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Building a resilient and sustainable food system in a changing world – A case for climate-smart and nutrient dense crops

Maysoun A. Mustafa[a,*], **Tafadzwanashe Mabhaudhi**[b], **Festo Massawe**[a,b]
[a]Future Food Beacon, University of Nottingham Malaysia, Jalan Broga, , Semenyih, Selangor, Malaysia.

[b]Center for Transformative Agricultural and Food Systems, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, , Scottsville, 3209, Pietermaritzburg, South Africa.

Abstract

Current food production and consumption practices have had negative impacts on the environment and are central to global health concerns. Using a mixed-methods review, we examined the nutritional and environmental impacts of our global food systems and addressed the apparent decrease in food sources and crop diversity, and its implication on sustainable and healthy diets. Moreover, we explored the merits of weighing the use of natural capital and agricultural inputs against the output generated in terms of nutrient density. Transforming our food systems to safeguard planetary health will require a shift towards sufficient production of nutrient dense crops that are environmentally sustainable. Such a transformation largely depends on valuing crops for their natural nutrient density and matching them to suitable environments.

Keywords

Dietary diversity; Environment; Health; Transformative; Nexus approach

1 Introduction

The current food production system is unsustainable in several ways; (i) it places intense pressure on both renewable and non-renewable natural resources (UNEP, 2016; Willet et al., 2019; Rockstrom et al., 2017), and (ii) currently accounts for about 70% of water use and 30% of global energy consumption (Lancet Planetary The Lancet Planetary Health, 2017; Rockstrom et al., 2017; IPCC, 2019). This situation is unsustainable due to declining levels of available water, energy constraints and ongoing climate change. Thus, encouraging systematic approaches in an attempt to bring about sustainable management of natural resources (Mabhaudhi et al., 2019a).

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[*]Corresponding author. University of Nottingham Malaysia, Jalan Broga, Semenyih, 43500, Selangor D.E, Malaysia. maysoun.mustafa@nottingham.edu.my (M.A. Mustafa), mabhaudhi@ukzn.ac.za (T. Mabhaudhi), festo.massawe@nottingham.edu.my (F. Massawe).

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A recent report by the Intergovernmental Panel on Climate Change (IPCC, 2019) indicated that agriculture, forestry and other land uses accounted for 23% of human green house gas (GHG) emissions, significantly contributing to the global climate crisis. Agriculture is one of the main contributors of biodiversity loss through land use changes, which convert natural habitats to intensely managed systems; and release pollutants, including GHGs into the atmosphere (Dudley and Alexander, 2017; FAO, 2019). This adversely impacts ‘food and nutrition security’ through reduced yield and nutrient quality and supply chain disruptions (IPCC, 2019). Biodiversity loss reduces nature’s buffering capability that rich ecosystems provide against natural disasters and diminishes important genetic diversity that reflects the worlds’ unique and varied biological and cultural heritages (IPBES, 2018). More importantly and in the context of this review, biodiversity is essential to nutrition security, providing a diversity of food sources to tackle both yield and nutrient gaps in our current food system (Cheng et al., 2017; Mustafa et al., 2019).

This review aims to examine the nutritional and environmental impacts of global food systems and to highlight the impacts of decreasing food sources and crop diversity on sustainable and healthy diets. Secondary to this, was to explore the merits of using natural capital, such as nutrient dense crops in transforming the global food system.

2 Approach

This paper provides a review of the current global food system and explores its limitations with regards to delivering on human wellbeing and sustainable environmental health outcomes. The paper aims to review our current understanding of sustainable food systems through a literature review of available knowledge on food security, nutrient deficiencies, and crop diversity. We chose broad terms reflecting “food systems”, “crop/agriculture diversity”, “food/nutrition security”, “sustainable food”, “nutrient density” while searching for available literature on ScienceDirect and Google scholar, in addition to specific terms that reflect central themes addressed in this review “carbon/water footprint”, “soil health”. A mixed-methods approach was adopted in the development of the supporting data presented in this review, which included both qualitative and quantitative aspects to examine the nutritional and environmental elements of the current global food systems and reflect on the declining food sources and crop diversity and their implication on sustainable and healthy diets. We calculated nutritional value and the estimated bioavailability of the crop species, as well as using available data on carbon footprint and water footprint from Audsley et al. (2009) and Mekonnen and Hoekstra (2014), respectively.

The first section (***cf***. Section 3) of the paper provides an overview of the current status and challenges facing the global food systems to establish the context for the study. The second section (***cf***. Section 4) reflects on opportunities for exploiting the diversity in crop species and matching them to suitable environments to tackle nutrient deficiencies in the soil and in diets, build resilience and protect the environment. In the following section (***cf***. Section 5) we set the scene for what would be a more sustainable and healthier food system and offer suggestions for how the global food system could be transformed towards being more inclusive, equitable, sustainable and healthier. Lastly, we conclude that a participatory approach to diversify food systems is necessary to address nutritional and environmental challenges concomitantly.

3 Challenges facing the global food system: balancing nutritional and environmental demands

The relationship between food security and nutritional outcomes is very complex, however, food insecurity is a key determinant of malnutrition (FAO, 2019). Crucially, our diet today is characterized by two prevailing sides:

A. Insufficient intake of protein, vitamins and minerals (Fig. 1a), which impedes both child growth and development as evidenced by global statistics on stunting and wasting (FSIN, 2019). Consumption of nutrient poor diets (especially micronutrient deficient foods) are the leading risk factors in the global burden of diseases, affecting an estimated three billion people worldwide (Forouzanfar et al., 2015; Global Nutrition Report, 2020). With more than 500 million undernourished people in Asia and 250 million in Africa, the world is not on target to meet the Sustainable Development Goal 2 SDG 2: Zero Hunger by 2030 (FSIN, 2019).

B. Prevalence of high-calorie nutrient-poor foods (Fig. 1b), as evidenced in urban settings and upper middle- and high-income countries (Baker and Friel, 2016). This has dramatically increased the proportion of populations who are overweight and obese to an estimated 30% with zero countries, thus far, on course to meet targets for obesity (Global Nutrition Report, 2020; FSIN, 2019). More than 2 billion adults globally are overweight and obese, facing risks of diet-related non--communicable diseases (NCDs) (Willet et al., 2019), and an estimated 3.8 million children are overweight, with 25% and 46% living in Africa and Asia, respectively, two continents that also face high prevalence of undernutrition.

Nutritional deficiencies increase the risk of infectious diseases and can impact the mortality and morbidity rate of a community (WHO, 2003). The Disability Adjusted Life Year (DALY) is a tool used for assessing the burden of a health condition by measuring the gap between current health status and ideal health status of a population in terms of years (WHO, 2003). Diet related NCDs are major contributors to the global burden of disease, which include type II diabetes and cardiovascular diseases (Dangour et al., 2017). As demonstrated in Fig. 1, malnutrition in its various forms is a global issue, however, sub-Saharan Africa (SSA) experiences the largest health burden due to nutritional deficiencies (Fig. 1a), while Europe and North America experience the largest health burden due to diet related NCDs (Fig. 1b).

While it is a complex relationship, a causal relationship does exist between these various forms of malnutrition and access to quality diets at a household or individual level (Bahn et al., 2020). Food-insecure households in upper-middle and high-income countries are often exposed to obesity due to consumption of low-quality diets that are high in calories, while lacking in essential micronutrients and proteins (Hawkes, 2008). Meanwhile, food-insecure households in lower-income countries are associated with higher risks of stunting, wasting and micronutrient deficiencies, with lower risks of obesity (Bahn et al., 2020). Nonetheless, more than one form of malnutrition can exist within the same community, as limited access to nutrient dense foods can contribute to both under- and over-nutrition (FAO, 2018). The co-existence of undernutrition, nutritional deficiencies and over-nutrition, “triple burden of malnutrition”, can impact one another with added disease and societal burdens as well as multigenerational impacts (FAO, 2018; FSIN, 2019). This is evident in the prevalence of childhood stunting and wasting along with overweight and obesity within the same communities (Global Nurition Report, 2020; FSIN, 2019).

Malnutrition among young children contributes to a staggering 60% of deaths from diarrhoea and 50% of deaths from pneumonia and malaria (WHO, 2010). A synergistic relationship exists between malnutrition and infectious diseases, such that natural immunity is compromised by malnutrition, increasing susceptibility to infectious diseases (WHO, 2010). Meanwhile, infectious diseases exacerbate malnutrition through reduced appetite, malabsorption and nutrient loss (WHO, 2010). As the current Covid-19 pandemic highlights, it is more crucial than ever to integrate interventions that target nutrition and infectious diseases.

A large proportion of the population face “hidden hunger”, characterized by deficiencies in vitamins and minerals (FSIN, 2019). A healthy diet consists of the essential nutrient requirements for well-being, which include 22 identified minerals that are essential for well-being (White et al., 2012). Global estimates place 30% of global populations facing anaemia, with half of the cases due to iron deficiency, 23% facing iodine deficiency, and 15% facing selenium deficiency; with deficiencies in zinc, calcium, magnesium and copper widespread in both developed and developing countries (IGN, 2019; Lopez et al., 2015; White and Broadley, 2009). Mineral deficiencies are largely associated with farming in areas with low mineral phytoavailability as well as consumption of staples with inherently low mineral concentration (White and Broadley, 2009). This paper will explore drivers of micronutrient deficiencies and approaches towards addressing issues within the current food system.

4 Opportunities for exploiting diversity in crop species

As estimated by FAO (2019), 103 crops out of a total of 30,000 edible plant species account for 90% of the global diet. Within these, three main crops – wheat, rice and maize - account for over 50% of plant based human food (Li and Siddique, 2018). The global production of rice, wheat and maize has steadily increased over time, according to the comprehensive Food and Agriculture Organization of the United Nations (FAO) statistical database (FAOSTAT, 2020). While the advancement of technologies and innovation in productivity has played a big role in their increased global production, extensification is closely linked to increased production of the three main cereals with associated negative trade-offs owing to land use changes and degradation. Continuing this path will push food production systems beyond the planetary boundaries (Rockstrom et al., 2009). As such, managing trade-offs between agriculture, environment and health for a sustainable and healthy food system is needed. The Global Consultation Report of the Food and Land

Use Coalition identified ‘ten critical transitions’ to transform food and land use (The Food and Land Use Coalition, 2019). Top on the list are healthy nutritious diets, sustainable agriculture and environmental protection.

Previous focus on food security was narrowed to the availability of adequate calories (Gustafson et al., 2016), resulting in a wider dependence on staple foods, as opposed to diverse diets. There are added challenges associated with changes in dietary habits towards ultra-processed and animal-based foods with lower nutritional value (Hertforth et al., 2019). The continued inequitable access to nutrient-dense foods is a persistent contributor of dietary risks and chronic diseases globally (Padyumna et al., 2018). Combatting micro-nutrient deficiency and diet related NCDs concomitantly is a key aspect of designing effective interventions for food and nutritional security.

The Food and Land Use Coalition (2019) estimate the global cost of undernutrition and tackling NCDs at $1.8 and $2.7 trillion a year, respectively. They also raise concerns about our dependence on a few major staple food crops and the risk of developing countries’ dependency on food imports, often driven by major multinational food corporations. As reported by Bene (2020), trade has positive impacts on food systems, until it plateaus upon a certain point. The Covid-19 pandemic is a testament to the fragility of the current food system and the dangers of an increasingly connected global food supply chain. As nations move towards protectionist policies and domestic stockpiling to increase their strategic reserves, the risk of price hikes increases, which is linked to food riots and political unrest (Bene, 2020; Almeida and Sousa, 2020). Such profound economic and social changes can aggravate poverty and weaken governance structures, and crucially, severe food shortages further increase the risks of infectious diseases and collapse of preventive public health measures (WHO, 2010). These are factors that cannot be compromised in the current climate.

Moreover, climate shocks can impact the affordability of healthy foods, thus placing nutritional and healthy diets out of reach of house-holds and individuals (Campbell et al., 2016). Affordability of healthy diets depends on the purchasing power of households, which is susceptible to climate shocks (White et al., 2010). Additionally, projected changes in suitability of landscapes for food production due to the changing climate, will likely impact food prices, and consequently markets and food accessibility to vulnerable households and communities (Havlik et al., 2014). Vulnerable communities, particularly resource-poor and marginalised, could see climate shocks undermining communal resources, thereby prompting further unrest and food shortages (Oppenheimer et al., 2014).

This highlights an important and complex interaction between food security and trade. Mrdalj and Bilali (2020) note that trade can impact food security through various channels, and emphasise the importance of inclusive agri-food markets and value chains. In the absence of inclusive agri-food markets, Haggblade et al. (2017) posit that the impacts of drought on reduced crop production would be drastically felt by vulnerable households within a community. The level of engagement in trade not only impact income and food prices, but it can also influence dietary diversity and quality (Mrdalj and Bilali, 2020).

Several factors can influence the process of diversifying diets to tackle micronutrient deficiencies (Fig. 2) and these will be discussed in section 4.1 to 4.4.

4.1 Not all crops are created equal: dietary diversity and nutrients

The current status calls for urgent action to diversify food sources and one way is through wider use of local, underutilised and indigenous crops to diversify food baskets and provide healthy diets. Naturally, there are differences between the bioavailable nutrients that exist across the different plant species, as evidenced in the selection of crops shown in Table 1. Table 1 provides a comparison of bioavailable nutrients across the three main cereals (and dry bean), and a selection of underutilised cereals and legumes. As demonstrated, protein content in the underutilised cereals and legumes was often higher than in the three main cereals and dry bean. This was also the case for the minerals iron, zinc and calcium, with a few exceptions.

There has been a global stride towards healthier and more sustainable dietary habits, with an increasing presence of food based dietary guidelines advising consumers on linkages between eating habits, food and health (Herforth et al., 2016). These are generally produced at a national level to influence consumer behaviour and health policies. More recently, the EAT Lancet report (Willet et al., 2019) was developed by a global commission of more than 30 scientists with the aim of establishing consensus on healthy and sustainable diets. The commission acknowledged the nutritional and environmental impact of the current food systems, advocating for more plant-based foods (Willet et al., 2019). With a focus on both ends of the food system - production and consumption – the commission shed light on the scale of agro-ecosystems and its impact on biodiversity loss, greenhouse gas (GHG) emissions and land use.

4.2 Linking soil health to nutritional content

Varietal differences within species can significantly affect micro-nutrient uptake by the plant, thus impacting nutritional quality. Moreover, ecological and climate conditions can play a key role in variations of nutritional content of food (Sokolow et al., 2019). Soil quality is a determinant of the micronutrient availability, a quintessential example being that of iron, zinc and selenium content in plants, which are primarily dependent on the soil type (Joy et al., 2014; Gregory et al., 2017).

Differences in selenium soil availability due to pH and other environmental factors can impact its availability in plants, with selenium uptake increasing with increasing pH (Temmerman et al., 2014). Other factors such as plant type, cultivar and growth stage can also play a role, for example Brassicas can accumulate higher levels of selenium as well as in different forms with added health benefits (Wiesner-Reinhold et al., 2017). Iron and zinc deficiencies are associated with well-aerated, calcareous or alkaline soils (Frossard et al., 2000; Broadley et al., 2007). In Malawi, Chilimba et al. (2011) demonstrated that soil type affected grain zinc concentration in maize, with a 30% increase noted for maize grown on vertisols. This translated to a difference in intake of 1.5 mg zinc per capita per day. Similarly, in Zimbabwe, Manzeke et al. (2019) assessed differences in zinc and iron concentration in maize, sorghum, finger millet and cowpea. They reported a 13% increase in grain zinc concentration on more productive fields, mainly attributed to better farmer management practices (Manzeke et al., 2019).

Competition for limited land resources with infrastructural demands or with protected areas leaves little opportunity for expanding agricultural lands (Dangour et al., 2017). Inherent soil properties as well as farmer management practices can positively impact human nutrition. Thus, it is of importance to maintain healthy soils on existing agricultural lands to support the anticipated growth in global food demand.

4.3 Effect of carbon dioxide levels on nutritional content

Although, elevated carbon dioxide (CO_2) levels have been linked to increased yield (Dong et al., 2018), research is now also pointing towards a decline in key micronutrients as CO_2 levels increase globally (Zhu et al., 2018). There is evidence that protein content as well as macro- and micro-nutrients of leaf and grain may decline as CO_2 levels increase (DaMatta et al., 2010). In an assessment of rice grown under elevated CO_2 levels, Zhu et al. (2018) reported 17.1% decline in Vitamin B1 (thiamine); 16.6% in Vitamin B2 (riboflavin); 12.1% in Vitamin B5 (pantothenic acid); and 30.3% in Vitamin B9 (folate). Moreover, protein, iron and zinc levels also reportedly declined (Zhu et al., 2018).

Similarly, rice, wheat, maize, pea and sorghum cultivars were grown and assessed under elevated CO_2 using free-air CO_2 enrichment (FACE) by Myers et al. (2014) who reported a decline in zinc, iron and protein content of many of these crops. Clear differences were reported between the response of the different crops, and the different cultivars, as well as the nutrients they had assessed (Dietterich et al., 2015). Reportedly, C3 plants, such as rice and wheat, were more susceptible to the effects of elevated CO_2 on nutrient density than C4 plants (Medek et al., 2017).

The continued dependence on rice and wheat as staples across global populations could place an estimated additional 150 million at risk of protein deficiency (Medek et al., 2017). This highlights a growing concern on the future of the food system, as anticipated CO_2-induced deficits of minerals and vitamins may negatively impact the nutrient density of food and health status of the population. Mabhaudhi et al. (2019c) argued for the promotion and inclusion of underutilised crops into the global food system as part of transforming agriculture under climate change. They highlighted several climate-health, climate-environment, climate-socio-economic, and land use-ecosystem services co-benefits that could be harnessed through such transformations.

4.4 Environmental footprint of selected crop species

Exposure to climate threats is drastically felt by farming communities, and severely impacts productivity. The impacts of climate variability and change on agricultural productivity include decline in crop yields, cropping areas and cropping density. In addition, nutritional status can be further aggravated due to reduced nutritional quality or dietary diversity of foods consumed. As climate variability and change continues to increase, these negative implications are expected to worsen (FSIN, 2019). Since 2005, an estimated 36% of countries that experienced a rise in undernourishment had encountered severe drought (FSIN, 2019). Climate variability and change can also have a direct relationship with conflict, and when both occur simultaneously, acute food insecurity has been reported (FSIN, 2019).

Mekonnen and Hoekstra (2014) have put forward metrics that measure the water footprint of crops. Using this indicator, a clear picture of the water efficiency of crops can be established (Table 2). In their study, they identified most fruits and vegetables possessing a low water footprint and high nutrient density (Mekonnen and Hoekstra, 2014). In a recent assessment by Nyathi et al. (2019), traditional vegetables performed significantly better in nutritional yield and nutritional water productivity when compared with alien vegetables. Such indicators that account for both nutrition and environmental considerations, are essential in our bid towards a more sustainable and resilient food system.

Estimated averages of the carbon footprint of different crop species (Table 2) adds a new lens to comparisons of performances of different crops. While the underutilised legumes (except for cowpea) are more water- and carbon-efficient than dry beans, the underutilised cereals were found to be less water-efficient than the main cereals. The integration of climate-smart and nutrient dense crops more broadly within cropping systems is important given the climate uncertainties that are faced. Model simulations of climate change impacts on crop production project a decrease in global crop production due to climate change (Porter et al., 2014). It was estimated that the impacts of climate change may have reduced maize and wheat production by 3.8% and 5.5%, respectively, in the period of 1980–2008 (Campbell et al., 2016; Lizumi and Ramankutty, 2015; Lobell et al., 2011).

5 Way forward: fixing our food system and exploiting crop species diversity

Dietary diversification through increased production and consumption of neglected and underutilised crops is one viable approach towards remedying this situation (White and Broadley, 2009; Massawe et al., 2016). This requires the recognition of the value of these crops, and approaches towards their wider adoption. Moreover, different farming and management systems that diversify landscapes or adopt technologies such as fertilisers and biofortification, can be valuable solutions. Finally, the move towards systems and nexus thinking are important contributions that will be outlined below.

5.1 Valuing crops for the natural nutrient density

Legumes, a traditionally important source of proteins, are now in major decline in global diets (Li and Siddique, 2018). Except for soybean and groundnut, legumes account for less than 2.5% of the global diet (Li and Siddique, 2018). Reclaiming the value of leguminous species will benefit both the environment (production under water limited conditions) and human health (protein and micronutrient supplies) (Cheng et al., 2019). Table 3 provides a comparison of different legumes and cereals to combat nutritional and water deficiencies.

Consumption of a diet based on multiple food groups is recommended for enhanced nutritional status (Mijatović et al., 2019). The micronutrient content of several underutilised grains is notably higher than in advanced cereals. For example, pearl millet has higher micro-nutrients (iron, zinc, riboflavin and folic acid) than rice, wheat or maize; and higher calcium content than both rice and maize (Adhikari et al., 2017). This can be supported by increased diversity within farming systems, which has the added advantage of increasing resilience and ability to tolerate stresses and shocks (Mijatović et al., 2019).

Inclusive markets can also support communities in diversifying diets and improving nutritional outcomes. In Cameroon and Ghana, Krishna Bahadur et al. (2018) reported that urban communities benefit from connected markets and improved access to diverse diets. On the other hand, rural communities in Rwanda were reportedly disadvantaged by unstable food markets that contributed to low dietary diversity (Weatherspoon et al., 2019).

In Nepal and Pakistan, Adhikari et al. (2017) noted a concerning trend of increasing malnutrition in the mountains. This was linked to a decline in the cultivation of underutilised grains. While these mountainous regions are agro-ecologically suitable for production of traditional crops that include barley, millet, sorghum and buckwheat, agricultural intensification within the region led to increased dependence on a small portfolio of crops (Padulosi et al., 2002). Consequently, a decline in dietary diversity was noted with these underutilised grains contributing to an estimated 8% of per capita food consumption while the three staples contribute 62% (Adhikari et al., 2017). Ultimately, high prevalence of malnutrition was reported in the region, as evidenced by the levels of stunting and wasting among young children (Adhikari et al., 2017).

5.2 Diversifying farming systems for enhanced resilience

Prevailing scientific evidence shows that yields in monocultures decline due to declining soil health and populations of soilborne pathogens thriving (Cook, 2006). Moreover, competition with weeds for limited nutrients further disadvantages the crops under production. In addition, modelling studies indicate that as temperatures rise, yields of major cereals will decline (Challinor et al., 2014). This encouraged a surge in research on agricultural diversification and its associated benefits for the agricultural systems.

In SSA, one of the most vulnerable regions to climate variability and change, water stress may further exacerbate food and nutritional insecurity (Chivenge et al., 2015). Chivenge et al. (2015) note the importance of strengthening agricultural biodiversity for ensuring food and nutritional security. They report a range of drought tolerant underutilised crops common within farming systems in SSA, including amaranth, wild mustard, sweet potatoes, wild melon, taro and bambara groundnut (Chivenge et al., 2015). Such drought tolerant crops support healthy diets in marginal environments and are well-adapted to the harsher environmental conditions encountered. From barley varieties that are adapted to high altitudes and cold climates of mountainous regions in Nepal, to quinoa that grows on saline soils of Pakistan, underutilised crops are important adaptations to ecological niches (Adhikari et al., 2017).

An effective approach towards supporting communities in combating malnutrition is the establishment of home-based vegetable gardens (Chadha et al., 2012). This is done through cultivating areas adjacent to homes with diverse crops of both nutritional and cultural value, and could incorporate indigenous vegetables (Chadha et al., 2012). Home gardens were explored as an intervention in Bangladesh that included training women in two rural districts to grow nutrient-rich vegetables such as water spinach, Indian spinach, amaranth (Schreinemachers et al., 2015). The intervention increased per capita production of leafy vegetables from 20 kg to 37 kg, and vitamin A and vitamin C supply increased by 189% and 290%, respectively (Schreinemachers et al., 2015). Similarly, in Indonesia, Thailand and Philippines, the introduction of home gardens, school gardens and market gardens demonstrated benefits in enhancing livelihoods and meeting the recommended dietary allowance of protein, calcium, iron, vitamin A and vitamin C (Chadha et al., 2012).

5.3 Management practices for enhancing nutrient availability within food crops

Increasing the availability of minerals in food crops can be achieved through two complementary approaches (White and Broadley, 2009). Firstly, improving mobility and solubility of minerals in the soil through agronomic approaches (White et al., 2012) can effectively increase its availability. Examples of this approach include management practices such as application of acidifying fertilisers for alkaline soils or use of dolomitic lime for acidic soils (White et al., 2012). Incorporation of suitable microorganisms and crop rotation with legumes can also enrich soil health and improve nitrogen content (White et al., 2012; Lin, 2011).

An important development for the agronomic approach is the advancement in geospatial techniques that can support analysis of soil maps, as evidenced by Lark et al. (2018) through their integration of datasets to map soil properties across England and Wales for better decision-making. However, without knowledge of the local conditions reflecting the accessibility of technologies to farmers as well as the temporal and geospatial variations within the landscape, our understanding of management practices and adaptation would be limited (Lizumi and Ramankutty, 2015). As Lizumi and Ramankutty (2015) emphasise, economic conditions can impact the available technologies for farmers, thus affecting their risk tolerance and decision-making when dealing with the changing climate.

When these essential elements are available and accessible in the soil, focus would then be on the uptake by roots and the redistribution of these elements to edible portions within the plant. Thus, the second approach focuses on developing crops with enhanced abilities to absorb the mineral nutrients and redistribute them to edible portions (White et al., 2012). Genomic selection can be a strong predictor to support breeding programmes (Velu et al., 2016). An exemplar approach is that of breeding crops for improved absorption and redistribution of mineral nutrients to edible parts of the plant known as biofortification (Bouis et al., 2011). This approach increases mineral availability in edible crops through conventional plant breeding or transgenic techniques to develop biofortified food staples (Bouis et al., 2011). This approach is largely dependent on supply and phytoavailability of the minerals within the rhizosphere, thus fertilisers may still be required to support plants in acquiring essential minerals (White and Broadley, 2009).

Moreover, developing crops with reduced antinutrients, such as oxalates and phytates, as well as crops with higher concentration of promoters, such as ascorbate and β-carotene, all play an effective role in enhancing absorption of essential minerals once consumed (White and Broadley, 2009). The success of this approach is not only dependent on successful breeding of high yielding nutrient dense staples, but also on the retention of the minerals after processing and cooking, and importantly the ease of adoption by farmers (Bouis et al., 2011). The bioavailability of minerals and the effectiveness of these various approaches in reducing DALYs is often adopted to assess and compare the merits of the approaches (Gregory et al., 2017). For instance, while breeding approaches to enhance iron and zinc bioavailability can be costed at 0.7–7.3 USD per DALY (Stein et al., 2006), fertiliser application was costed at 81–6457 USD per DALY (Joy et al., 2015) with foliar fertilisers being more cost-effective than the application of granular fertilisers. Although breeding techniques are a highly cost-effective technique, fertiliser application is often encouraged through subsidies and other incentives.

5.4 Shifting to transdisciplinary and systems thinking

This co-existence of inter-related food, economic, environmental, and social drivers has shifted knowledge generation and innovation platforms (Choi and Pak, 2006; Wickson et al., 2006), and created overlapping mandates within government programmes (Leydesdorff and Meyer, 2006). The overlapping of institutional mandates necessitates transdisciplinary approaches to contextualise and embed inter-disciplinary knowledge (Bunders et al., 2010), with the aim to understand complexity and facilitate sustainable systems. In this regard, systems thinking allows for consideration of the food system and its complexities by using a comprehensive lens that examines the inter-linkages between agriculture, nutrition, health and economic development. The integration of all these different elements (agriculture, environment and health), highlight a truly complex arena that cannot be resolved through a single disciplinary approach. Hence, the need to subscribe to a food system approach.

In many ways, the food system already encompasses such institutional overlaps as it straddles the production and marketing of food, as well as consumer related behaviour (Dangour et al., 2017). Food chains are complex with multiple power dimensions, and it is imperative to understand where and how food is produced and transported. However, livelihoods of food producers should not be threatened by the push towards available, affordable and accessible healthy food (Waterlander et al., 2018). Spikes in food prices due to poor harvests and dependence on a few species of plants had clear impacts on populations worldwide, as can be seen in the rise in political instability and the occurrence of major riots in more than 20 countries due to food crises (Dangour et al., 2017; Lagi et al., 2011).

5.5 The role of nexus thinking in transforming the food system

A better grasp of natural resources and their capacities to support the provision of water, energy, food, land and materials calls for an appreciation of the synergies and trade-offs between resources (Bleischwitz et al., 2018). Nexus approaches facilitate the move from siloed approaches towards a more comprehensive assessment of the interlinkages between these resources through transdisciplinary and multi-sectoral efforts (Bleischwitz et al., 2018). In recognition of the interlinked nature of resources, an important research discipline that has arisen is the Water-Energy-Food Nexus, that attempts to carefully consider the major interactions between these three sectors (Nhamo et al., 2018). Strong linkages exist between the three sectors of water, energy and food, which are under increasing pressure due to competing demands emanating from population growth, improved standards of living, urbanization, globalization and trade, and the changing climate. In addition to linkages between water, energy and food, sustainable food systems also derive from linkages between agriculture, environment and health (Mabhaudhi et al., 2019b).

The relationship between agriculture, environment and health is complex, and the interactions between these spheres could have trade-offs and synergies. The key is to identify main drivers that influence these linkages, as well as the desired outcomes (Fig. 3). As Sokolow (2019) identifies, an example for a target that carefully addresses these complexities is Target 2.4 (under SDG 2 – Zero hunger), which calls for “sustainable food production systems and resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters, and that progressively improve land and soil quality” (UN, 2015). Most targets for food and nutritional security were based on ending hunger and enhancing nutritional status, without much consideration of the environmental costs of achieving that. While achieving SDG 2 is a feat that addresses economic, social and environmental considerations, the interlinkages with other goals must be considered. Although the SDGs have specific targets for ending poverty (SDG 1), improving health (SDG 3), clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), climate action (SDG 13) and protecting biodiversity (SDG 15) (UN, 2015), they are a set of indivisible and complex goals requiring urgent action and partnerships (SDG 17) to implement them.

An understanding of the interlinkages between the goals and their targets is required to identify trade-offs and synergies between the different SDGs, and for successful implementation and monitoring of the SDGs. (Nilsson et al., 2017) explored interlinkages between the SDGs, capturing the synergies as well as competing demands and calling for coordinated policy interventions. They identified strong positive links between SDG 2 and SDG 3, such that improved health outcomes are key in enhancing agriculture and nutrition status, while better agriculture and nutrition allow for improved ecosystem functioning, rural income, and overall health and well-being (Nilsson et al., 2017). Meanwhile, SDG 2 is highly dependent on SDG 6, with potential to negatively impact the progress towards achieving SDG 6 (Nilsson et al., 2017). Traditional intensive agricultural practices rely heavily on exploiting land and water resources, which directly hinders progress towards SDG 6 (Nilsson et al., 2017). Thus, the need for targets specifically addressing resilient agricultural practices and environmental implications by assessing environmental footprint of producing it. The promotion of sustainable intensification, which seeks to balance increases in agricultural productivity with environmental concerns, would be more aligned to achieving the SDGs. Achieving the SDGs by 2030 requires cross-cutting approaches that carefully consider the interlinkages between the different goals and the pressure points associated with achieving set targets on other interlinked targets.

6 Concluding remarks: A holistic food systems approach

As Waterlander et al. (2018) stress, in order to address challenges of malnutrition, there is a need for a systems intervention that considers the multifaceted dimensions of how food is grown, processed, distributed, commercialized and consumed. Albeit the complex relationship between food security and nutritional outcome, the food system can play a key role in meeting targets for improved nutrition (Ruel et al., 2018). It has the potential to influence key determinants of nutritional outcomes, that include dietary quality, income and livelihoods, women empowerment (Ruel et al., 2018). However, the current food system faces economic challenges and has serious limitations that impact both human and environmental health (Waterlander et al., 2018). Establishing a balance between agrobiodiversity and environment, between farmers and consumers, and across all four components is essential to produce food in a sustainable way for improved human health and livelihoods in current and future generations (Fig. 4). Moreover, with the looming threat of changing climates and increasing GHG emissions from agriculture, such an intervention is more urgent than ever before.

The twin approaches of matching crops to suitable environments for enhanced agricultural productivity and nutrient quality, and exploiting the diversity in crops for diversified and resilient farming and food systems should go hand in hand with public health interventions – such as dietary guidelines – as well as industrial and technical innovations to make food more available and affordable globally (Waterlander et al., 2018). Developing healthy and sustainable diets requires dialogue to continue across agricultural sciences, food and health sciences, environment, culture, economics and trade and more, to establish a holistic food systems approach that carefully considers the competing demands and synergies within the system; this calls for a transdisciplinary approach.

The interactions between SDGs is an emerging discourse within science and needs to be featured more prominently in discussions on agriculture and food systems. Due to its central role, agriculture fits within a diverse range of SDGs. It can advance the progress of SDGs or impede their implementation. Meeting the food demands of a growing population should not impair the planet’s long-term capacity to produce food. Land, water, biodiversity and other vital resources ought to be used efficiently in the process of food production – which is the value added by sustainable nutrient-dense crops. Changing weather patterns, along with growing population, and changing consumer behaviour are all anticipated to impact on global food security (Lizumi and Ramankutty, 2015). The food systems approach seeks solutions that achieve food security in a changing climate through good nutrition as opposed to merely ensuring the availability of sufficient calories (Campbell et al., 2016). Feeding the growing population with nutritious, safe and healthy food will require re-evaluation of the current food system to include nutritional and environmental demands as key components of a healthy food system. This entails a shift from a productionist approach to a more outcomes-based approach.

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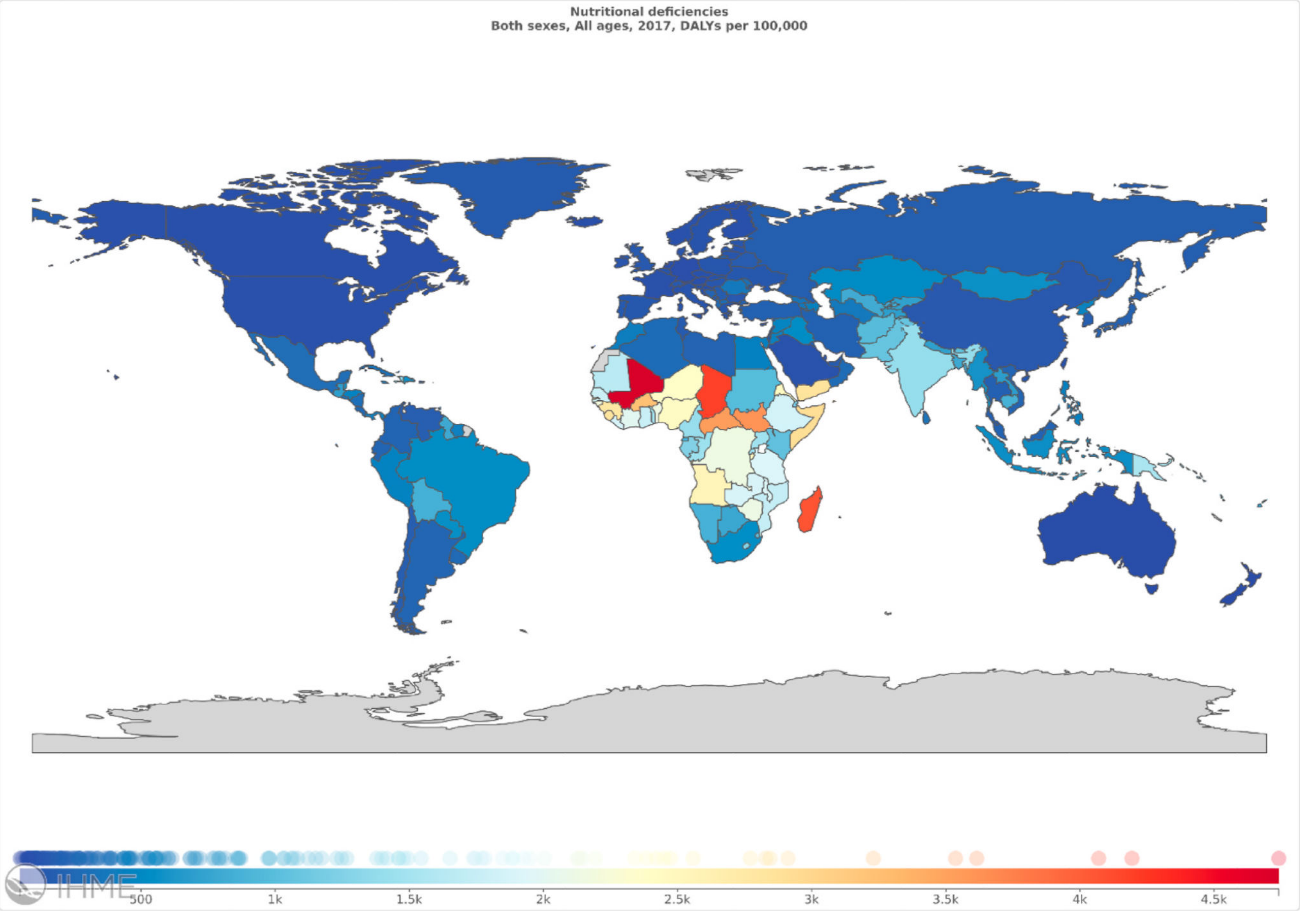

Fig. 1a. Global Disability-Adjusted Life Year (DALY) due to nutritional deficiencies (protein-energy malnutrition, iodine deficiency, vitamin A deficiency, dietary iron deficiency and other nutritional deficiencies) (IHME, 2017).

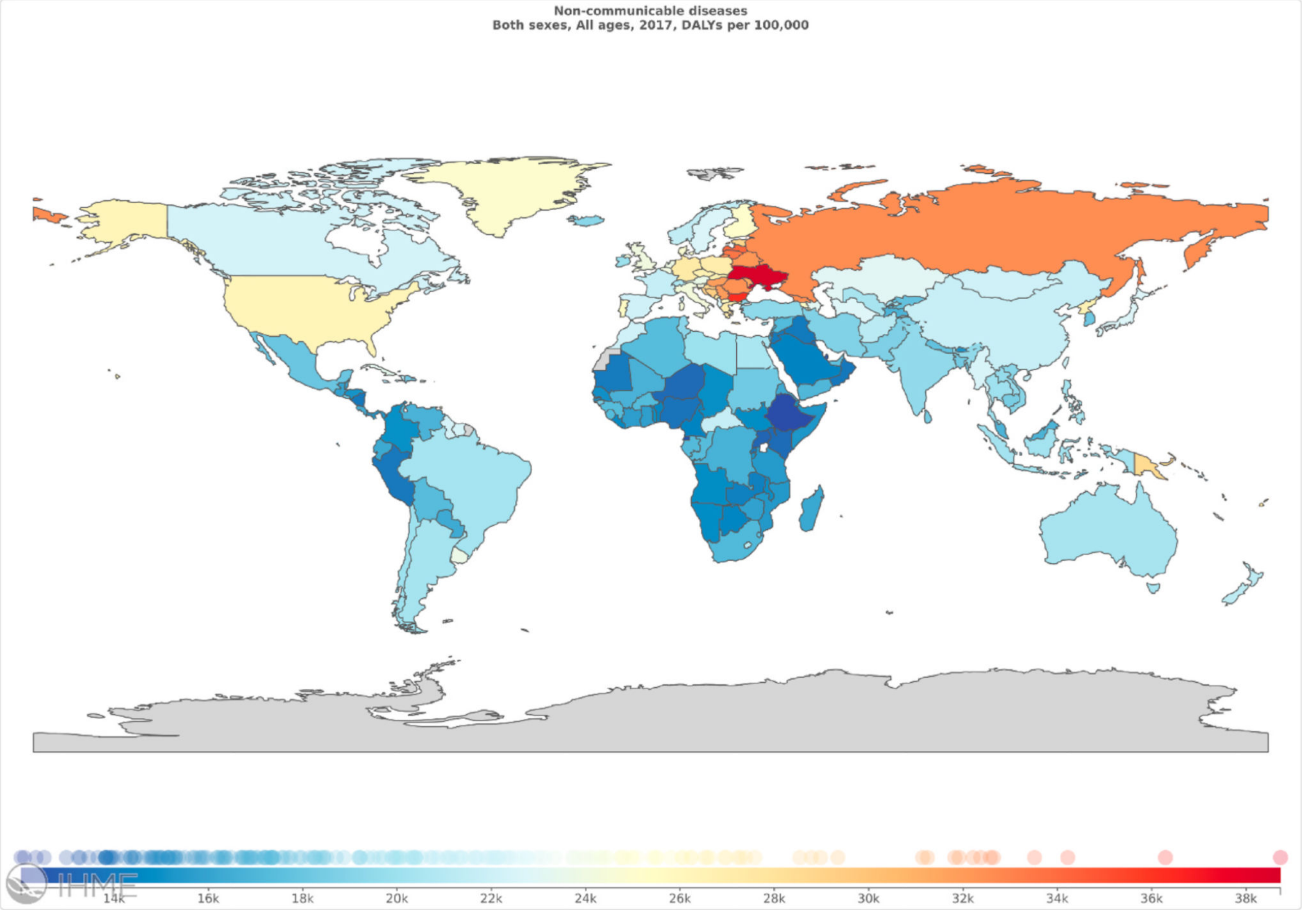

Fig. 1b. Global Disability-Adjusted Life Year (DALY) due to non-communicable diseases (NCDs) (IHME, 2017).

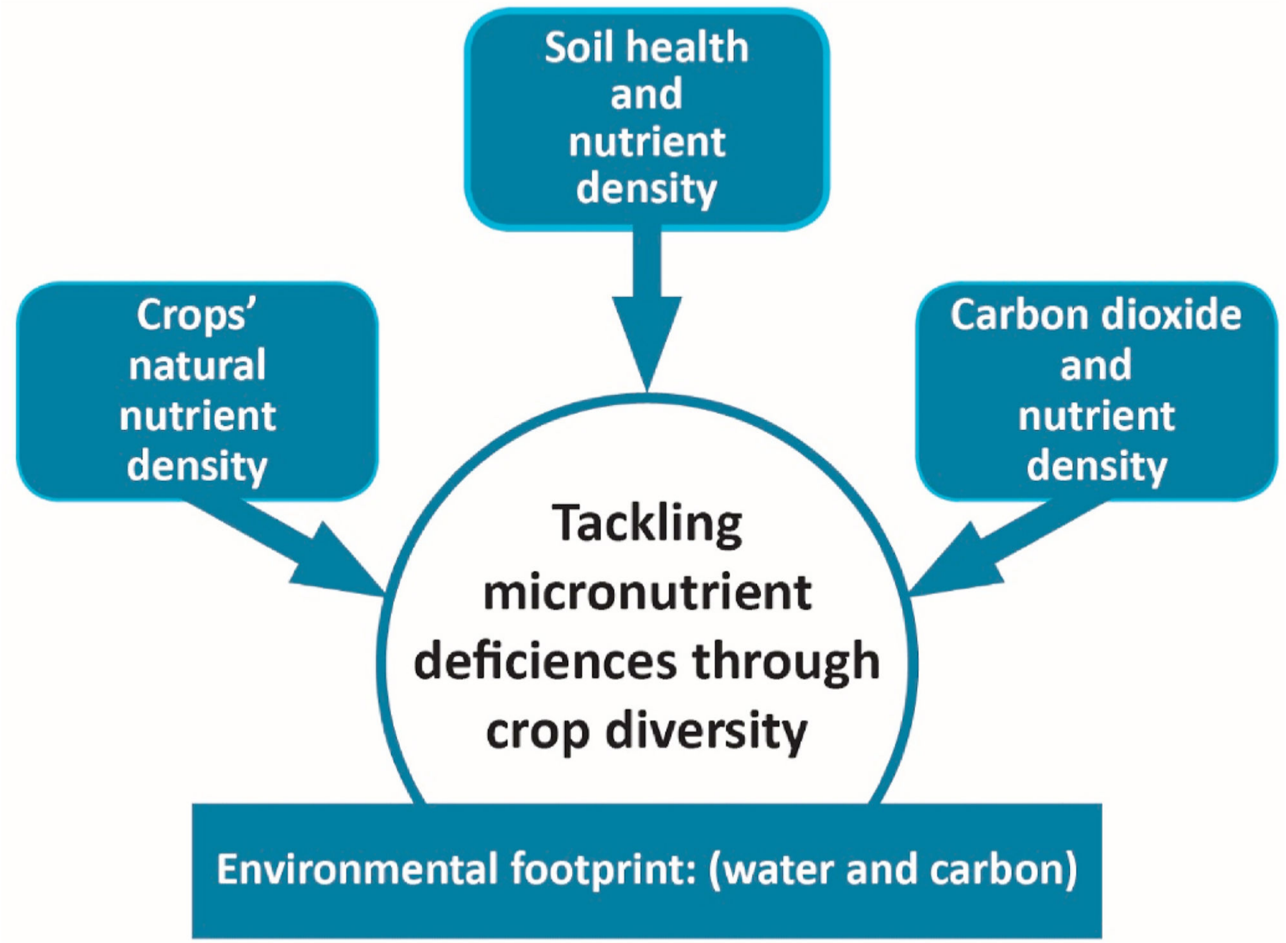

Fig. 2. Factors of environmental and nutritional sustainability that impact the nutrient density of crops, and influence the crop's capacity to tackle micro-nutrient deficiencies.

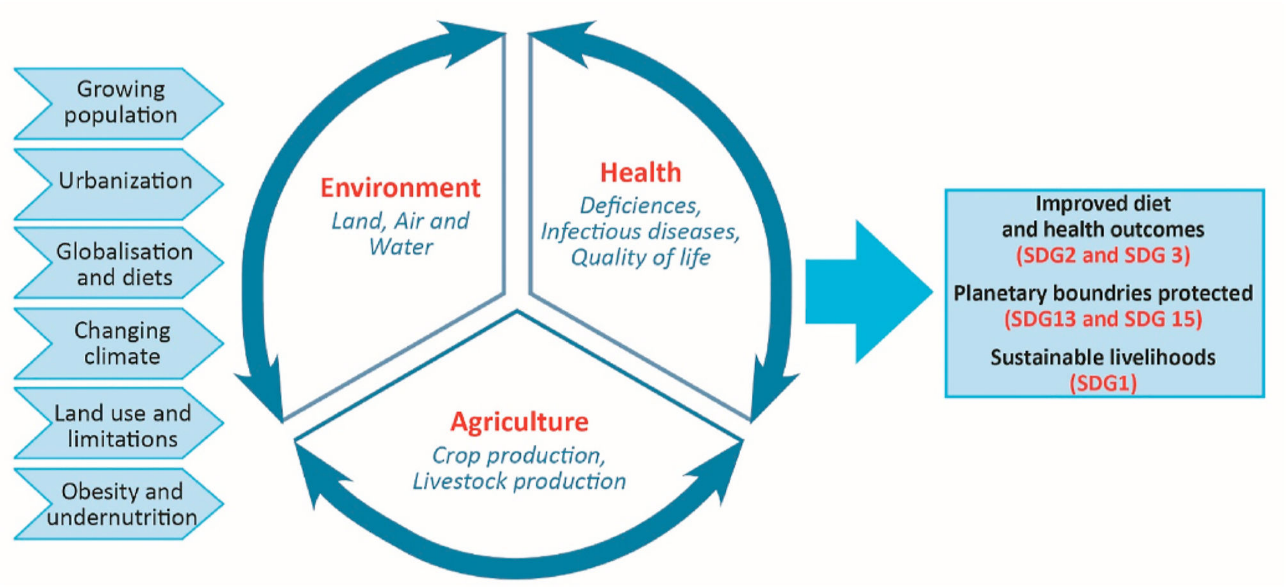

Fig. 3.

The linkages between Agriculture, Environment and Health nexus with the associated drivers (growing population, urbanization, globalisation and diets, changing climate, land use and limitations, obesity and undernutrition) and desired outcomes of this interlinked system (improved diet and health outcomes, protection of planetary boundaries, sustainable livelihoods). (adapted from Mabhaudhi et al., 2019b).

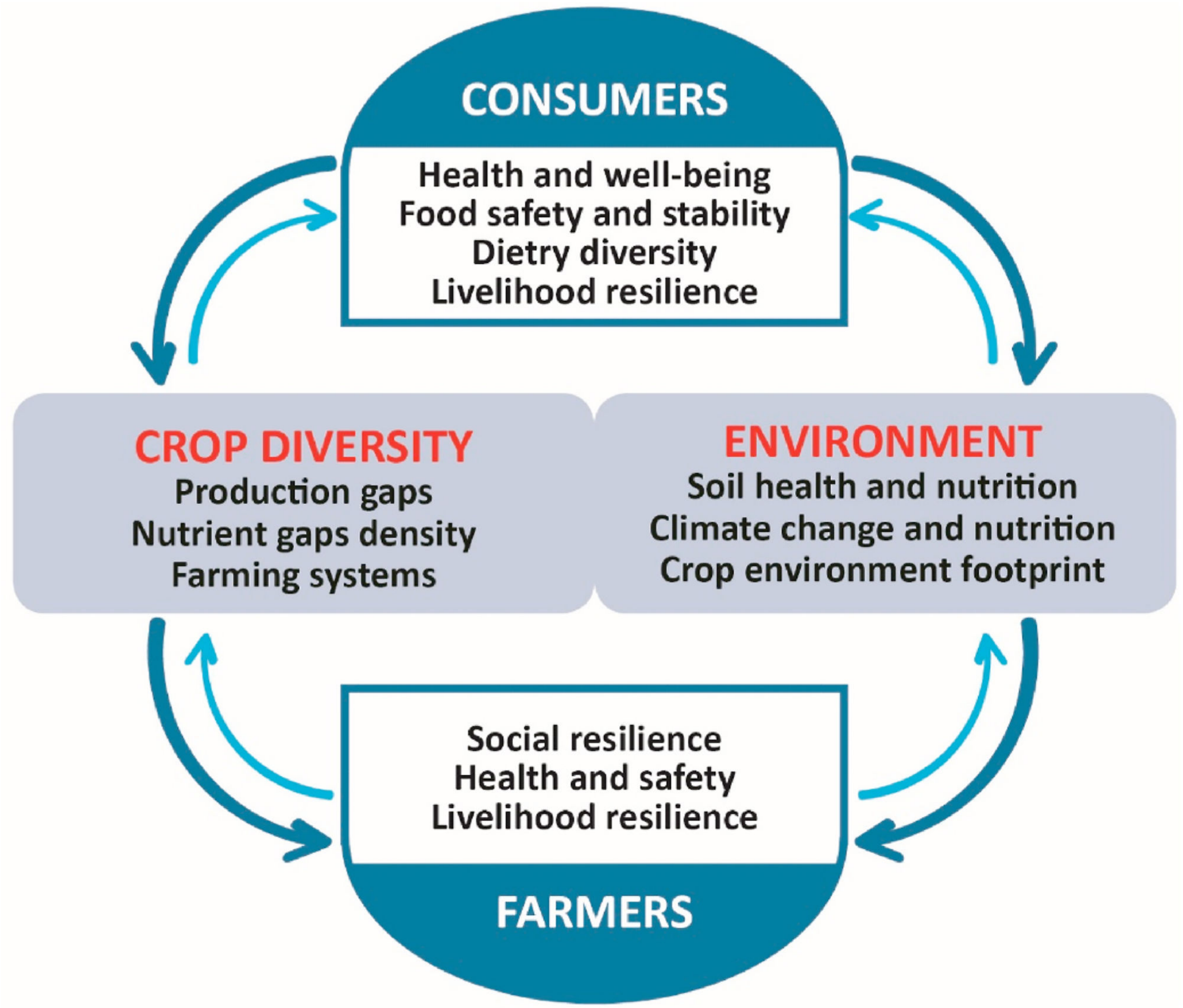

Fig. 4. Sustainable food system approach interlinking agrobiodiversity, environment, farmers and consumers.

Table 1

A comparison of bioavailable nutrients across selected crop species. For cereals and legumes, we assumed bioavailability of 65% and 35%, respectively, of selected nutrients.

Crop type	Scientific name	Nutrients					
		Protein (g/100g)	Carbohydrate (g/100g)	Fibre (g/100g)	Iron (mg/100g)	Zinc (mg/100g)	Calcium (mg/100g)
Maize	*Zea mays L.*	1.78	15.93	1.56	0.26	0.15	1.3
Pearl millet *	*Pennisetum glaucum*	2.27	15.15	0.26	0.39	1.4	1.95
Sorghum *	*Sorghum bicolor*	5.2	54.6	5.2	1.4	0.08	–
Rice	*Oryza Sativa*	1.76	17.88	0.26	0.13	0.3	7.15
Wheat	*Triticum aestivum*	2.02	10.2	1.69	0.65	0.37	6.5
Cowpea *	*Vigna unguiculata*	2.85	7.11	1.26	1.07	0.65	9.1
Chickpea *	*Cicer arietinum*	3.12	7.28	2.31	1.02	0.54	17.15
Bambara groundnut *	*Vigna subterranea*	4.86	2.91	2.91	1.01	0.56	13.65
Dry beans	*Phaseolus vulgaris*	2.75	6.2	2.56	0.81	0.36	13.9
Mung bean/green gram *	*Vigna radiata*	2.46	6.7	2.66	0.49	0.29	9.45

*Denoted underutilised crops for ease of comparison.

Table 2

A comparison of global averages for water footprint (Mekonnen and Hoekstra, 2014) and carbon footprint (Audsley et al., 2009) across selected crop species.

Crop type	**Scientific name**	**Global Average Water Footprint (m^3/ton)**				**Global Average Carbon Footprint (kg CO2-eq/kg)**
		Green Water	**Blue Water**	**Grey Water**	**Total**	
Maize	*Zea mays L.*	947.20	81.23	193.93	1222.35	0.45
Pearl millet *	*Pennisetum glaucum*	4305.76	57.16	114.63	4477.55	0.47
Sorghum *	*Sorghum bicolor*	2857.40	103.05	87.12	3047.56	0.88
Rice	*Oryza Sativa*	1145.52	340.78	186.50	1672.80	3.50
Wheat	*Triticum aestivum*	1277.21	342.46	207.42	1827.09	0.52
Cowpea *	*Vigna unguiculata*	6840.72	9.77	55.47	6905.96	0.61
Chickpea *	*Cicer arietinum*	2971.74	224.24	981.36	4177.34	0.80
Bambara groundnut *	*Vigna subterranea*	3162.35	70.56	33.60	3266.50	–
Dry beans	*Phaseolus vulgaris*	3944.78	124.86	983.17	5052.81	1.55
Mung bean/green gram *	*Vigna radiata*	2217.37	249.96	650.20	3117.52	–

* Denoted underutilised crops for ease of comparison.

An important direction in the current conversation on food systems is the emphasis on personal behaviour while encouraging accountability and monitoring of personal carbon footprint. Estimated averages of the carbon footprint of different crop species (Table 2) adds a new lens to comparisons of performances of different crops. While the underutilised legumes (except for cowpea) are more water-efficient and carbon-efficient than dry beans, the underutilised cereals were found to be less water-efficient than the main cereals.

Table 3

A comparison of recommended food choices to combat nutritional and water deficiencies (Mabhaudhi et al., 2019b)

Nutritional needs	Recommended food choice		Recommended food choice under water limited conditions	
	Legume	**Cereals**	**Legume**	**Cereals**
Protein	[*]White lentils; soybean	Sorghum; wheat	Bambara groundnut; groundnut	Sorghum
Carbohydrates	Bambara groundnut; lentils	[*]Equally suitable	Bambara groundnut	Sorghum; millet
Energy	[*]White lentils	Equally suitable	Groundnut	Sorghum; millet
Fat	[*]Groundnut	Equally suitable	Groundnut	Sorghum; millet
Vitamin A	[*]Common pea	–		–
Micronutrients	[*]Soybean	Equally suitable	Bambara groundnut	

[*] Denotes alternative due to superior nutritional content.