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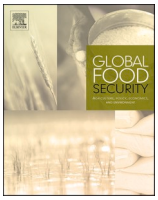

Fruit and vegetable biodiversity for nutritionally diverse diets: Challenges, opportunities, and knowledge gaps

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ABSTRACT

Planetary health brings together intrinsically linked issues of human health and natural systems. This paper reviews evidence of how agrobiodiversity underpins dietary diversity for current human populations in the context of fruits and vegetables, and ways to maintain and improve these for future generations.

Both the conservation and sustainable use of fruit and vegetable biodiversity and the consumption of diverse diets are sub-optimal, and in many contexts getting worse. Agrobiodiversity and nutrition are linked through food availability, access, conservation and consumption, with potential win-wins but notable trade-offs for policy and action through time, place, agrobiodiversity use, and equity. We pinpoint research gaps and call for inclusive deliberation for action.

1. Background

The idea of planetary health brings together intrinsically linked issues of human health and the state of the natural systems on which we depend (Dangour et al., 2017). Within this framework, it has long been understood that nutrition and biodiversity are connected (Johns and Eyzaguirre, 2006). Fruits and vegetables are an important part of diets – providing essential nutrients, phytonutrients, and fibre for health (FAO, 2021) – and of agrobiodiversity – about 1,100 vegetable species are recognized worldwide (Meldrum et al., 2018) and there are at least 1, 250 documented fruit species in Latin America alone (Bioversity International, 2021). Over millennia, human activities have shaped fruit and vegetable biodiversity towards our dietary preferences, which have co-evolved with the availability of different fruits and vegetables in different agroecological settings. The use and maintenance of this biocultural heritage in contemporary food systems depends on a wide range of social, cultural, political, environmental, and economic factors, and there is an important interplay between current and future availability of fruit and vegetable biodiversity, and current and future dietary diversity, within these complex contexts.

This paper reviews literature produced in the fifteen years since Johns and Eyzaguirre's initial study on the issue of biodiversity and nutrition more broadly (Johns and Eyzaguirre, 2006). We focus specifically on recent evidence of how fruit and vegetable biodiversity underpins dietary diversity for current populations, and evidence on ways to conserve and improve these for future generations. The aim is to bring together key research findings to frame what we know about links between fruit and vegetable biodiversity and dietary diversity. A food systems lens – encompassing all the elements and activities that relate to producing, transforming, delivering, and consuming food for humans – is used to better understand the links between healthy people and a healthy planet (HLPE, 2017, 2020), and identify challenges and opportunities; knowledge gaps for further research; and support for decision-makers and practitioners in achieving global development goals.

2. Changes and challenges

2.1. Threats to fruit and vegetable biodiversity

While overall biodiversity is defined as the sum of all living organisms at the genetic, species, and ecosystem levels, *agro*biodiversity is more narrowly defined as the range of species, varieties, and ecosystems - together with crop wild relatives, pollinators, and other associated

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organisms - which are used by humans for food and agriculture (FAO, 2004; Frison et al., 2011). Agrobiodiversity sustains and stabilizes both agro and natural ecosystems of food production and harvesting, and is the source of genetic diversity for developing future foods that can tolerate changing environments and keep pace with changing food needs and preferences.

Fruit and vegetable biodiversity is part of agrobiodiversity. For the purpose of this review, this is defined as any genetic planting material of fruit and vegetable species, and their wild relatives, for current and future food and agriculture, in line with the concept of Plant Genetic Resources for Food and Agriculture (PGRFA). Besides the large number of vegetable and fruit species that occur worldwide, crop wild relatives are a special group of genetically-related species of fruit and vegetable species, which can be used in breeding new varieties because they can provide characteristics related to climate resilience and other desirable traits (Kilian et al., 2021). Below the species level, local fruit and vegetable varieties and wild populations of fruit and vegetables are also part of a biocultural heritage with unique tastes and histories (Dwivedi et al., 2019; van Zonneveld et al., 2018). These provide for distinct food cultures, as well as an important source of genetic variation needed for developing new cultivated varieties with traits to ensure current and future food supplies (Jansen et al., 2020; Kilian et al., 2021; Schouten et al., 2019).

Contemporary fruit and vegetable biodiversity continues to decline in farmers' fields, at landscape level, and generally in ecosystems, in parallel with the rapid global decline in overall biodiversity (Díaz et al., 2019). Ecosystems in 88% of the world's 846 terrestrial ecoregions are poorly conserved, degraded, or disappearing as a result of human actions (Dinerstein et al., 2017). The richness and abundance of wild fruit and vegetable species, as well as the crop wild relatives of fruit and vegetable species and pollinators and seed dispersers, decline with the degradation and loss of these ecosystems under the pressures of land-use change, global climate change, and other threats (Díaz et al., 2019; Pilling et al., 2020). Not all crop wild relatives are threatened, and several benefit from environmental degradation when they become weeds or invasive (Syfert et al., 2016). But endemic and other narrowly-distributed wild relatives are the most vulnerable to extinction caused by land use change and degradation following the criteria of the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (Cadima et al., 2014; Khoury et al., 2020; Scheldeman et al., 2006).

Four out of five studies on crop genetic erosion has found evidence of crop diversity loss, the magnitude varying by species, geographic scale, and region, as well as analytical approach (Khoury et al., 2021). So far, most genetic erosion studies have been done on cereal crops and their wild relatives; few studies are available on the rate of varietal and genetic losses in fruit and vegetable species (Khoury et al., 2021). For some crops, such as tomato, farmers have already replaced most local varieties in many regions (Cebolla-Cornejo et al., 2012; Walters et al., 2018) and the development of new varieties relies almost entirely on the planting materials safeguarded in crop genebanks and seed-saver networks (Bauchet and Causse, 2012). But whereas tomato is relatively well represented in existing genebank collections, the genetic resources of most other fruits and vegetables are poorly conserved in genebanks, or not at all. For example, 39% of 883 globally-assessed wild fruit and vegetable species requires urgent conservation because they are poorly or not conserved in genebanks or in protected areas; another 58% has a medium priority for conservation; while only 3% is well conserved (Khoury et al., 2019). A quarter of the 1,100 recognized vegetable species worldwide have no samples at all conserved in any genebank (Meldrum et al., 2018), and most fruit tree species and their wild relatives, particularly those of tropical origins, are challenging to conserve in genebanks because their seed does not tolerate the desiccation and low temperatures of orthodox seed storage, and most fruit cultivars have specific genetic combinations that can be maintained only through vegetative propagation (Dawson et al., 2013). Without better conservation options on farms, at landscape level, and in protected areas, and without genebank back-up, these fruit and vegetable genetic resources are at risk of being lost as land use, climate, and agriculture change.

2.2. Changing dietary diversity and fruits and vegetables

Dietary diversity is defined as the variety of foods consumed in a certain time period, and thus far has been described for children, women, and households, with higher individual dietary diversity associated with better nutrient adequacy (Arimond and Ruel, 2004; Arimond et al., 2010). Therefore, from a food system perspective, diversifying diets both within and across food groups is a key strategy. Consuming a diversity of fruits and vegetables—with the nutrients, phytonutrients and dietary fibres contained therein—is important for good health (FAO, 2020). Studies have suggested intake ranges of 300–600g per day (200–600g of vegetables and 100–300g of fruits) to meet the twin goals of human health and sustainable food supply without overly negative effects on the environment (particularly through water use and chemical inputs) (Afshin et al., 2019; Loken et al., 2020; Willett et al., 2019). The World Health Organisation (WHO) recommends adults to eat at least 5 portions or 400g of fruits and vegetables per day for protective nutritional effects (World Health Organisation, 2003), with national food-based dietary guidelines translating these into recommendations to eat multiple portions of a variety of fruits and vegetables each day (Herforth et al., 2019). Despite this need for diversity, intraspecific fruit and vegetable biodiversity, and diversity of diets within the fruit and vegetable food group in particular, are little explored in nutrition, which tends to look for diversity across food groups only (World Health Organization, 2015).

Globally, the intake of fruit and vegetables remains low for a majority of the population (Afshin et al., 2019; Kalmpourtzidou et al., 2020). Low fruit and vegetable consumption is among the top five risk factors for poor health, with over 2 million deaths and 65 million Disability-Adjusted Life Years (DALYs) attributable to low intake of fruits, and 1.5 million deaths and 34 million DALYs attributable to low intake of vegetables worldwide each year, and particularly in low- and middle-income countries (Afshin et al., 2019). Low consumption of fruits and vegetables is a global problem: only 7% of countries in Africa, 7% in the Americas, and 11% in Europe reach 240 g/day of vegetables per person on average (Kalmpourtzidou et al., 2020). Looking at within-country variation, only 20% of individuals in low- and middle-income countries reach the recommendation of 5 servings of fruits and vegetables per day (Frank et al., 2019).

The nutrition transition, whereby global diets are moving away from local traditional patterns through changing demographic and food system drivers, may make diverse fruits and vegetables either more or less locally available, depending on context (Global Panel on Agriculture and Food Systems for Nutrition, 2016; Popkin et al., 2020). While global fruit and vegetable supply has started to increase proportional to staple crops in recent decades, global focus remains predominantly on cereal production (Gould, 2017), and documented supplies remain insufficient for most countries to meet the WHO recommendation: in 1965, sufficient fruits and vegetables ($\geq$400 g/day) were available for 17% of the global population, increasing to 55% in 2015 (Mason-D'Croz et al., 2019). Supply varies widely: in Africa, only 13% of countries have an adequate vegetable supply, while in Asia 61% do (Kalmpourtzidou et al., 2020). All of these data are limited, likely missing the proportion of neglected and underutilized and wild-harvested food species, missing food loss and waste, and missing within-country variation. In Africa particularly, the consumption of wild vegetables is reported in many countries (Achigan-Dako et al., 2011; Maundu et al., 2009), but data are unavailable on consumption frequency or amount across the continent, and the level of wild harvest is rarely documented.

Fruits and vegetables purchased through markets are unaffordable for many, with three billion people, and up to 90% of the population in

some countries, unable to afford diverse healthy diets in 2017 (Herforth et al., 2020). Fruits and vegetables appear more affordable than staple foods when comparing prices per micronutrient, where they are likely to be a relatively low-cost source of varied vitamins, minerals, and phytonutrients – but this is not how most families choose their food, with particularly poorer households focusing on acquiring calories. Even if fruits and vegetables are available, accessible and affordable, most people still do not consume sufficient quantities (Hall et al., 2009), particularly if they are not considered an acceptable or desirable food choice, for instance due to food safety concerns, taste, convenience, or cultural appropriateness, or if people have low knowledge or awareness about the importance of fruit and vegetables for health (Aggarwal et al., 2016; Ha et al., 2020; Hammelman and Hayes-Conroy, 2014),.

2.3. Bringing fruit and vegetable biodiversity and dietary diversity together

Food availability, accessibility, affordability, and desirability are therefore the food system links between agrobiodiversity and dietary diversity (Toledo and Burlingame, 2006; Turner et al., 2018) with more species-diverse food associated with better micronutrient-quality diets (Lachat et al., 2018). In specific agricultural diversity studies, and mainly in rural areas, agrobiodiversity has been associated with dietary diversity at the local level: greater crop diversity managed by farming households is usually associated with greater dietary diversity at the farm household level, though depending significantly on local agro-ecological context(Jones, 2017). Associations between crop diversity and fruit and vegetable intake have been seen specifically in some studies (Herforth, 2010; Jones et al., 2014), though many do not examine this connection explicitly, and fruits and vegetables are often combined into a single food group or assessed together with other plant foods such as pulses. Magnitudes of association tend to be very small when only factoring in cultivated foods (Jones, 2017), prompting some to suggest that increasing production diversity is not an efficient tool to improve nutrition at the household level (Sibhatu and Qaim, 2018).

Associations may be stronger when including wild food plants in agrobiodiversity metrics in contexts where these are eaten: In Kenya, for example, when food plants collected from a wider landscape are taken into account, a one unit increase in household access to agrobiodiversity (species diversity score) is associated with a 13% increase in probability of micronutrient adequacy in the diet (Oduor et al., 2019). In a similar way, a case study in Tanzania found a significant association between diversity of vegetables produced or collected from the wider landscape, and micronutrient adequacy and dietary diversity (Keding et al., 2012). In some settings and seasons, wild-harvested fruits and vegetables contribute significantly to nutrient intake (Powell et al., 2013) and incomes (McMullin et al., 2021), with estimates of a billion people relying at least in part on foods gathered in their surrounding environment (World Health Organization, 2015). In some contexts analysed, up to 75% of consumed vegetables and fruits are gathered rather than cultivated or bought (Powell et al., 2015).

Despite the wide occurrence of food gathering, it has been suggested that reliance on collecting wild food plants is often a coping mechanism in the face of scarcity, rather than an active choice, which needs to be better understood (Jones, 2017). In addition, overharvesting is a threat to the genetic resources of some wild-harvested species, and high demand for wild food plants could reinforce this threat, or even deteriorate whole ecosystems. For example, in the case of buruti, an ecologically important palm species from the Amazon that is valued for its vitamin-A rich fruits, people destructively harvest female plants, degrading wild buruti populations with potentially negative impacts on species richness and carbon stocks of Amazonian peatlands (Bhomia et al., 2019; Endress et al., 2013). Similar cases of overharvesting have been observed around the world, and there has been call to domesticate threatened food plants so that people can grow them in their yards or farm fields, to reduce harvesting pressure on wild populations while making these nutritious foods available and accessible to a wider public (Akinnifesi et al., 2006; Sundriyal and Sundriyal, 2003). In parallel, research and development initiatives are supporting decision-makers and communities in the implementation and monitoring of sustainable fruit and vegetable harvesting practices at landscape level (Van Loon et al., 2021).

While agrobiodiversity may have only moderate associations with dietary diversity at the household level, availability of a diversity of fruits and vegetables is a prerequisite for diverse diets at the food system level. As a sum of local changes, in food systems globally food plant diversity is associated with a food system's capacity to provide sufficient nutrients through different environmental, social, and economic shocks (including population growth and climate change), but over the past five decades this capacity has declined in all regions except Asia (Nicholson et al., 2021; Pingali, 2012). Studies have found that existing agrobiodiversity is underutilized in national food systems, with species consumption globally moderate, and lowest in low-income countries (Jones et al., 2021) and many food species limited to consumption in small geographic regions (Lachat et al., 2018) - though caveats on the limitations of data on wild and local foods, discussed above, still apply.

The current food system in many ways contributes to agrobiodiversity loss (Hunter et al., 2016), and fruit species and to a lesser degree vegetables are among the major crop types dependent on pollination services that are in decline (Gallai et al., 2009). Changing diets globally as a result of socio-economic, demographic, agricultural, and food system pressures is a process that while it can bring opportunities of scale and trade, can also be seen as a narrowing of the food base on which humans depend (Frison et al., 2006; Powell et al., 2013; World Health Organization, 2015). Large structural changes such as globalization of supply chains and societies, and changing demographics and urbanisation, have shaped food regimes over the past half-century to prioritise foods that are less perishable and more globally tradable (Lang and Heasman, 2015; Magnan, 2012), side-lining perishable fruits and vegetables requiring local production, processing, or complex food chains to get them safely from farm to fork. Large-scale, high-input monoculture production systems for pineapple, banana, and avocado among other commercial fruit crops, have led to excessive environmental degradation and biodiversity loss (Magrach and Sanz, 2020; Ploetz, 2021; Shaver et al., 2015). In the case of banana, genetic impoverishment has led to a highly vulnerable supply system that largely relies on a single clone that is susceptible to Panama disease, threatening global banana supply (Kema et al., 2021; Ploetz, 2021).

In addition to the micronutrients in fruit and vegetable species that we know about, there are also a range of phytonutrients and bioactive compounds across fruit and vegetable species, whose nutritional functions are still poorly understood (Lutaladio et al., 2010). Despite issues of bioavailability of nutrients and the various effects of processing and cooking on available nutrients, dietary diversity within fruits and vegetables is likely to be important, and conserving fruit and vegetable biodiversity for current and future availability may protect health through food in ways we don't yet know.

3. Options and actions

3.1. Maintaining fruit and vegetable biodiversity for current and future generations

Several important trends are increasing the conservation and use of fruit and vegetable biodiversity in food systems at global and local levels. In addition to the fact that the proportion of fruit and vegetables in global food production is increasing (Gould, 2017; Khoury et al., 2014; Martin et al., 2019), advanced technologies are now accessible to public and private breeders and researchers globally to mainstream the use of genetic diversity for developing new varieties of fruits and vegetables (Jamnadass et al., 2020; Schouten et al., 2019). Cities are becoming important hubs of crop diversity because immigrants bring planting material from their home areas (Rimlinger et al., 2021; Taylor

and Lovell, 2014), while at the same time the coverage of protected natural and biocultural environments has tripled in the last 40 years (Pringle, 2017), and at least 35% of the terrestrial protected areas are owned and/or managed by local and Indigenous communities, who play an important role in maintaining agrobiodiversity worldwide (Díaz et al., 2019). Although these trends could possibly bend the curve of decline in fruit and vegetable biodiversity, they may not completely halt, let alone reverse, the loss. For example, the expansion of protected areas provides some opportunities for conservation, but ecosystems in these areas may be degraded already, and fruit and vegetable biodiversity within the landscape may decline (Pringle, 2017).

Crop wild relatives stand further away from people's diets and are often relevant for breeding only. Their conservation is taken up by many governments in protected area management (Dulloo and Maxted, 2019), but crop wild relatives of fruit and vegetable species are still of low priority compared to those of cereals and pulses; it is important to raise awareness about the need to conserve the former as well.

Local fruit and vegetable species and varieties are still maintained and shared by farmers and communities in different production systems (Dulloo et al., 2017). These plants provide nutritional and food security, income-generating opportunities, and ecosystem services, and contribute to cultural identity (Sthapit et al., 2016), and also represent a valuable conservation of biodiversity for food. To preserve these, governments and societal actors can recognize the custodian farmers and communities who maintain these unique and traditional production systems, such as governments in some countries are doing already for important agricultural heritage systems (Koohafkan and Altieri, 2011). Governments and societal actors can further support these farmers and communities to establish or maintain seed networks, and encourage equitable business linkages to markets for more resilient livelihoods based in maintaining biodiversity, through incentives and regulation (Dulloo et al., 2017).

Complementary to local conservation on farms and in protected areas and local seed-sharing, large national and international fruit and vegetable germplasm collections have been established in genebanks in North America, South America, Asia, and Europe (Byrne et al., 2018; Cunha Alves and Azevedo, 2018; Engle and Faustino, 2007; Jacob et al., 2015; Loskutov, 2020; Van Den Houwe et al., 2020). They safeguard fruit and vegetable biodiversity to improve availability of planting material for food and nutrition of current and future human generations, and are a source for breeding and germplasm exchange to develop new foods for new tastes or new agricultural conditions. Sub-Saharan Africa presents a gap in the genebank network; only one out of three countries in this region has a national crop genebank (World Bank, 2017). Investment in genebank infrastructure in this region would help to maintain and document sub-Saharan African fruit and vegetable genetic resources. At the same time, several collections from the existing genebank network are vulnerable because they have large backlogs of old or original fruit and vegetable germplasm samples that require propagation and re-storage (Fu, 2017).

Complex access and benefit sharing policies and regulations, in particular domestic policies and regulations that implement the Nagoya Protocol of the Convention on Biological Diversity (CBD), increasingly govern international efforts to conserve and use the diversity of local varieties and wild populations (Brink and van Hintum, 2020). These policies recognize the rights of countries and local communities over genetic resources within their territories, yet all countries and communities depend on each other for genetic resources of fruit and vegetable species for food and nutrition, including neglected and underutilized species (Khoury et al., 2016; van Zonneveld et al., 2021). This interdependence is expected to increase under global climate change (Burke et al., 2009), and regulations will need to evolve alongside.

Currently, germplasm exchange of most fruit and vegetable species is limited, including because they are underrepresented in the Multilateral System of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty) that is established to enhance exchange of plant genetic resources for food and agriculture between countries. Furthermore, debates about the relationship and interplay between breeders' rights and farmers' rights are ongoing (Dias, 2011; Gupta and Negi, 2019; Salazar et al., 2007), affecting the development of new plant material and the use of seed by growers. The 2011–2021 Global Crop Wild Relatives project led by the Crop Trust showed how global partnerships for collecting, conservation, and germplasm availability are possible for crop wild relatives of fruit and vegetable species that fall under the framework of the Plant Treaty, such as banana, apple, eggplant, and carrot (Müller et al., 2021). Similar workable agreements enable rescue of germplasm of other fruit and vegetable species and give farmers, breeders, and researchers access to planting material for food and nutrition; these agreements provide a framework for access and benefit sharing following all applicable current laws and regulations at national and international level (Brink and van Hintum, 2020).

3.2. *Enabling access to a wide range of fruits and vegetables*

Promoting neglected and underutilized food plants, such as many traditional fruit and vegetable species, is a key policy option that addresses both healthy diets and agrobiodiversity (Pedersen et al., 2020). The pool of underutilized plant biodiversity includes fruit and vegetable species with exceptionally high nutritional value, such as micronutrient-rich African leafy vegetables adapted to rain-fed conditions (Maundu et al., 2009) and vitamin-rich Amazonian fruit trees that withstand flooding and waterlogging (Van Loon et al., 2021; van Zonneveld et al., 2020), giving impetus to connections between biodiversity and nutrition. The latest generation of food-based dietary guidelines starts to move in the direction of more diverse diets – but these efforts can better consider cultural acceptability, and may require promotional efforts to increase the willingness of consumers to shift their diets to new or forgotten foods and diversify within the fruit and vegetables food groups (Davis et al., 2021). Alongside improving availability and access, the challenge is to enhance consumer choice of, and preference for, these foods. There is clear evidence that focusing on education at all levels is to some extent effective for modifying behavioural changes in general, whether dietary or environmental (Alderman and Headey, 2017); and nutrition literacy, social norms for healthy eating, and self-efficacy are key components of health-related behaviour change (Eker et al., 2019).

We know less for fruits and vegetables in particular, though the general evidence on dietary behaviour change can be tested, and social marketing has been used to promote a return to diverse traditional vegetables in several contexts (Powell et al., 2015). Nutrition literacy programs generally target women, who are in many cases custodians of household nutrition and of local agrobiodiversity, but there will also be a need for community-targeted messages to change social norms around both diets and conservation (Van den Bold et al., 2013). There are reasons that changing food demand might help to reverse the trends reducing agrobiodiversity and homogenizing food systems: There is greater global awareness about the benefits of diverse diets with sufficient fruits and vegetables, though this knowledge has not reached all populations equally. Encouragingly, some neglected and underutilized fruit and vegetable species have regained relevance in urban diets through public and private initiatives in gastronomy and niche markets for local, healthy, or ethnic food (Borelli et al., 2020), and appealing to aspiration can be a powerful promoter of foods. But decades of work on the nutrition transition makes it clear that these positive food system and dietary changes are the exception rather than the norm (Popkin et al., 2020).

Deciding what to eat is embedded in the broader food environment, and within people's daily realities (Blake et al., 2021). Promoting home and community fruit and vegetable production, or facilitation of foraging, is a small-scale option where the agrobiodiversity and broader context allows (Baliki et al., 2019; Powell et al., 2015; Schreinemachers et al., 2016), but approaches are needed that can clearly provide for the nutritional needs of large (often urban) populations. Addressing

affordability of fruits and vegetables is key to creating an environment where all can access a healthy diet, given that most people buy at least a proportion of their food, and affordability can come from a combination of lower retail prices of diverse fruits and vegetables (through productivity improvements, reduced postharvest losses, or increased market efficiency for stable prices) and higher incomes (from inclusive economic growth, living wages, and social safety nets) (Hirvonen et al., 2019). Cheap food is not necessarily good for healthy diets, fair livelihoods or agrobiodiversity however, so a focus on affordability through equitable economies is important where foods are purchased (Benton et al., 2021), and decisions will have to be made regarding priorities and trade-offs (below).

Big-picture policy and political drivers – including research and development investment focus, trade regimes, and a focus on calorie security rather than nutrition – have oriented food systems away from pathways prioritising diverse fruits and vegetable species in diets, and away from agronomic and food system paradigms that might promote a return to more biodiverse production systems and diverse diets (Leach et al., 2020; Patnaik and Oenema, 2015; Rosset and Altieri, 2017; Vivero-Pol et al., 2018). The policy environment in terms of evidence, politics, and capacity – and the framing of these – is important for sustainable change in biodiversity and diets (Hunter et al., 2016), though in global analyses the political commitment is low for conserving and using fruit and vegetable biodiversity (Jones et al., 2021) and for improving nutrition (te Lintelo and Lakshman, 2015). This is despite efforts such as the Voluntary Guidelines for Mainstreaming Biodiversity into Policies, Programmes and National and Regional Plans of Action on Nutrition, endorsed by the Commission on Genetic Resources for Food and Agriculture (CGRFA) in 2015, which recognize many of these issues but do not hold powers of accountability for their action.

3.3. Synergies and trade-offs

There are potential synergies between a food systems approach to nutrition and an integrated conservation of fruit and vegetable biodiversity on farms, at landscape level, and in protected areas (Powell et al., 2013). Linking agrobiodiversity and nutrition can in theory address some of the negative consequences of current food systems (Johns and Eyzaguirre, 2006): Promoting diverse food consumption can promote conservation of agrobiodiversity; and promoting agrobiodiversity is a practical approach for dietary diversity, food security, and rural development, so there are win-wins to be had in theory (Toledo and Burlingame, 2006). There are also potential trade-offs between preserving agrobiodiversity and enabling diverse diets for everyone everywhere, alongside promoting fair food system livelihoods, which need to be resolved through evidence, policy engagement, and inclusive dialogue.

Clearly, more availability of a variety of fruits and vegetables is needed for human populations to meet dietary recommendations, but there are different ways to achieve this, with implications for the use of crop biodiversity at different geographic scales. For sustainable use of fruit and vegetable biodiversity a wide range of approaches depending on contexts, including sustainable intensification and diversification approaches to improve yields while adapting climate change, have been suggested to maintain fruit and vegetable production and livelihoods while minimizing environmental degradation (Godfray and Garnett, 2014; Schreinemachers et al., 2018; van Zonneveld et al., 2020). Participatory approaches that consider multiple criteria including agronomic, environmental, social, economic, and political factors have prooved useful to guide decision-making in balancing sometimes competing interests in making these production decisions (van Zonneveld et al., 2020).

Producing sufficient fruits and vegetables can have relatively high requirements for land, water, and chemical inputs, depending on context and production method (Aleksandrowicz et al., 2016), and with one third of global greenhouse gas emissions produced by the food system there is a need to better understand the role of fruits and vegetables in land and input use (Crippa et al., 2021). While we can in theory produce sufficient fruits and vegetables for healthy diets within planetary boundaries (Willett et al., 2019), achieving national food-based dietary guidelines has been found to be incompatible with climate and environmental targets in a majority of 85 countries studied (Springmann et al., 2020). One key solution is a better use of fruit and vegetable biodiversity in breeding globally to make varieties available to producers that are nutrient-rich, eco-efficient in production, and adapted to changing climate conditions. Producing according to context is another key solution. Local production, home garden production, and food gathering may be important sources of biodiverse plant foods in many contexts, to buffer food production homogenization and increase the use of fruit and vegetable diversity at national and local levels (Bharucha and Pretty, 2010; Galluzzi et al., 2010; Schreinemachers et al., 2015). Urban agriculture also brings opportunities for agrobiodiversity in urban spaces (World Health Organization, 2015), with benefits including reducing food losses along the value chain by producing food closer to where it is consumed; creating jobs for urban populations; improving quality of life through greening of urban environments; and closing nutrient cycles by re-using urban waste (Lutaladio et al., 2010). Agroecology research and practice in particular tries to develop, test, and promote practices that promote sustainable production and equitable diets through inclusive and participatory approaches (Méndez et al., 2015; Rosset and Altieri, 2017), and considers the potential of local fruit and vegetable species for sustainable production in specific agroecological zones and adaptation to changing climates (Nabhan et al., 2020; van Zonneveld et al., 2020; Waha et al., 2018).

Current discourses encourage integrated approaches between different conservation practices (Dulloo et al., 2017) and between environmental sustainability and human diets (Willett et al., 2019). Notwithstanding, there are trade-offs among conservation of biodiversity as an end in itself vs. leveraging fruit and vegetable agrobiodiversity to provide food options and improve diets, given scarce resources. The approaches mentioned above prioritise agrobiodiversity conservation for human food, which while important for us humans, is not necessarily all that is needed to preserve levels of biodiversity that the planet requires to function well. Within the context of a diet for a healthy planet, there are trade-offs and synergies between leveraging agrobiodiversity to improve diets with more volume of vegetables and fruits, and making food production more eco-efficient with an investment in a broader conservation of biodiversity and environmental sustainability. There are also trade-offs among our ability to preserve the biodiversity of different species, and our requirements in diets: Typically, small and orthodox seed of many vegetables and berries can be saved in genebanks and seed saver networks for exchange, breeding and future use (Hong et al., 1996). In contrast, many fruit species can only be maintained in field collections, or by conserving living tissue in tubes (in vitro), or through cryopreservation in liquid nitrogen because they usually have large and recalcitrant seed that cannot be stored for long time periods (Panis et al., 2020). Appropriate planting material is one of the major bottlenecks for farmers to grow a wide range of fruit and vegetable species (McMullin et al., 2021), so genebanks of vegetable and fruit species can actively engage with different users groups to provide inter- and intraspecific crop diversity for developing and growing planting material with high nutrient values for a win-win scenario (Smale and Jamora, 2020; Stoilova et al., 2019). The fruit and vegetable biodiversity conserved in genebanks and by seed saver networks complements plant genetic resources maintained in farmer fields, at landscape level, and in protected areas (Dulloo et al., 2017). Connecting these genebanks and networks to these efforts on the ground optimizes conservation of fruit and vegetable biodiversity while providing local users opportunities to access new and diverse planting material. The latter being particular relevant under climate change. The way and extent these different practices are implemented and connected may differ depending contexts, with different implications for different societal groups in the food system.

In practice, decision-makers and societal actors may need to make a

choice between the contemporary use of certain species and varieties in production systems to feed today's population, and conserving agrobiodiversity at a broader scale (including todays' neglected and underutilized species and varieties) to safeguard a biocultural heritage and to keep future food options open. Decisions need to be made about the levels and type of fruit and vegetable biodiversity to be conserved at national and local levels with an eye on the future, depending on the local and global importance and potential of certain species and varieties for human diets under climate change, and in the context of global efforts of conservation and germplasm exchange, such as the Global System of PGRFA (Engels and Ebert, 2021). Also with an eye on future generations, agrobiodiversity promotion through school gardens, sometimes in combination with locally-procured school meals, combines early nutrition education and diverse production as a potential win-win engaging with future eaters and conservers (Hunter and Monville-Oro, 2020; Shrestha et al., 2020). Further down the food system, reduction of food prices through market efficiency and food production homogenization can lead to agrobiodiversity losses, so a trade-off in some contexts is between affordability of food and the availability of agrobiodiversity, which requires further understanding and debate on agrobiodiversity use in value chains and the amount of investment to counteract agrobiodiversity losses through rescue and conservation. Considering trade-offs between current and future populations is part of these deliberations, including with a focus on intergenerational equity (Nisbett et al., 2021).

Regarding equity for today's human populations, some of the most nutrition-insecure people live in some of the most biodiverse areas, so issues of nutrition equity and conservation should be considered in national and international policies to link fruit and vegetable biodiversity to dietary diversity (Herrero et al., 2017; Johns and Eyzaguirre, 2006). For example, while the Amazon is a hotspot of fruit and vegetable biodiversity, these territories are also characterized by complex socioeconomic problems that affect local agrobiodiversity as well as health and welfare of indigenous communities, such as the nutrition transition and poor health and sanitation infrastructure (Borges et al., 2015; Coimbra et al., 2013). Costs and benefits of conservation and fruit and vegetable production do not accrue equally or fairly in different dimensions of the food system – but different facets of equity have been described (Nisbett et al., 2021), and can be explicitly factored in to inclusive decision-making processes to debate trade-offs and decide priorities at different levels.

4. Knowledge gaps

Overall, there is considerable literature focused on agrobiodiversity for local diets, including the role of fruit and vegetable biodiversity in populated rural areas; but far less on biodiversity in urban areas, and not enough understanding of the nuances of different agroecological or socio-cultural contexts or production approaches. There are also research efforts highlighting national-level agrobiodiversity and its use in food systems, and specifically on metrics for measuring this, though little looking at the impacts of national policies on the crossovers identified above. Trading and international interdependence are relevant topics at regional and global levels, with some literature on broad food system changes and their impacts on agrobiodiversity and dietary diversity, but there is little literature looking at fruits and vegetables at this level. Below we highlight key research and knowledge gaps from this review.

A key knowledge gap is that we don't have good data on the diversity of fruit and vegetable species in farmer's fields or landscapes, as well as in genebanks, especially within species. There is often high nutrient variability among fruit and vegetable varieties, a clear link between agrobiodiversity and nutrition, but data are limited on this, and particularly for neglected and underutilized food plants (Johns and Eyzaguirre, 2006). These include many traditional fruits and vegetables relevant for local production and harvesting but often left out of data collection, policy considerations and agricultural extension (Hunter et al., 2019; Raihana et al., 2015). Many locally cultivated and wild-harvested food plants are missed in available dietary and production data (Jones et al., 2021), limiting our knowledge about real diets and food environments; at the same time, fruit and vegetable species – which have very different agronomic, trade, and nutritional profiles – are often lumped together into a single 'fruits and vegetables' group, further hampering nuanced research efforts (Harris et al., 2021). Investment in screening the diversity of neglected and underutilized fruit and vegetable species can reveal varieties with high nutrient content (Yang and Keding, 2009) providing evidence for nutrition and marketing messages to promote diet and crop diversification with more fruit and vegetable species among households and producers, and a basis for breeding of nutrient-rich varieties.

There is also a key knowledge gap in the diversity of fruit and vegetable species in people's diets. There is little research available on what is eaten where, in particular the use of wild-harvested food plants (World Health Organization, 2015), though in some places and in different languages there may be ethnobotanical and anthropological literature that can be drawn on more than it currently is – and that rescues and recognizes traditional knowledge from local voices that still can be heard in some places on how to grow these species, and how to process them for food consumption. There is also a gap in terms of why different fruits and vegetables are preferred in different places, and in the role of nutritional information, aspiration, and gastronomy in inspiring people to eat more diverse plant foods. The lack of data on intra-species food composition, and the context-specificity of diets, means that more research is needed to provide more general policy advice (Hunter et al., 2016).

Much of the research on agrobiodiversity in food systems and for diets has focused on rural parts of middle-income countries, where smallholder farming is common, but other regions are important to understand. Rural and urban communities in some middle- and high-income countries especially in Asia and the Mediterranean region have retained aspects of traditional biodiverse production systems in combination with the maintenance of traditional food consumption customs, and seem to have better health outcomes compared to those regions which have not – at least so far (Johns and Eyzaguirre, 2006). To which extent biodiverse wild-harvested fruits and vegetables are accessible for urban dwellers and can be used for food-plant harvesting, also remains to be investigated (Rimlinger et al., 2021; Shackleton et al., 2017). Low-income countries are particularly under-represented in food system studies of fruits and vegetables for healthy diets (Harris et al., 2021).

We also need better evidence as to how greater agrobiodiversity in general would bring benefits in terms of healthier diets and more sustainable food production. While raising crop diversity at the level of individual farms may indeed not be the most effective strategy to increase dietary diversity in those households (Jones, 2017), at the food system level producing diversity is of course a necessary precondition for being able to consume a diversity of foods, and we need to better understand those pathways. There is little research on effective strategies to promote more diversity in modern or informal supply chains (from producers and traders to processors and vendors), and there is a need to better understand this missing middle and trade-offs among scaling production for broader availability in diets, and conserving fruit and vegetable agrobiodiversity and the broader environment. More research is needed on the potential of agroecological practices to make fruit and vegetable production more compatible with national climate and environmental targets.

Given the range of factors important in understanding the links between agrobiodiversity and dietary diversity – from plant genetic resources and ethnobotany, to nutritional screening and breeding, to socio-cultural behaviours and political economy – interdisciplinary research is clearly needed (Hunter et al., 2016; Méndez et al., 2015). Bringing this research together into a body of evidence can be difficult,

as even standard epidemiological studies of agrobiodiversity and dietary diversity can use quite different measures and metrics (Jones, 2017), but it is urgent given rapidly changing diets and declining fruit and vegetable biodiversity.

5. Conclusion

This paper has brought together key research to frame what we know about the links between agrobiodiversity and dietary diversity in the context of fruits and vegetables, and to clarify knowledge gaps for further research. Planetary health through the conservation of fruit and vegetable biodiversity and the consumption of diverse diets is lacking, and in many contexts getting worse. Agrobiodiversity and nutrition are linked, so addressing them together can bring synergies in terms of valuing both issues together and building on the other's gains. There are also potential trade-offs however, and the impacts on health, sustainability and equity of policy or practice change in each area should be closely monitored.

The evidence reviewed here is an input into policy engagement, but more research is clearly needed – particularly in the context of fruits and vegetables, which have not been the focus of most agrobiodiversity or dietary diversity research. In the meantime, and building on what we do already know, food system actors from global experts to national governments to local communities must have input into global guidelines and context-specific actions that ensure different perspectives, needs and interests are balanced equitably, for instance through mechanisms such as the UN Committee on Food Security. Building on food system synergies among diverse diets, conservation, and sustainable use of agrobiodiversity is possible, but acknowledging and debating trade-offs and the winners and losers from change is also vital as we move on from the 2021 UN Food Systems Summit and COP26 and seek to improve fruit and vegetable food systems for all.

Contributions

J.H. and M.v.Z wrote the paper drawing on contributions of two working papers written for the Scientific Group of the UN Food Systems Summit. E.G.A.D, B.B., I.D.B., D.C., I.d.J., B.d.S.P., M.E.D., L.G., R.K., S. M., S.M.M., M.Q. and P.S. provided input to the original working papers, and critically reviewed the current paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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