions and agronomic decisions with consumers' choices (and acceptability of simulated options in terms of consumers' preferences) and nutritional outcomes. Small-holder farmers are vital for developing countries' economies, supporting today one-third of humanity[99]. Farm households, while increasingly selling and relying on markets, represent an 'easier to control for' food system at the smallest scale.

In the case of small-holder farmers in developing countries, the deciding entity is both a producer and a consumer. In the existence of market failures, non-separability regarding production and consumption decisions has to be assumed, and a farm-household approach becomes necessary[100]. Several attempts have been made to couple bio-economic and farm-household models[85,101–104]. In particular, the Joint Research Centre, with the CIHEAM-IAMM and other partners, further developed the FSSIM model of the European Commission for application in developing countries. The FSSIM-Dev (Farm System Simulator for Developing Countries) model is a bio-economic farm-household optimisation model, with a first application to Sierra Leone[105]. A household module has been added to the modular structure of FSSIM. Production, and related environmental outcomes, as well as food consumption are outputs of the model. Conditionally on the quality of the data about the environmental impacts associated with each production activity, and about food consumption and associated nutritional intakes entered and generated out of the model, such a model could assess the farming practices best suited to improve different sets of nutrition and/or biodiversity indicators and the associated trade-offs. In a normative approach, this approach could help define optimal combinations of activities and resulting diets. In a more positive approach, it could identify through simulation analysis the factors more likely to help attain some of these optimal combinations.

Conclusion

A wider deployment of agricultural biodiversity is key for the sustainable delivery of a more secure and nutritious food supply. The importance of nutrient diversity for human wellbeing calls for dietary diversification. However, the quality of nutritional supply and human health are in danger because of losses in biodiversity. Biodiversity benefits affect social–ecological systems all along the food value chain, from agricultural activities, food processing and consumption patterns to nutrition and health status. There is a call for system approaches to capture the dynamic processes between and within the food system activities, nutrition and health, and environmental outcomes. Computational complex systems modelling techniques aim at capturing the co-evolution of human and biological systems, and the complexity of human decision-making[10]. They allow exploring key processes and outcomes of the analysed systems for food and nutrition security, delivering innovative and deeper insights at the environmental level. Food consumption behaviours play a central role in driving us towards the sustainable food system. Understanding how food supply translates in nutrition-adequate consumption patterns, together with capturing choice determinants and underlying consumer's perceptions of environment-friendly practices, are crucial to help guide changes towards sustainable uses of resources for nutrition. Food consumption behaviour has not attracted enough attention from the sustainability community. Further research requires knowledge of the concepts and insights from a wide range of disciplines to tackle the complexity and diversity of influences at work in food choices. Joint efforts are needed in addressing food and nutrition security through a multidisciplinary and multisectoral approach to social–ecological systems.

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Conflicts of Interest

None.

Authorship

T. A. and P. P. were responsible for the study conception and design. T. A., P. P. and G. F. conducted the review and acquisition of data/material. T. A., P. P., B. C. and G. F. contributed to the analysis and interpretation. T. A. and P. P. drafted the manuscript, and B. C. and G. F. undertook the critical revision.

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