

PATHWAYS OF STAPLE CROP PRODUCTIVITY THROUGH AGROBIODIVERSITY TO DIET DIVERSITY: EVIDENCE ON LINKS AND TRADE-OFFS

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1. INTRODUCTION

The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, adopted by the General Assembly of the United Nations in September 2015, provide global policy orientation for the work of development organizations and research institutions such as the CGIAR. Of particular relevance to the scope of work of the CGIAR is SDG2. SDG2 aims to “end hunger, achieve food security, improve nutrition and promote sustainable agriculture.” Targets established under SDG2 include not only doubling agricultural productivity, but also an end to all forms of malnutrition, while maintaining the genetic diversity of seeds, cultivated plants and their related wild species, among others.

Analyses of SDG goals/targets have displayed the vast and complex interactions among and within SDGs and targets (ICSU 2017, Campbell et al. 2017; Machingura and Lally 2017; Scharlemann et al. 2016). Integrated trade-off models and frameworks have been proposed as decision-making tools. These generally rely on indicators measured with interdisciplinary data sets collected at various scales, or expert elicitation, followed by optimization or scenario analysis (e.g., Fuso Nerini et al. 2017; Kanter et al. 2016). For example, in one of their trend scenarios, Kok et al. (2018) predict that increased productivity through technological improvements, greater use of ecological methods in agriculture and forestry, and consumption changes could contribute to avoiding biodiversity loss of 3.1–3.5% in terms of mean species abundance by 2050. Conducted at a global scale with aggregated data, these encouraging results depend in large part on key assumptions such as “bending the curve” of stagnating rates of yield growth with “land sparing” innovations, combined with “transformative changes” in consumption preferences away from rising shares of livestock products in the diet—which the authors call “caring” innovations. Trade liberalization is assumed.

Science Forum 2018 (SF18) will address three major types (topic areas) of interactions among the goals of reducing poverty, improving nutrition security, and enhancing natural resource management. The topic areas have been selected based on their relevance to the CGIAR’s agricultural research agenda. The purpose of the papers commissioned to address these interactions is to draw implications for the international agricultural research agenda in general and, in particular, the research portfolio and program design of CGIAR.

This paper explores specifically the potential interactions of breeding for staple crop productivity with 1) sustainable conservation of agricultural biodiversity; and, 2) dietary diversity. We “focus” on staple crop productivity precisely because popular (and some scientific) perceptions¹ have been that raising staple crop productivity via the paradigm of the Green Revolution directly caused the narrowing of crop genetic diversity and resulted indirectly in the erosion of other components of agrobiodiversity. The process of modern plant breeding was perceived as fostering genetic uniformity when compared to the heterogeneous, adaptive landraces that then dominated agricultural landscapes in developing countries (alongside, in some regions, the earlier products of modern plant breeding). The work of CGIAR in partnership with national plant breeding institutions then supplanted these with shorter, modern varieties of the same crop while pushing other, less input-intensive crops into the margins. By restricting the range of foods produced for consumption on small-scale farms, the model is also thought to have contributed to reducing dietary diversity.

Reflecting the broader literature on SDGs and trade-off analyses, we suspect that the linkages and trade-offs embedded in (1) and (2) are multiple and not necessarily uni-directional. Synergies may be observable empirically or unobservable, but feasible. Here, we seek to summarize main points in the published literature that tests hypotheses related to linkages and trade-offs. Given our orientation toward the historical mandate of the CGIAR and partner institutions, we consider maize, wheat and rice as the major “staple crops” for the purposes of this paper. Strictly speaking, these are the most “highly bred” crops in the CGIAR portfolio of food crops and they have also received the largest shares of agricultural research investment since its formation. Elven and Krishnan (2018) show that from 1972–76, cereals represented an average of slightly over 55% of a total of 191 million USD in expenditures, but the share of cereals gradually declined

¹ Examples that represent some of the perspectives include Harlan (1972), NRC 1972, and Shiva (1993).

to an average of around one third (of a total of 529 million USD) over the 2002-2006 period. Considerably smaller shares were devoted to the categories of legumes, roots and tubers, bananas/plantains, livestock, trees, fish and water. While potato, legumes, sorghum and millet, banana and plantains constitute major shares of diets in many countries within the scope of CGIAR activities, historically, some of these been referred to as “minor,” “neglected” or “orphan” crops from the standpoint of total research investments and scientific knowledge (Naylor et al. 2004). Dietary diversity, measured at the household or individual level, is applied as a broad measure of food security and nutrition adequacy. We discuss this concept and alternative operational measures below.

For agrobiodiversity, we invoke the widely used definition of the Convention on Biological Diversity as rephrased by FAO (2016): “Agricultural biodiversity includes all the components of biological diversity of relevance to food and agriculture together with the components of biological diversity that constitute the agro-ecosystem; the variety and variability of animals, plants and micro-organisms at the genetic, species and ecosystem levels, that sustain the functions, structure and processes of the agro-ecosystem. This diversity has been shaped by farmers and communities for millennia and remains a key element of the livelihood strategies of poor, small-scale farmers throughout the world. Agricultural biodiversity, including wild relatives of genetic resources, is a fundamental resource for the continued improvement of varieties and breeds, and needed to cope with changes.”

Agricultural biodiversity is a subset of biodiversity, but boundaries between agricultural biodiversity and biodiversity are permeable and artificial. During the course of human history, modern human activities, and notably agriculture, have degraded biodiversity (Campbell et al 2017; Foley et al. 2011; Pereira et al. 2012). Yet, agrobiodiversity cannot exist without humans—and this is the fundamental feature that separates it from other components and forms of biodiversity. At the same time, other components and forms of biodiversity that can exist with human activities, such as forests and wild grasslands, support human activities.

Next, in Section II, we use a heuristic diagram of decision-making on a household farm to trace the pathways from adoption of productivity-enhancing technology through the components of agrobiodiversity to nutrition outcomes, represented by dietary diversity. In Sections III and IV, we examine the hypotheses that increasing staple food productivity 1) reduces agrobiodiversity, and 2) reduces dietary diversity. In Section V, we suggest some general conclusions regarding synergies and trade-offs and identify cross-cutting themes.

2. PATHWAYS FROM STAPLE FOODCROP PRODUCTIVITY THROUGH AGROBIODIVERSITY TO DIET DIVERSITY

There appears to be a science policy consensus that sustaining agrobiodiversity is a necessary condition for sustaining food production. This is especially the case given the joint current challenges of producing diets that are adequate in micronutrients as well as calories, promoting farming systems that continue to serve as primary livelihood among the rural poor in a rapidly urbanizing world, and reducing negative effects of intensive production on the environment (FAO 2016; Tilman et al. 2011; Kanter et al. 2016; ICSU 2017; ODI 2017; Scharlemann et al. 2016).

The importance of agrobiodiversity is indicated by the scale and scope of the benefits it generates, in which scientific research to improve foodcrop productivity plays a key role. Private benefits accrue locally to farmers through the value they derive from producing and consuming the harvest locally. Breeding for quality traits in staple food crops enables farmers to adapt to changes in consumer demand in the marketplace; conferred traits such as biotic and abiotic tolerance allow producers to adapt to environmental change. (Seed companies and plant breeders also earn private benefits from crop improvement, but since they cannot appropriate all of these, public funds are also needed to attain investment levels that are socially optimal.) Over a crop-producing landscape or within an agroecosystem, the extent of tolerant varieties grown, the portfolio and spatial diversity of varieties and species influences vulnerability to plant pests and diseases, and to environmental stresses. Offsetting this vulnerability generates a public value or benefit to producers and consumers in the community, region or nation. Global public benefits are also associated with protecting against genetic erosion. This preserves the options to a) use known genes and gene combinations in extant varieties or species, and b) discover unknown genes and gene combinations for future food production or other purposes (Lipper and Cooper 2009; Smale 2006).

The interactions among components of an agroecosystem are multidirectional and exceedingly complex². Figure 1 is an effort to visualize the pathways linking agricultural research on staple food productivity and adoption through agrobiodiversity to diet diversity from the perspective of decision-making within an agricultural household. Agricultural research generates combinations of adapted seed varieties, recommended soil and water management practices that may or may not be adopted in pieces and sequences. Adoption, when it occurs, is heterogeneous (e.g., Sheahan and Barrett 2017). Sources of heterogeneity include the range in capital resources among smallholders, varying constraints on the supply of information and technology, and differentiated agroecologies. Initial adoption in no way ensures continued use.

Continued use of a new technology set (sustained adoption) is likely to occur when it increases the value of output per unit of input relative to current production methods over successive growing seasons. When markets are imperfect, the decision price for farmers reflects both market prices and the household-specific endowments that affect transactions costs (de Janvry et al. 1991). When farming households produce less than they need of the staple food crop, as long as it costs less to produce than purchase, adoption of yield-enhancing technology sets may lend them to shift more land into the crop until they meet their needs for self-sufficiency. If they meet their needs with a smaller land share, productivity change enables them to shift to other crops with higher value. If they are commercial producers of the staple food, and staple food crop prices are relatively high, they may shift more land into the crop. Over time, however, if widespread diffusion occurs, we expect the price of the staple foodcrop to decline, followed by aggregate land shares.

Adoption of a new technology set has immediate consequences for family labor use on and off-the farm, affecting labor productivity, wages, and income earned by members and the household as a whole. Other consequences may be

² See, for example, p. 13 of <http://www.fao.org/3/a-i6602e.pdf>.

less immediately visible, such as the externalities from use of pesticides, herbicides and fertilizers on the farm, on other farms, and on the surrounding commons of forests, pasture and water resources in the local agroecosystem.

Thus, in terms of agrobiodiversity, we can expect changes in yield, area, land share, and the overall mix of species and genetic mix of crops and livestock, including varieties and breeds—but in various directions depending on the timing and context. Spatial and temporal distributions of crop and livestock diversity are shaped by aggregated patterns of adoption – which in turn are shaped by both the socio-economic heterogeneity mentioned above and agroecological conditioning factors such as climate, incidence of plant diseases and pests. Economic incentives for production choices are influenced by market infrastructure. Input use changes and externalities ripple through the micro-agroecosystem around each cluster of farms, affecting soils and water biota—and these feed back to the farm and farm productivity.

A few studies in the applied economics literature have tested the effects of crop diversity on crop productivity and resilience at the farm and regional scales of analysis. In France, Donfouet et al. (2017) found a positive effect of crop diversity on overall productivity, particularly in lower rainfall areas. Using historical data, Omer et al. (2007) demonstrated the positive effects of non-cropped areas, hedgerows, and plant species diversity on the production frontier of the cereals system in the eastern UK.

Input distance functions and stochastic frontier models have been used to test complementarities and economies of scope, or the economics of diversification on individual farms. In Bangladesh, Rahman (2009) found strong evidence of diversification economies among most crops except the enterprise combination of modern rice and wheat, along with significant efficiency gains—concluding that crop diversification is a desirable strategy for agricultural growth. In Papua, New Guinea, Coelli and Fleming (2004) found that diversification economies were weakly evident between subsistence food production and both coffee and cash food production, but discerned diseconomies of diversification between coffee and cash food production. Significant technical efficiency gains were made from diversification among broad cropping enterprises. In Vietnam, Nguyen (2017) showed that diversifying by integrating cash crop and food crops generated significant complementarity and potential economies of scope.

Moving outside the sphere of production, when markets are perfect, all output is traded and farm enterprises purchase their food. Purchasing power, market supply, and consumer preferences dictate diet. But in the low and middle-income countries that are within the mandate of the CGIAR, where markets remain imperfect, incremental production gains can affect food consumption through two direct pathways, depicted as a thick blue fork in Figure 1: changes in income earned through crop sales by individual members of the household or the household as a whole, and changes in consumption of the harvested product on the farm. Food competes for income (derived from value of production crop sales and other sources) with expenditures on health care and education, and other aspects of daily life, including savings.

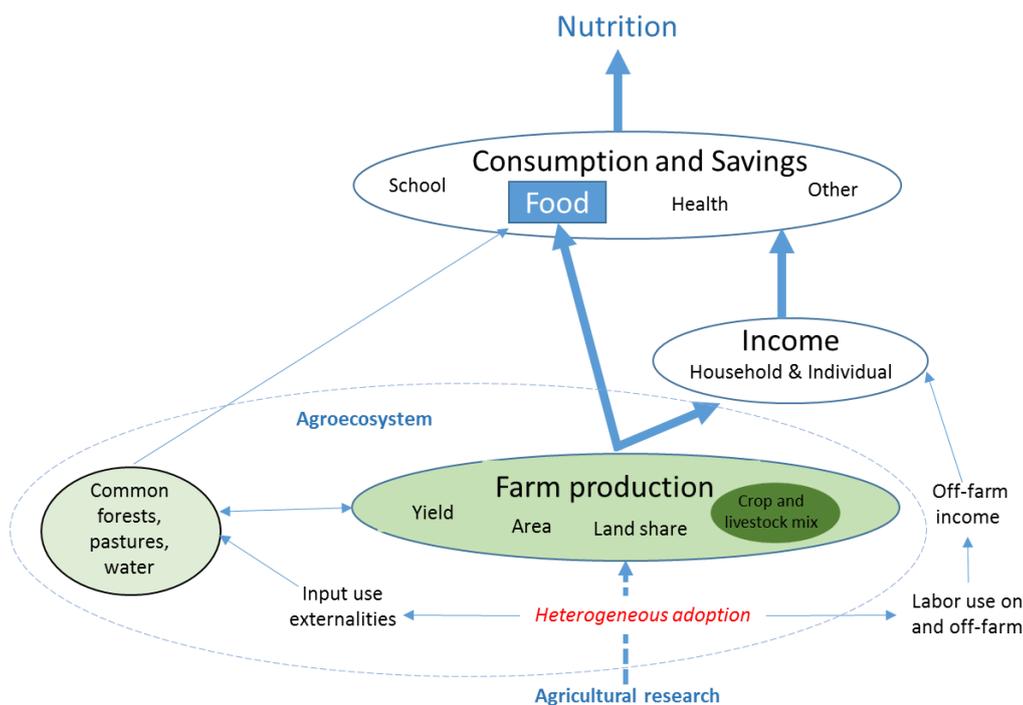


Figure 1. Pathways from agricultural research on staple crop productivity through agrobiodiversity to dietary diversity on household farms
Source: Authors. *nutrition can be represented by a metric of dietary diversity

Changes in cash income, depending on the source and household member, may entail a change in the basket of food purchased on the market and how it is distributed within the household. Changing farming and activity portfolios generate different income streams, perhaps leading to different consumption choices through aspects such as timing and seasonality. Combined, these complex decision pathways determine nutritional status of household members.

Whether a change in farm production will improve or worsen nutrition depends on how large are the income changes, the source of the income changes, and how expenditures will change with rising income (Hoddinott 2012). Hoddinott also emphasizes that the household may make some decisions collectively or individually—particularly over use of income or consumption from production on plots that are managed by individuals for their own private use or income-earning activities outside the farm³. By introducing other components of agrobiodiversity, we also see that the interactions of farm production with access to food from common pastures, forests and water may be significant.

Reviewing the literature on agriculture-nutrition linkages, Carletto et al. (2015) find four key recurring factors cited, regardless of pathway definition: 1) food prices 2) income from agriculture 3) consumption of own production due primarily to market imperfections, and 4) factors linked to gender. Figure 1, which is based on the theoretical framework of the agricultural household, highlights the second and third factors, with reference to the fourth. In this paper, we focus on only one indicator of nutrition: dietary diversity.

³ Feedback loops are not portrayed explicitly in Figure 1 but are significant. Chung (2012) emphasizes that nutrition is not so much an outcome as a critical input for household production, which includes farm work but also domestic activities and childcare. Hoddinott (2012) describes how the processes of agricultural production, including physical demands and exposure to toxins and pathogens, influence health and via health, nutritional outcomes. Feedback loops are also fundamental with respect to ecosystem services, which are both an input to and outcome of household production decisions.

3. HYPOTHESIS I: RAISING THE PRODUCTIVITY OF STAPLE FOOD CROPS REDUCES AGROBIODIVERSITY

A) The problem

Zimmerer (2010) discusses how agrobiodiversity consists of multiple analytic levels and spatial management scales that are subject to complex interactions. Cox and Wood (1999) argued that genetic diversity is the fundamental building block of ecological and organism diversity. Looking only at one component, crop genetic diversity, we see already an example of contradiction. From a plant breeding perspective, maintaining genetic diversity in the breeding stock is a goal because genetic variation is the source of heterosis, especially with respect to functional traits of economic importance, including biotic and abiotic tolerance. To some extent, genetic diversity serves as a proxy for future genetic combinations and allelic discoveries. Across a micro-agroecosystem in farmers' fields, however, there are likely to be trade-offs between the spatial diversity of varieties grown and productivity. In any given year, a possibilities frontier could be defined showing the maximum aggregate yield possible for any feasible level of diversity, for a particular group of cultivated varieties (Figure 2).

Hypothetically, planting all of the area to the single highest-yielding variety attains the highest total production, with zero varietal diversity. In high potential production zones, such as irrigated areas, farmers might pay heavily in net income foregone if they choose to grow a combination of varieties that are lower-yielding. In production zones with lower yield potential and greater yield variability, combinations of varieties might be optimal, indicating a different point on the curve. In some situations, both yield and diversity might be increased, suggesting a move from the interior of the curve toward the frontier of possibilities (see example for wheat in Pakistan, in Heisey et al. 1997)⁴.

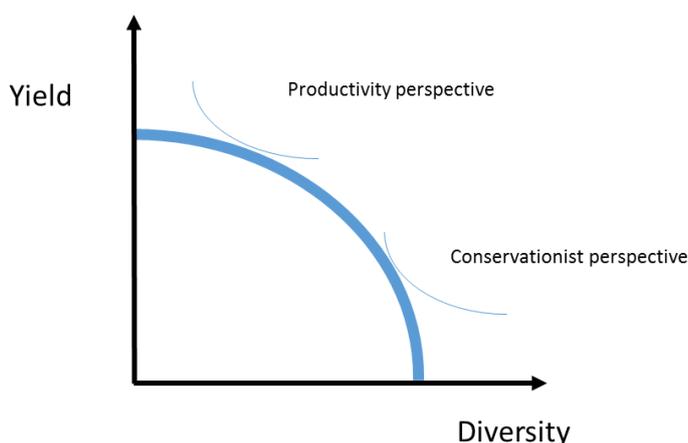


Figure 2. Hypothetical relationship between productivity and crop genetic diversity in a cropping region with fixed land area.

Source: adapted from Heisey et al. (1997).

Expected yields are only one metric of meaning to farmers. A number of studies have tested the relationship between various indicators of crop genetic diversity and yield variability in rice, wheat, barley and other cereals, including yield variance and skewness (downside risk), using farm data at household and regional scales. Generally, these have shown that infra-specific diversity on farms is associated with less exposure to production risk (Smale et al. 1998; Widawsky

⁴ Economics principles suggests that maintaining intra-crop diversity should occur to the extent that trade-offs with productivity are consistent with social preferences. These may be more or less weighted toward long-term goals of diversity conservation, as indicated by the tangents of the social indifference curves and production frontier. Fixed land area generates the concavity.

and Rozelle 1998; Di Falco and Perrins 2003, 2005; Di Falco and Chavas 2006; Di Falco et al. 2007; Di Falco and Chavas 2009). These analyses are reviewed by Di Falco (2012).

In recent years, land use and climate change, in addition to changes in on-farm seed use, have renewed concerns for protecting against the continued loss of valuable genetic resources—in particular, wild and weedy relatives. How should decisions be made about whether to conserve genetic resources in situ or ex situ? As long ago as 1967, resource economist John Krutilla recommended the identification, via scientific assessments, of a minimum reserve to meet the needs of science but also the demand for “esoteric” consumer tastes. Though modern biological techniques can in some instances modify the size of the crop genetic resource stock, proponents of in situ conservation of cultivated crops would argue that certain alleles may be lost as the spatial pattern of crop varieties grown in farmers’ fields changes with economic development. Some food amenities around which culture is now defined in local communities and “esoteric” (luxury) food attributes for which consumers in post-industrial societies might be willing to pay may also disappear.

Benefit-cost ratios by type of conservation are expressed conceptually in Figure 3. In simple terms, globally, least cost conservation of crop genetic resources on farms will occur in sites that are most highly ranked in terms of expected future benefits to producers and consumers and where, because farmers’ private incentives for conservation are greatest, public interventions to encourage them to do so will be least (II). In these sites, private and social costs will be least because farmers are already bearing the costs of conservation. Where the contribution to genetic diversity is assessed to be relatively low and no unique traits have been identified, there may be no need to invest in any form of genetic resource conservation (III). If the contribution to genetic diversity is great but the value on farms is low, ex situ conservation is the only viable alternative (IV).

Plant genetic resources in the agroecosystem that are not managed by farmers, such as wild and weedy relatives, are not explicit in this diagram, which was originally developed to describe landrace conservation. Wild and weedy relatives may provide valuable services within local agro-ecosystems (Tyack and Dempewolf 2016). As applied genetics advances, new tools enable access to broader gene pools (McCouch et al. 2012), in turn enhancing the global public value of some of these genetic resources. In situ (not on-farm) reserves may be justified, though these may be at high risk due to habitat loss. Recently, Castaneda-Alvarez et al (2016) modeled the distribution of over 1000 taxa related to 81 crops, identifying 70% of these as high priority for collection because of their underrepresentation in gene banks. Over 95% were insufficiently represented relative to the full range of geographic and ecological variation.

A scale dimension is also missing from Figure 3. That is, plant genetic resources can be locally, but not globally valuable. Would local gene banks then be justified to protect against natural disasters at the local scale? Under what conditions can global conservation efforts be justified to protect communities against local losses? There are numerous examples of restoration of materials to farming areas beset by natural or human-made disaster (Varma and Winslow 2005).

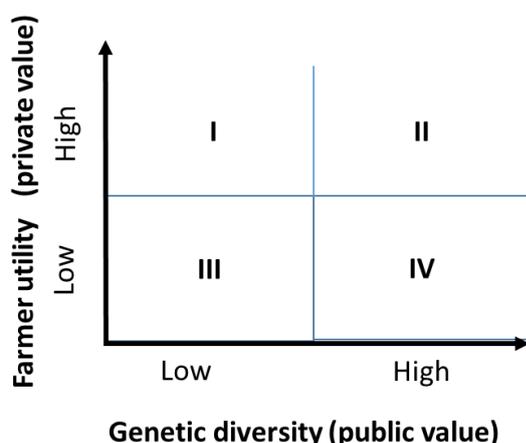


Figure 3. Notional benefit-cost ratios and conservation type.

Source: adapted from Smale and Bellon (1999).

One of the justifications for promoting on farm and in situ (in reserve) conservation in addition to ex situ conservation is the argument that genetic resources evolve differently under conditions of natural and human selection. Geneticists have often depicted the complementarity of the two approaches, and there are also some outstanding examples of direct distribution of gene bank materials to farmers ([Major 2018](#); Hawkes, Maxted and Ford-Lloyd 2000; King 2003) and linking gene banks with farmer seed systems (Westengen et al. 2018; Barbieri et al. 2014).

B) Is the productivity of staple foodcrops a major contributor to the expansion of agricultural lands?

Recognizing the importance of the agricultural ecosystem in crop productivity, other than moisture availability, the two strongest, immediate drivers of production increase in staple food crops are: a) land area change, and b) yield changes through genetics innovations, farming practices, and management of plants, soils and water. Yield changes are accomplished through adoption and adaptation of genetics innovations, farming practices and management of plants, soils and water. To what extent have changes in yield and area each contributed to production?

Ramankutty et al. (2018) distribute crops according to changes in recorded yields and harvested areas between 1961 and 2014, examining the ratios of 2014/1961 values (Figure 4). Data indicate that over the past half-century, changes in yield rather than area explained most of the production gains within the three major cereals (rice, wheat and maize). By contrast, dramatic increases in area appear to have generated proportionately more of the production gains observed in oil palm, rapeseed and soybeans. These outliers may represent cases such as the precipitous expansion of soybean production in Brazil and the exploitation of oil palm in Indonesia (see, for examples, Angelsen and Kaimowitz 2001). FAOSTAT data assembled by Ritchie also shows that from 1961 to 2014, cereal production per person rose due to yield rather than area expansion (<https://ourworldindata.org/yields-vs-land-use-how-has-the-world-produced-enough-food-for-a-growing-population>, accessed September 9, 2018). However, Grassini et al. (2013) find that while this pattern may hold true through 2000, since 2002, more than 25% of the increase in demand for staple food crops has come from expansion of crop area.

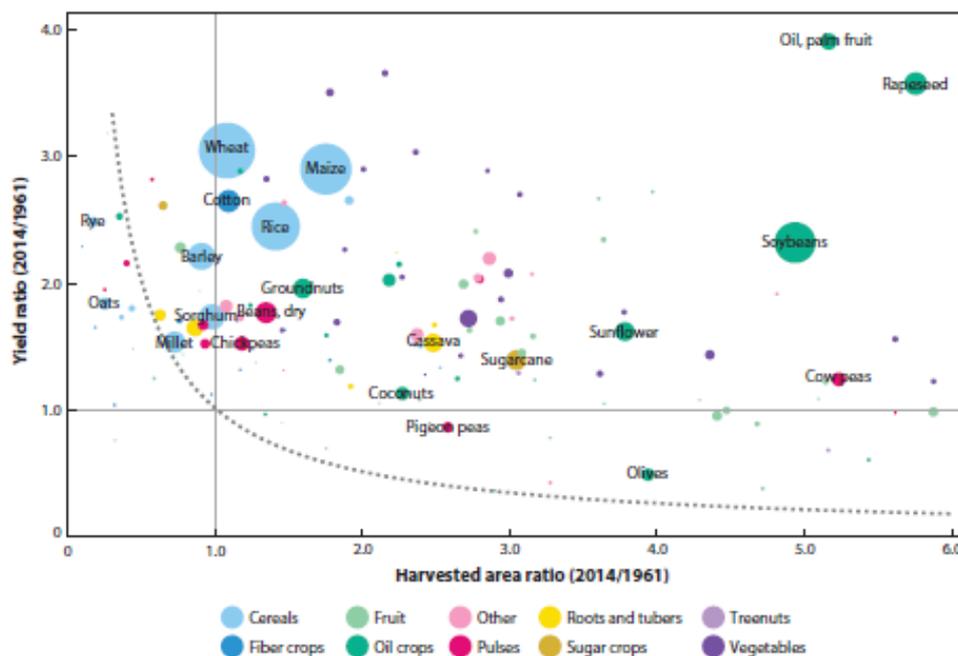


Figure 4. Relationship of yield change to area change in production of major crops worldwide.

Source: Ramankutty et al. (2018). Notes: data from <http://www.fao.org/faostat/en/#home>. Vertical axis shows 2014/1961 yield ratio and horizontal axis shows the 2014/1961 harvested area ratio. Crops above the dotted curve had production increases over the time period. Circle size represents crop harvested areas in 2014, and color refers to major crop group.

Ramankutty's useful portrayal of the global data also masks noteworthy regional variation—on both axes. For example, Meyfroidt (2017) reports that although most of the area of major food staples such as cereals, roots and tubers has been relatively stable over recent decades at a global scale, and most of the area contraction has occurred in developed economies, with areas continuing to advance in Africa and Southeast Asia and stagnating in Southern Asia, South and Central America. Ritchie finds that in Mexico, India, China and Brazil, land use per person has declined in cereal production, but in Brazil, the environmental trade-offs have been greater with the expansion of agriculture into forests and the Amazon.

Historically, agriculture is cited as one of the major causes of changes in land use that entail biodiversity loss and alteration (Pereira et al. 2010); Campbell et al. (2017) identify agriculture as the major reason that humankind is “exceeding planetary boundaries.” On one hand, food production is only one of several competing uses for productive and accessible land—also including biofuel production, urbanization and intensive forestry (Lambin et al. 2013). For example, Bren d'Amour et al (2017) conclude that urban expansion will result in a 1.8-2.4% loss of global croplands by 2030, with most of that loss occurring in Asia and Africa. On the other, there is evidence that not much land remains to be brought under cultivation without high social and environmental trade-offs (Deininger et al. 2011). Koh, Koellner and Ghazoul (2017) conduct the thought experiment showing that in theory, more optimal use of existing farmlands—without any change in total land area harvested—could meet future crop demands of cereals and oilseeds *if* cultural, social and institutional barriers were overcome.

From Meyfroidt's (2017) perspective, much of the global agricultural expansion and associated deforestation over the recent decades is not directly related to production of staple food crops but to that of a set of commodities with high income- and price-elasticity of demand, including product such as beef, oil, and sugar, which mainly support the diets of urban and middle class households in developed and emerging economies. Certainly more production per unit area

sometimes leads to expansion of crop area if labor is saved while yields rise and crops can be sold more profitably because staple food prices are high. Not all yield-enhancing technology is labor-saving, and with widespread diffusion, in the absence of other price supporting policies, staple food prices decline.

Byerlee, Stevenson and Villoria (2014) differentiate technology-driven intensification from market-driven intensification, attributing land expansion and deforestation for export crops to the second of these. Technology-driven intensification results from changes in output per unit of input (e.g., yields), and can result in expansion of cultivated area depending on where it occurs and how profitable it may be. The authors argue that technology-driven intensification can also spare land, but cannot arrest deforestation without governance of natural resources. Market-driven intensification occurs when crop mixes change in response to market prices and relative profitability. Brazil and Indonesia contain 35% of the total carbon stored in tropical forests and produce the largest emissions from forest loss (Baccini et al. 2012). According to Meyfroidt (2017) and Byerlee (2014), production of commodity crops (coffee, cocoa, rubber, oil palm) is more closely linked to deforestation than is production of staple foodcrops.

The notion that growing the same amount of food on less land can spare land for nature is traced to Norman Borlaug (“the Borlaug hypothesis”) and even earlier to Paul Waggoner, but was picked up by conservationists during the 2000s (Ramankutty et al. 2018). For example, modeling land-sparing as compared to wildlife-friendly farming, Green et al. (2005) concluded that the best type of farming for species persistence depends on the demand for agricultural products and on how population densities for species on farmlands change with yield. At that time, the empirical evidence they cite suggested that high-yield farming might allow more species to persist.

Several studies have explicitly tested whether the Green Revolution and its aftermath spared land or not. Evenson and Gollin (2003) applied the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which is a multimarket, multi-country model to test the Borlaug hypothesis for CGIAR crops (not only wheat, rice, and maize). Their simulations indicated that in the absence of the CG’s research (1960-2000), crop yields would have been higher in developed countries because lower production in the developing world would have driven up prices, encouraging farmers in richer countries to intensify. Crop areas would have been larger in 2000 by 3-4% without modern varieties, with higher estimates of 8-9% for rice.

For ten crops (including maize, wheat and rice), Rudel et al. (2009) found that between 1970-2005, agricultural intensification was not generally accompanied by decline or stasis in cropland area at a national scale except in richer countries in temperate climates with grain imports and conservation set-aside programs. In most countries yields increased, but cultivated areas did not decline. Like Byerlee, Stevenson and Villoria (2014), they also concluded that raising yields cannot be assumed to lead to cropland abandonment without policies that encourage it. Higher prices would have driven area expansion in all countries (by 3-4%), with greater savings in rice (8-9%).

Burney et al. (2010) applied an approach similar to Borlaug’s to estimate that agricultural intensification has avoided 161 gigatons of carbon emissions from 1961. Criticizing earlier studies because of their simplicity, Stevenson et al. (2013) applied the Global Trade Analysis Project Agro-ecological Zone model (GTAP-AEZ). They describe GTAP-AEZ as better able to model land competition with noncrop uses and the effects of land rents and factor markets. Their results uphold the Borlaug hypothesis, indicating that without crop germplasm improvement from 1965, crop area in 2004 would have been 18-27 million hectares larger—and much of this land would have been found in developing countries. They argue that technologies adopted on crops with high income elasticity grown near forest margins, such as oil palm, are likely to induce deforestation; those adopted on crops with inelastic demand on existing cultivated area, such as cereals, are less likely to do so.

Hertel et al. (2014) then applied the Simplified International Model of Prices Landuse and the Environment (SIMPLE), re-examining the period addressed by Rudel et al. (2009). They concluded that the Green Revolution was not only sparing in land but also in carbon dioxide, but that the prognosis for Sub-Saharan Africa would only be similar if global agricultural markets remain segmented.

C) Do we see a relationship between breeding for productivity increase and diversity of crops grown?

How land sparing actually influenced crop composition remains unclear in the studies cited above. Ramankutty et al. (2018) state that agricultural landscapes are increasingly under monocultures or monocultures in rotation, dominated by a few crops such as cereals or oil crops, without reporting the evidence. Based on analysis of FAOSTAT data, Dwivedi et al. (2017) report that globally, between 1961 and 2013, the land area planted to wheat, rice, and maize increased from 66% to 79% of all cereals while the land area planted to other cereals (barley, millet, oats, rye and sorghum) declined from 33% to 19%.

From a regional perspective, Ramankutty et al. (2018) report that currently, areas with large amounts of crop diversity appear to be concentrated in parts of Europe, Africa, Asia, and West South America, with low diversity in Australia, North and South America. When we also take the wild relatives of crops into consideration (Castañeda-Alvarez et al. 2016), the most critical collecting gaps are found in the Mediterranean and the Near East, western and southern Europe, Southeast and East Asia, and South America (Figure 5).

We have not found many published studies that directly test the effects of raising staple food crop productivity on the diversity among crops as a result of the Green Revolution. Some case studies compiled in Smale (2006) test whether adoption of modern maize, wheat or rice affects the richness or evenness of varieties or crops grown on farm in a single year of survey data in a particular farming system. The direction of effect varied by context. Coromaldi, Pallante and Savastano (2015) used the LSMS-ISA from Uganda to demonstrate that the effect of adoption of modern varieties (mostly maize) on the richness and evenness of crops grown by farming households was always negative, though the magnitude of the effect differed by agro-ecological zone and soil type.

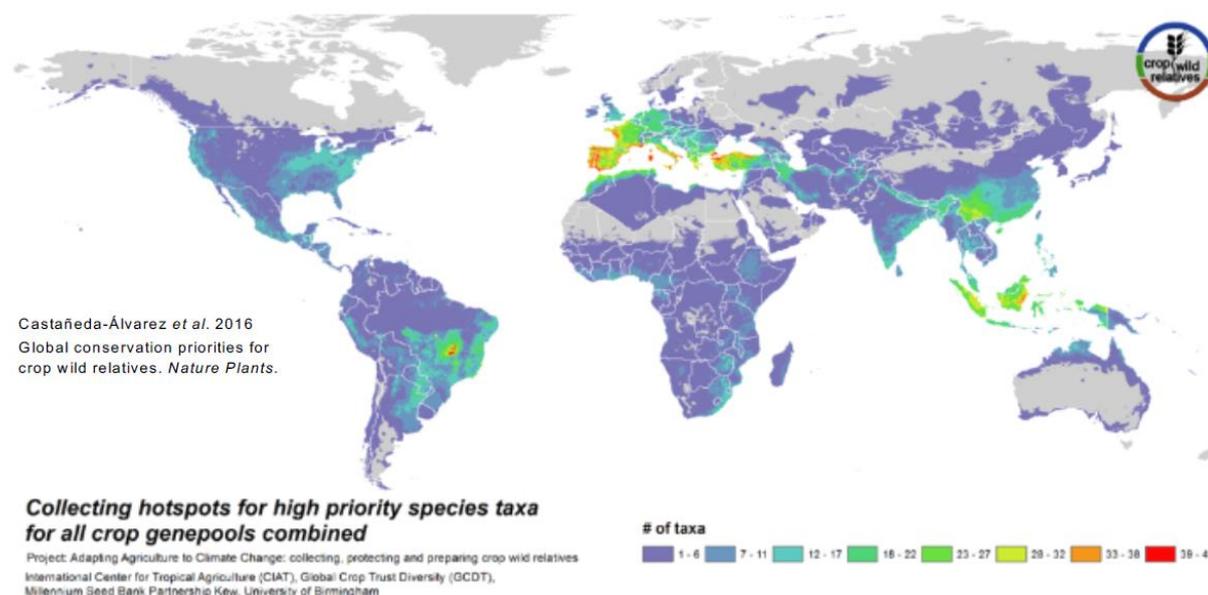


Figure 5. Collecting hotspots for high priority species taxa for all crop gene pools combined.

Source: Castaneda-Alvarez et al. 2016.

Kurosaki (2003) analyzed historical, district-level data (1903-1992) from the area of Pakistan that is roughly equivalent to the state of Punjab pre- and post-Partition—a locus of the Green Revolution. He found rising concentration of crop acreage in districts with higher and rising productivity over time, consistent with specialization according to comparative advantage. However, he found that the concentration of area in wheat (as measured by the Herfindahl index, or sum of

squared area shares) remained constant throughout the period and declined for rice after the 1940s. This suggests that cultivated land remained available for other minor crops.

Although other studies likely exist, the most common arguments linking staple foodcrop productivity and crop species diversity appear to be based on theory and direct observation of the processes of change induced by the Green Revolution, particularly in its locus—the wheat and rice baskets of Asia. For example, Dwivedi et al. (2017) observe that the most important cropping system in South Asia, the rice–wheat cropping system of the Indo-Gangetic Plains, “revolutionized agriculture during the green revolution which, on the one hand, enhanced food and nutritional security, and displaced legumes from the system on the other”(p. 845).

Pingali’s (2017) observations are excerpted here. Agricultural intensification (the increase in output per unit of land used in cultivation, land productivity, or “yield”) affects crop diversity through 1) changes in land use (see above) and 2) the crop choice. Lands that have high agricultural productivity potential, such as the irrigated and high rainfall lowlands, and lands with high soil fertility tend to become the focus of intensification efforts as population densities rise. Concentration of area in input-responsive crops such as rice and wheat over millets, pulses and root crops was observable in the irrigated, Indo-Gangetic plains of South Asia—a process that preceded but was accelerated by the Green Revolution (both early and late periods).

In contrast, a greater crop diversity tends to be observable in rainfed environments and where soil types and microclimates are highly variable. Crops grown in the less favorable environments often yield less and respond less to higher input use as compared to those grown intensively in the more favorable environments. Certain cereals (also staples), such as traditional millets and sorghum, tend to be better adapted to harsher environmental stresses, such a drought, high temperatures, or flooding. Farmers in stress prone environments often plant crops in the same field, including more than one cereal, but also legumes and cucurbits. An example is the milpa system of Mexico (maize, beans, squash, also including wild native greens, or quelites), which endures. Singh (2000) cites data from the Indian Center for Agricultural Research which shows that in the Green Revolution center of Haryana State, at two points in time (1965-66 and 1995-96), rice and wheat replaced pulses, pearl millet and sorghum as the dominant food crops. Rice represented only 13% of area in the 1965-66 wet season, but covered 34% in 1995-96. The percentage sown to wheat in the winter grew from 43% to 64%.

While it may be feasible to develop time-series, cross-sectional data series at different scales of analysis to chart changes in area shares planted to rice, wheat and maize relative to other crops, such spatial distributions would not capture the agronomic interactions among plants within their agroecosystem. Nor would these distinguish monoculture from crop mixtures. Most public data are based on the primary crop grown and the complexity of the analysis increases exponentially with each additional crop in the field. In large-scale datasets, even classifying intercropping and rotations in a scientifically rigorous way poses challenges. An example is reported in Plourde et al. (2013), who used remotely sensed land cover layers to examine rotation practices in the Central USA. They concluded that despite the complex sequences of cropping patterns, in that region, major crops have moved toward monoculture cropping in the past decade. The appropriate counterfactual is required, as in the case of studies that estimated the effects of the Green Revolution on land use and production (above).

A 1994 study by Reynolds sheds light, however, on one assumption of the Green Revolution regarding monoculture. In fact, high-yielding wheat lines of the Green Revolution appeared to be less sensitive to interplant competition (from the same or another crop species) than the lower-yielding lines. Contrary to widely held perceptions, the yield progress of CIMMYT lines seemed to be associated with a “communal trait,” defined as a relative lack of response to the removal of neighboring plants. Reynolds et al. (1998) cite a similar study by Duvick (1992), on maize hybrids.

Crops compete not only for land and water, but for investments in research and value chain development. Kahane et al. (2015) spell out the range of benefits of “neglected and underutilized” crop species for health and nutrition, environmental sustainability and prosperity of human populations. Many have a lot of genetic variability because they have not yet been intensively bred or studied by research institutions. Kahane et al. (2015) rename these crops

“development opportunity crops,” also highlighting the agronomic and economic synergies of growing minor alongside major crops. Just how to invest in these crops to conserve their diversity while enhancing their commercial value in a way to exploits these synergies is a key question.

D) Does modern plant breeding for productivity gain in major staples lead to loss of infra-specific diversity on farms?

The concern for erosion of crop infra-specific diversity, and thus the capacity of food production systems to response to unforeseen changes, is now long-lived. Numerous papers have been written on this topic, including Harlan (1975), NRC 1972, Shiva (1993), and FAO’s State of the World’s Plant Genetic Resources for Food and Agriculture (1998), which was based on 154 country reports. In 2010, the second report of the State of the World’s Plant Genetic Resources for Food and Agriculture (2010) found that “it was not possible from the information provided in the country reports to make definitive statements about overall trends in on-farm diversity since 1996” (the first report). Further, while “it seems clear that diversity in farmers’ fields has decreased for some crops in certain areas and countries and the threats are certainly getting stronger,” ...“attempts to rigorously measure changes in crop genetic diversity in published literature have not yielded the expected evidence of erosion”(p.4). Nonetheless, the report summarizes a number of concerns for genetic erosion, uniformity, and vulnerability raised in the country reports and covering a range of crops that is not limited to the three major cereals.

As predicted by Jack Harlan (1972), we can surmise that modern varieties of the major cereal crops have largely replaced “the ancient patterns of diversity” in the fields of farmers. Both modern and traditional patterns of variation coexist, but on vastly different scales. On farms, in situ, the genetic diversity in landraces is distributed within local plant populations named and managed by farmers in their fields. In modern varieties, genetic diversity is distributed spatially and temporally across a crop-producing area, allocated among more than within varieties. A “domesticated” form of diversity is found within agricultural landscapes, and is complemented in situ by wild and weedy relatives found are distributed in natural systems, and often on the edges or interspersed in farming systems. Ex situ, diversity in all three of these types is found in the working collections of plant breeders and housed in gene banks. Genetic diversity can be generated through ex situ plant breeding or on-farm, participatory plant breeding; it can also be accessed with genotyping and marker-assisted selection (McCouch et al. 2012).

But has the breeding and diffusion of modern varieties resulted in genetic narrowing? In fact, the timing and cause of genetic narrowing in the major cereal crops is a matter of historical and scientific perspective. Modern cereal cultivars have developed through three main phases of selection: (1) subconscious selection by the earlier food growers in the process of harvesting and planting; (2) deliberate selection among variable materials by farmers living in settlements and communities; (3) purposeful selection by professional breeders using scientific methods. The last two phases continue simultaneously (and interactively, as in the case of “creolized” varieties) today. Though it is clear that the patterns of genetic variation in farmers’ fields have changed over time, the hypothesis that the spread of modern varieties caused genetic erosion cannot be tested because it “goes beyond our knowledge of the facts of genetic erosion” (Wood and Lenné 1997; Smale 1997).

Further, there are a number of studies that do not support the pessimistic viewpoint that the genetic base of modern varieties is restricted and tends to narrow (Witcombe, 1999). For example, nearly 90% of the modern varieties grown in farmers’ fields in 1997 (excluding China) are CIMMYT-related, meaning that they are CIMMYT crosses or selections from CIMMYT crosses released as varieties, or they have proximate or more distant CIMMYT ancestors in their pedigrees. CIMMYT-relatedness does not imply uniformity, however, since these lines are a vast array of germplasm constituted by genetic recombination of different sources of materials from throughout the wheat growing world. Genealogical analysis shows: (1) a significant positive trend in the number of distinct landrace ancestors in the pedigrees of over one thousand varieties of spring bread wheat released by national agricultural research systems in the developing world since 1966; and (2) a significantly higher number of different landrace ancestors among releases that are

CIMMYT-related vs. those with no known CIMMYT ancestry (Smale 2002). Numbers of landraces in and of themselves do not constitute diversity since their genetic contribution is likely to be small. In modern breeding programs like those of rice, wheat and maize, landraces are typically (but not always) distant ancestors. Rather, these numbers demonstrate conclusively that germplasm with different genetic backgrounds is continually brought into the crossing blocks of CIMMYT and national program collaborators through an international research system. Though the numbers are smaller for rice than for wheat, Gollin and Evenson's findings (1997) demonstrate a similar breadth of genetic backgrounds.

Cumulated scientific evidence presents a strong case that while the molecular genetic diversity and genealogical diversity of CIMMYT wheats was maintained or increased from 1965 to the turn of the century, their performance with respect to yield stability, nitrogen use efficiency, genetic resistance to disease, and tolerance to heat and drought has improved (summarized in Smale et al. 2002). The genetic diversity in CIMMYT lines represents a lower bound on the diversity of the wheat germplasm currently available in national programs since national breeders cross them with their own material.

More recently, with updated tools, Warburton et al. (2006) examined the genetic diversity of wheat materials including the synthetic wheats derived from wild species with molecular markers, finding that the latest materials were not significantly different from landraces in terms of genetic distances from other landraces. Xia et al. (2005) assayed the genetic diversity of CIMMYT maize lines with simple sequence repeat markers, and found that these originated from 35 mostly broad-based populations and pools with mixed origins. There was no clear evidence of clustering, and the mixed composition of subtropical, tropical midaltitude and highland maize populations and pools indicated that large amounts of variation had been incorporated into CIMMYT germplasm.

Independent of the CGIAR, and more recently, van de Wouw et al. (2010) conducted a meta-analysis of 44 published studies on genetic diversity trends in crop cultivars released in the last century using molecular methods. They found no clear trends, over eight field crops, including rice, maize and wheat. They observed a drop in the 1960s compared to the 1950s, and thereafter a recovery in the diversity found among released varieties. Excluding wheat, which was the most heavily represented crop among the studies, did not change the findings.

While the research cited above suggests that scientists have worked to counter genetic narrowing in staple foodcrops within their improvement programs, there is still concern that the portfolio of varieties grown by farmers may be genetically uniform or susceptible because few are cultivated relative to those released and those that are cultivated are old. The greater genetic diversity among released varieties has the potential to generate strong on farm benefits but if few are grown and few are replaced over time that potential impact is could be negligible.

For example, the State of the World's Plant Genetic Resources for Agriculture (2010) found that as in the case of wheat, maize represents a rare instance of improved genetic diversity and allelic richness in varieties released that are based on CIMMYT germplasm. However, most individual countries reported the loss of older varieties and landraces from the farming system. The document states that all teosinte populations are now threatened. Other country reports raised concerns about the uniformity of rice varieties in farmers' fields, loss of specific rice landraces, and extinction of wild species in the primary genepool due to unfavorable climate conditions, variety replacement and habitat loss. Further, data compiled throughout Sub-Saharan Africa, covering numerous CG crops, illustrated the old age of most varieties grown by farmers (Walker and Alwang 2015). Spielman and Smale (2017) explore the issue of turnover of modern varieties, noting that even in developing countries where seed markets are commercially active, policy and research emphasis is often placed on the adoption of improved varieties rather than their replacement by newer, better performing varieties (such as those with enhanced tolerance to biotic and abiotic stresses). They suggested a sequence of policy reforms and investments to speed varietal turnover.

What is the evidence concerning the diversity of crop landraces on farms? Other than country studies of the second report of the State of the World's Plant Genetic Resources for Agriculture (2010), we found one in-depth study with global implications. A study by Jarvis et al. (2008) exploited detailed data from several years of on-farm research in

eight countries (Mexico, Morocco, Hungary, Nepal, Peru, Burkina Faso, Ethiopia and Vietnam) and 27 crop species. The authors examined the spatial diversity of farmer-recognized “units of diversity” (taxonomic groups, named varieties, or morphotypes) with ecological indices of spatial diversity—richness, which measures the density of the diversity unit per unit of area, and evenness, which accounts for relative abundance. Considerable diversity of farmers’ traditional varieties was encountered on individual farms and particularly at the scale of the community. They observed that genetic diversity units of major staples had higher richness and evenness than nonstaples, and that richness for clonal species was much higher than that of other breeding systems. In some cases, they found that much of variety richness was held at low frequencies in communities, suggesting that these are maintained as insurance; in other cases, a more even frequency distribution of varieties was found, implying that farmers select these to meet a range of current needs. Jarvis et al. (2008) also conclude that a major force in maintaining crop genetic diversity of traditional varieties on farms is a large number of small farms “adopting distinctly diverse varietal strategies.” In other words, this implies a high density of farms with heterogeneous variety objectives.

4. HYPOTHESIS II: RAISING THE PRODUCTIVITY OF STAPLE FOOD CROPS REDUCES DIETARY DIVERSITY

A) The problem

Malnutrition represents the number one risk factor in the global burden of disease, affecting over one in three persons (GLOPAN 2016). Paradoxically, undernutrition persists in many regions alongside micronutrient deficiency and new trends in obesity—a situation often referred to as the “triple burden” of malnutrition (Gómez et al. 2013). Poor diet is also a primary cause of non-communicable disease. A global review by (Imamura et al. 2015) shows that while consumption of healthy foods rose and that of unhealthy foods declined in higher income countries between 1990 and 2010, the opposite appears to have been the case in some lower income countries of Africa and Asia.

Rising incomes and urbanization drive diet transformation in agricultural economies with lower incomes (Haggblade et al. 2016). Burgeoning urban populations demand larger marketed food shares from farmers, creating longer supply chains that include storage, processing, and packaging. Rising incomes lead to shifts in urban and rural consumption out of starchy staples (maize, millets, sorghum, roots, tubers, pulses) toward more perishable foods, such as meat and dairy products, fresh fruits and vegetables. Both rural and urban consumers eat more processed foods and foods prepared outside the home in restaurants, fast-food outlets and in street stalls. This pattern is visible worldwide (e.g. Popkin and Reardon 2018, Tshirley et al. 2015), where over time, diets have also become increasingly homogeneous (Khoury et al. 2016).

Can improving staple crop productivity contribute to “bending the curve” toward than away from better diets as incomes rise? Pingali (2015) argues that there is a “growing disconnect” between the “staple grain fundamentalism” of the Green Revolution and the actual amounts of cereals demanded in human food consumption. There is continuing debate over whether the global food supply of major cereals (maize, wheat, rice) is adequate or not. Since Sen’s discourse on entitlements, some have argued that the fundamental cause of food security is inequality in access to food rather than supply. While policies promoting cereals production to ensure caloric availability have been generally successful, today’s food security challenges involve nutrient balance. Pingali (2015) reports that excess cereals supplies (amounting to close to 1.3 billion tons in 2010) are diverted to feed, industrial uses, and stocks. Depending on the stage of structural transformation, consumers demand smaller shares of cereals directly as food and increasing shares of meat, dairy, animal products, vegetable oils and sugars.

Next, we summarize the empirical findings regarding the linkages suggested in Figure 1.

B) Does plant breeding to raise yields affect dietary diversity?

The broadest base of evidence on the linkages between staple crop productivity and nutrition is through the income effect, but much of this evidence seems to remain inconclusive due to methodological concerns. In Tanzania, for the agricultural sector as a whole, growth has not translated to significant improvements in nutrition outcomes “at large” (Ecker et al. 2011). Masset et al. (2012) reported limited effects of agricultural interventions aimed at improving child nutrition in their review, citing methodological weaknesses. Similarly, Ruel and Alderman (2013) found that while the need to raise incomes and reduce prices by boosting agricultural production was indisputable, the evidence supporting the nutritional effects of agricultural programs was inconclusive in part due to the poor quality of evaluations. Webb and Kennedy (2014) reviewed 10 studies conducted from 2000 to establish agriculture-nutrition linkages, concurring that, regardless of differences in approach and methods, empirical evidence demonstrating the “plausible and significant” impacts of agricultural interventions on nutrition outcomes remained “scarce.”

Specifically, “although there is clear evidence that investment in agricultural technologies has, on average, improved yields, increased caloric consumption, and/or increased incomes, there is still confusion about the mechanisms through which agriculture can enhance nutritional status” (Webb and Kennedy 2014:131). Part of this they attribute to ambiguity in how nutrition is defined and measured, suggesting that core metrics for measuring short- to longer-term effects of agriculture on nutritional status need to be identified and tested. Carletto et al. (2015) report other reviews that cast similar doubts, including studies of programs aimed at promoting nutrient-rich crops.

Stepping back to the pathway from staple food productivity to income, after reviewing the literature and conducting their own analysis of data from Ethiopia and Uganda, Alwang et al. (in press) conclude that “direct, short-term impacts of increased productivity to increased income may be limited in magnitude”—in part because of partial adoption and in part because of land scarcity. They suggest that indirect impacts on income through other pathways, such as labor productivity or resource use, may be substantial but are more difficult to measure. In studies by Dillon et al. (2015) and Kumar et al. (2015) find that income has a smaller effect on dietary diversity than crop production diversity in Nigeria and Zambia, respectively.

Some policy documents appear to assume that crop diversification contributes to household income security and employment through the potential to produce higher value products (e.g., FAO 2012). Yet, as seen in Figure 1, these relationships are not at all direct. Using a panel data set from Ethiopia, Michler and Josephson (2017) show that households growing a diverse set of crops are less likely to be poor than those who specialize. Crop diversity reduces the changes that a non-poor household will fall into poverty, as well as the chances that a poor household will remain in poverty. Also in Ethiopia, a regional study by Taffesse, Dorosh & Asrat (2011) states that despite considerable space for adoption of productivity-enhancing inputs in staple food production, growth in agricultural incomes will require diversification and a shift toward higher-value crops. Crop diversity in and of itself provides little policy information, however—unless we know more about the crop composition. Further, the direction of the relationship between crop diversification and farm income depends on the location of a producing region or country along the path of structural transformation toward commercialization. More diversified growers may be poorer in places where specialization is a viable economic strategy (Pingali and Rosegrant 1995).

Pellegrini and Tasciotti (2014) test the effects of crop diversification (the number of food crops grown) on crop income and two indicators of dietary diversity (food count and food group count, similar to HDDS) using data from national surveys that represent eight developing and transitional economies. All econometric results for countries considered together or separately demonstrate positive linkages.

Remans et al. (2014) conduct the second cross-country comparison we have found, finding that for low income countries, the diversity of agricultural goods produced is a strong predictor of the diversity of food supply. For middle and high income countries, national income and trade are better predictors. The household-level analogy is that for lower income households, production diversity plays a more important role than diversity introduced through market purchase. At higher incomes, the converse is true.

C) Does raising on-farm diversity enhance diet diversity?

Two recently published reviews examine the emerging evidence on the linkages between crop production diversity on farms, nutrition and diet diversity in lower- and middle-income countries. Jones (2017a) applies rigorous qualitative methods to 21 studies, while Sibhatu and Qaim (2018a) conduct an econometric meta-analysis of 45. Most studies used dietary diversity as an indicator of diet quality—an aspect that has been criticized since it provides little “downstream” evidence on anemia, child illness, other aspects of child malnutrition (Jones 2017a).

Further, most studies measure agrobiodiversity simply as counts of crops or crop groups; a study conducted in Malawi by Jones (2017a) explores effects on on-farm varietal diversity. A few analyzed by Sibhatu and Qaim (2018a) applied ecological indices of on-farm crop diversity (Shannon or Margalef, which control for relative abundance); the count is only a crude measure of richness. None of these includes the concept of genetic distance or dissimilarity.

Both reviewers conclude that the effect of on-farm crop diversity on dietary diversity is generally positive but small in magnitude. The econometric results of Sibhatu and Qaim (2018a), indicate that farms would have to produce 16 additional crop or livestock species to increase dietary diversity by one food group. A larger effect is observed in studies conducted in Sub-Saharan African than in Asia. Their evidence does not support the perspective that increasing farm production diversity would be an effective way to enhance dietary diversity. They assert that many of the 21 studies summarized by Jones (2017b) were reported as showing positive associations when in fact they demonstrated mixed and insignificant results.

Jones (2017a) reports a positive relationship between on-farm crop diversity and dietary diversity among individual household members in addition to households as whole. He also finds a threshold effect, or turning point, beyond which an additional crop species or group on the farm has no further effect on dietary diversity. Recognizing the distinction between subsistence farming vs. income-generated changes in dietary diversity, he emphasizes the lack of articulation of the market access relationship in the studies he reviewed. Variables such as numbers of nearby markets or market proximity do not reveal the diversity of foods available for purchase at affordable prices in local markets, or the nature of market participation by farm household members. Does the quality of local markets limit or expand the ability of households to diversify their diets through purchases, and how does this vary by context?

A set of interrelated studies conducted in different contexts (Lipper, Cavatassi and Winters 2012) explored the relationships between farmer participation in local markets, sustainable use of crop genetic resources, and household welfare, measured as food security and dietary diversity. Among pigeon pea growers in Kenya, participation in the output market had a positive and significant effect on food security, but no effect on dietary diversity (Asfaw et al. 2012). In Mali, Smale et al. (2012) found that purchasing millet grain in markets enhanced food security but reduced dietary diversity, suggesting that scarce cash was directed toward meeting staple food needs first. The greater the area planted to millet, the lower are both the food insecurity and dietary diversity scores. Food insecurity is reduced when more millet is available but, at the same time, there may be more dependence on millet in the diet. In minor millet production in India, impacts of market participation on either outcome generally were not significant, perhaps because the additional income was sufficient only to purchase more of the carbohydrate staples they already consume but not to buy other components, such as those that include protein and fat (Takeshima and Nagarajan 2012).

Sibhatu and Qaim (2018a) note that various studies showed strong relationships between a number of other factors, including but not limited to market access, and dietary diversity; in some cases, the coefficients on these factors were

larger than the coefficient on crop diversity. Lack of attention to seasonality, potential endogeneity and more robust causal influences were shortcomings of most studies they reviewed. In a study about integrating vegetables into the maize-based system of Tanzania, Rajendran et al. (2017) the study found that simply increasing Simpson's Index does not influence dietary diversity of farm households due to the presence of interaction effect between Simpson's Index and crop income. Revenue generated from diversifying crops and changes in other endowments are much more important.

Most studies reviewed by Jones (2017a) were conducted in Sub-Saharan Africa, and therefore that results may not be applicable to other regions. However, studies analyzed by Sibhatu and Qaim (2018a) included countries in southeastern Europe, the Americas, Asia and Sub-Saharan Africa. Compared to the qualitative study, the quantitative study enabled the estimation of mean effect sizes. Jones (2017a) is also concerned about the quality of research design in the studies he reviewed, most of which relied on cross-sectional data and did not fully analyze heterogeneity. Almost all examined outcomes only at the household scale. Remans et al. (2011) found no correlations between functional diversity, food and nutrition at the household scale of analysis, associations among these parameters were observed at the village scale.

At the other extreme, an analysis by Herrero et al. (2017) used spatially-explicit global datasets to estimate production of crops, livestock, aquaculture and fish products, converting these into key nutrients, calories and protein. They then estimated the relative contribution of farms of different sizes to production and to production diversity per geographic pixel using the Shannon index. They found that at the global level, although farm size and production diversity vary greatly across regions, both small and large farms have key roles in food and nutrition security.

Regression analysis of household data from Indonesia, Kenya, Ethiopia and Malawi Sibhatu, Krishna and Qaim (2015) demonstrates that market access has positive effects on dietary diversity that are greater than farm production diversity. As suggested by Jones (2017a), regression models show that when production diversity is already high, the association with dietary diversity becomes insignificant and possibly negative—which they explain as a consequence of income opportunities from specialization foregone. Sibhatu and Qaim (2018b) continue this analysis, showing that markets tend to be more important than on-farm diversity as determinants of dietary diversity when they are functioning properly and households have access to them. They argue that a policy promoting diversification on farm could “foster subsistence,” worsening the quality of diets. Instead, the “type of diversification should follow market incentives”(p. 57). Based on their analysis of food consumption among pre-school children on farms in Ethiopia, Hirvonen and Hoddinott (2017) concluded that the positive effects of production diversity on dietary diversity do not hold for households that have access to food markets. They argue for agricultural interventions that contribute crop diversification at a regional and national level, and deepening market integration in remote areas to enhance the availability of foods.

In Malawi, Jones et al. (2014) found a consistent negative association between the proportion of food consumed from on-farm production and household dietary diversity, also observing that households allocating a larger share of their cultivated land to market crops had both more diverse diets and more diverse farm production. In that land-scarce context, they explain that the option to earn income from a new crop may motivate production diversification with positive effects on diet diversity if the crop is also consumed in part. Also in Malawi, Koppmair et al (2016) concluded that reducing the walking time to the district market by one hour would have a larger positive effect on dietary diversity than producing one additional food group on the farm. In addition, the marginal effect of farm diversity disappears for the sub-sample-half that is closest to market.

Taking endogeneity into account, Bellon, Ntandou-Bouzitou and Caracciolo (2016) tested the interrelationships among on-farm diversity, market diversity and dietary diversity with a simultaneous equations system. Econometric results showed that on-farm and market diversities were positively related to the dietary diversity of mothers even when market opportunities, seasonality and other socio-economic factors were considered.

D) Does diversity of wild plants enhance dietary diversity?

In 34 studies conducted in areas with high biodiversity, Penafiel et al. (2011) found that local food biodiversity was shown to be an important contributor to nutritious diets, including energy intake, micronutrient intake, and dietary diversity. The authors included all edible plants and animals from wild and cultivated areas in their literature search. Powell et al. (2015) reviewed numerous studies on both wild and cultivated areas in Latin America, Asia and Sub-Saharan Africa, grouping them by home gardens, capture fisheries and aquaculture, wild foods, forests and tree-based systems.

According to Powell et al. (2015), contrary to assumptions, a large share of wild foods come from agricultural areas or around the homesteads in rural areas. The management of these species ranges from zero management to near domestication or “escaped” species which are cultivated under some circumstances. Important for dietary diversity is that the source, type and relative share of wild foods in the diet varies greatly from one social and ecological context to another. They are abundant in some contexts and scarce in others. Wild foods make up a significant portion of diets in some studies, and are often described as having low energy contributions but significant contributions of micronutrients. In some countries almost all vegetables consumed are wild (Vietnam) and in other locations these are absent (Amerindians). Bushmeat and insects are also reported in a number of studies. A major constraint on this information is lack of data on nutrient composition of wild foods. Some studies have shown that adding wild foods to the consumption basket several times per week can reduce the costs of meeting nutrient adequacy. Powell et al. (2015) also recommend additional analysis of mediating factors for wild food consumption, such as market access.

Forested landscapes, tree cover and tree-based agricultural systems contribute to food security both directly through food and fodder and indirectly, through ecosystem services (Sunderland et al. 2013). Ickowitz et al. (2014) argue the need for a better understanding of the relationship between forests and human nutrition. They use survey and tree cover data for 21 African countries to test the associations among various parameters. They find a statistically significant positive relationship between tree cover and dietary diversity, particularly for fruit and vegetable consumption but not for animal source food consumption. Powell et al. (2015) conclude that although existing studies “report relationships between dietary intake and tree cover, the pathways...remain a ‘black box.’ (p. 545). They suggest that while forests may provide income sources, communities living closest to forests tend to have lower incomes. Broegaard et al. (2017) examined the role of agriculture-forest landscapes in the provision of wild food in the communities undergoing rapid land use transformation in northern Laos. They found that wild food contributed less to human diets in areas where pressure on land from commercial agriculture and conservation was more intensive, with implications for protein deficiency. Thus, approaches need to consider not only commercial agriculture but also biodiversity conservation programs that change how rural people collect wild foods.

Delvaux, Gomez and Paloma (2018) explore utilization of common pool resources by rural households in Nigeria using a nationally representative dataset. They find that access to common pasture and water resources is significantly associated with less reporting of food insecurity, but that access to forests is associated with food insecurity—perhaps because these households are more isolated and vulnerable. As income rises, the relative importance of these resources diminishes. There is no clear indication that they serve as seasonal safety nets.

Gender and intrahousehold aspects are mentioned or formally tested only rarely in this literature, although these are a primary motivation for the work on dietary diversity and also many of the indices used to measure it. Out of the 45 studies reviewed by Sibhatu and Qaim (2018a), only 9 examined effects on women’s diets and nutrition. Of these, two reported positive findings and for seven of them, results were mixed. Mixed results suggest that intrahousehold negotiations may affect access to production resources or decisions over use or marketing of the harvested production. Differential access to off-farm income sources may also play a role—but in these reduced-form models, pathways are unclear. The study by Jones et al. (2015) in Malawi reports a stronger relationship between on-farm crop diversity and dietary diversity among female-headed households compared to male-headed households.

A study by Nyantakyi-Frimpong (2017), based on five years of repeated fieldwork in northern Ghana, suggests that dietary diversity scores are most affected by rights to land and food resources as these are mediated through the type of

headship (male-female, de facto or de jure), seniority and status. Because of unequal access to production resources between men and women, farm production diversity might not be the best strategy for improving the dietary diversity of women and their children.

5. CONCLUSIONS

In this background paper, we have sketched some of the main pathways from agricultural research to improve staple food crop productivity through agrobiodiversity to diet diversity on small-scale, household farms that operate without fully developed markets. We have sought to assemble evidence on linkages and trade-offs from meta-analyses, reviews and case studies presented in the literature. Our definition of agrobiodiversity is drawn from the CBD as adapted by FAO, and we refer to various well-researched metrics of agrobiodiversity and to diet diversity as an indicator of well-being and nutritional adequacy (Annexes).

In operational terms, agrobiodiversity is a permeable rather than a bounded subset of biodiversity. By definition, because land is limited, there is a trade-off between promoting biodiversity conservation and promoting agricultural commodities. Where we are situated and chose to operate, however, could be within the production possibilities frontier that expresses this trade-off, where we can make win-win choices.

For this reason, we begin by summarizing some of the arguments and evidence concerning agricultural and land use patterns. The historical role of agricultural expansion and intensification in changing land use patterns and contributing to species loss seems widely accepted. Yet, we find no clear evidence that historically, raising the yields of rice, wheat and maize has diminished the availability of land for other crops or uses. In recent times, commodity crops such as oil palm and soybean seem to have played a greater role in deforestation, in response to market incentives for products with high income elasticity of demand rather than technological impetus in the staple food crops. Recent studies that model the counterfactual more fully conclude that the Green Revolution was land-sparing or land-neutral, at least in its locus of South Asia and probably in other regions. However, they do not depict the same process for Sub-Saharan Africa's future Green Revolution.

With respect to the effects of breeding for productivity in staple food crops and inter-crop diversity, we find few clear links in the literature. Again, the changing composition of crops grown away from coarse cereals, legumes and root crops is related to fertilizer response and profitability; sorghum and millet persist in marginal production zones. A study conducted in Punjab of Pakistan finds no change in the concentration of area in wheat; another conducted in Haryana State of India shows substitution of rice and wheat for other crops. There is a lot of detail and debate about what is “good” crop composition in the biological literature, which we do not cover here. Here, we cite a number of micro-economics case studies confirming input complementarity, economies of scope, and reduction in yield variability through crop diversification. We wonder how such prescriptions can be applied at larger scales, and what they would mean for policy. Even in fully developed markets, crop diversification occurs because of agroecological diversification that affects input-output relationships in farm production. Should policies promote species diversification (crop, livestock, tree) on farms? If so, how and at what cost in terms of opportunities foregone? Bowman and Zilberman (2013) explore the economic determinants of diversified farming systems (DFS), as proposed by Chambers and Conway (1991), which includes the concept of functional biodiversity at multiple temporal and spatial scales. In addition to the importance of managing risks on farms, they describe the role of niche and specialty markets, and policies and regulations, in supporting or discouraging diversification.

We concur with the predictions of Jack Harlan (1972) and others that the “ancient patterns of diversity” have been displaced in the fields of farmers. Yes, infra-specific diversity as it was known in 1950 is not observable today—and thus, we are missing the counterfactual data. We find encouraging evidence that since the narrowing of genetic diversity of the 1960s, genetic diversity of major food crops has actually expanded in recent decades—in part due to new breeding techniques, such as synthetic hexaploids that re-enact the evolutionary, naturally-occurring cross of tetraploid wheat with a diploid wild grass ancestor. In parallel, we cite a meta-analysis of studies on the richness and evenness of landrace (farmer-managed units of diversity) in numerous countries and species. That said, the evidence suggests we do need to be concerned about how best to distribute the conservation of cultivated and wild plant species in situ and ex situ, which of the taxa should be collected immediately for ex situ storage because of threatened habitat, and to what extent we can promote complementarity between in situ and ex situ conservation through markets and other means.

There is no clear evidence that agricultural research to improve the productivity of staple food crops, as it is conducted today, reduces agrobiodiversity; on the other hand, there is no evidence that it promotes it. The crucial importance of breeding to maintain or increase yield potential held constant, given the evidence on diminishing rates of yield grown in the three major grains, would it not make sense to re-allocate research investments to some “development opportunity crops” that are complementary to these in agronomic and economic terms?

Linking staple food crop productivity to changes in dietary diversity is challenging given the multiple and complex pathways. First, we cite the evidence that as incomes rise, even in lower income countries, diets are shifting away from consumption of the three major world cereals directly as food toward other food groups, including meat. Diets are also increasingly homogeneous, on a global scale. We note the argument that major cereals are currently oversupplied on a global scale and diverted to other uses, such as feed, biofuels and stocks. Against a backdrop of the triple burden of malnutrition, some question the “staple food fundamentalism” that still emphasizes caloric availability rather than nutrients. Rather than supply keeping up with demand, will demand keep pace with supply? Should livestock diets be diversified?

While there is ample evidence that in the aggregate, raising agricultural productivity is associated with better nutrition, there is less evidence about how this occurs and even less to confirm that agricultural programs designed to enhance nutrition have been effective. We found several country-level and cross-country comparisons that show positive linkages between crop diversity, income, and diversity of foods supplied or consumed in low-income countries. In higher income countries, trade plays a larger role in the diversity of consumption.

Several meta-analyses review numerous studies relating the diversity of crops grown on small-scale farms to the diet diversity of households that operate them. Most point to the relatively small size of the effects of on-farm crop diversity on household diet diversity, although at least one study finds an important relationship between plant species diversity at the village scale and diet diversity of household. Most call for better analysis of the role of markets, expressing concern over any policies to encourage crop diversity on farms as a means of enhancing diets. We cite several reviews of studies about the role of species in wild areas and forests, outside of the farm, in overall nutrition. Quantification is more difficult in most of these, since nutrient composition may not be known.

ANNEX. COMMENTS ON METRICS

1. Metrics of agrobiodiversity

Recent efforts by scientists at Bioversity International have led to the development of an Agrobiodiversity Index that spans the food system. Sthapit et al. (2017) propose: “three scientific foundations to measure agrobiodiversity index for each food sub system. They are: i) contributing to safe and healthy diets, ii) contributing to sustainable production, and iii) contributing to plant breeding and healthy seed systems and conservation options for ensuring sustainable food systems globally. The three key dimensions /components of sustainable food systems are outlined below. 1. Agrobiodiversity in consumption and market systems includes diversity in diets and diversity in the markets contributing to healthy diets. 2. Agrobiodiversity in production systems includes diverse species, cultivars and functional traits in the production at farm, landscape and ecosystem, which contribute to sustainable agriculture. 3. Agrobiodiversity in genetic resource management systems includes diversity in conservation in genebanks and in-situ/on-farm contributing to current and future options of biological diversity available for conservation. The key agrobiodiversity (ABD) index related indicators are outlined for each of the food subsystems. For market and consumption, the key indicators are food group diversity available in the market and used in diet. Species and varietal diversity are key indicators for ABD in production system. Similarly, access to species and varietal diversity in seed system and % area under specific crop varieties on-farm are potential indicators for genetic resource management systems. They can be applied across number of food system components as mentioned above in providing novel insights on measuring and monitoring on each of the food system components and interactions among components. These indicators in each dimension will help to measure how diversity is changing over time.” (p. 172). It may be possible to improve upon some of the indicators (e.g., ecological indicators of spatial evenness and richness for 2 and 3 when analyzing data from farmers’ fields); indicators of genetic distance or dissimilarity in 3, where molecular data may be available). More importantly, however, they point out that their index is applicable, comprehensible, and operates at multiple scales, as is needed for policy.

2. Metrics of dietary diversity

While there is no universal index of diet quality, there is some agreement on what a healthy or non-healthy diet would include: a diversity of foods with energy levels appropriate for age, sex, and disease status and physical activity; essential micronutrients; and limited intake of free sugars and salt, sugary snacks and beverages, and processed meat (GLOPAN 2016). Dietary diversity metrics are important for empirical research not only because of whether they are validated or not but because of what is or is not included.

Dietary diversity is used as a broad measure of food security and nutrition adequacy. More diverse diets are positively correlated with greater energy and macro and micronutrient intakes, and more favorable anthropometric measures in adults and children (Arimond et al., 2010; Steyn et al., 2006). Diets consisting of a limited number of food items, especially starchy staples, can lack the macro and micronutrient adequacy despite meeting calorie requirements.

A substantial literature has been developed and applied to measure diet diversity. The Household Dietary Diversity Score (HDDS) and Individual Dietary Diversity Score (IDDS) have been employed as indicators of diet quality. The first represents a snapshot of the economic ability of a household to access a variety of foods (Kennedy, Ballard and Dop 2013) or energy availability (Leroy et al. 2015); the Individual Dietary Diversity (IDD) score distinguishes among household members. Minimum Dietary Diversity for Women (MDD-W) is a more recently developed indicator of micronutrient adequacy for women of reproductive age (Martin-Prével et al. 2015). Many other indicators have been proposed. Recently, for example, Cockx and Weerdt (2016) employed the Berry index (1975), which is related to the Herfindahl index of market structure, and expresses the concentration or “inequality” of consumption among food categories. Other outcomes, such as shares of certain categories of food purchased (sweets and sodas) or consumed outside the home, serve as indicators of potentially unhealthy effects (Smight and Subandoro 2007).

As a proxy for diet quality, dietary diversity is a summary index conceived in large part to reduce the burden on survey respondents brought about by other forms of time-consuming, anthropometric measurement. Although associations with other indicators may be strong, like any other summary, it masks important variables in nutrient intake. Remans et al. (2011) provided novel metrics to test the relationship between the diversity of agricultural species in a landscape and human nutrition using the ecological concept of functional diversity, which relates to the diversity of functional traits. They found that adding or removing individual species can have “radically different” outcomes for nutritional diversity, and that associations between functional diversity, food and nutrition indicators were significant at the village scale but not at the household level.

In a later, macro-analysis, Remans et al. (2014) proposed a Shannon index for species diversity among food items, a modified functional attribute diversity score, and the percent of energy coming from foods that were neither grains nor tubers (starchy staples). Their analysis provided unique insights. For example, countries in West Africa showed high Shannon species diversity of food items produced, although most of these items, which are staples (rice, maize, sorghum, plantain), tended to be similar in nutrient composition, resulting in low functional diversity and a high percent of energy coming from staples. Taken together, these three metrics provide a more comprehensive view of nutritional diversity than any single metric. Lachat et al. (2017) propose diet species richness, or a count of the number of species consumed per day, to assess nutritional adequacy and food biodiversity of diets. They recommend reporting the number of species consumed during dietary assessment since this measure cuts across the dimensions of human and environmental health. Their analysis revealed a positive association of food species richness with dietary quality in both the wet and dry seasons among vulnerable populations in areas with high biodiversity.

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