



Closing Research Investment Gaps for a Global Food Transformation

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Recent calls for a global food transformation have centered on simultaneously improving human and environmental health, recognizing that food and nutrient diversity have declined over time while food systems have exacted a heavy climate and ecological toll. Grain legumes and coarse grain crops provide important human nutrition and environmental benefits, but the production and consumption of many of these crops remains relatively low compared to major commodities, such as maize, wheat, rice, and soy. Outstanding hurdles to scaling up these “minor commodity” crops include (among other things) their relatively lower yields, and lower farmer adoption, based partly on actual or perceived profitability and marketability. We hypothesize that these limitations are attributable in part to unequal funding for these crops’ research and development (R&D) both on a national and global scale. In the United States, we show that investment patterns for a snapshot of USDA-funded research grants from 2008 to 2019 consistently favor major commodity crops, which received 3 to 4.5 times more funding and 3 to 5 times as many grants than the minor commodity crop groups. This current USDA funding allocation poses a barrier to food system transformations. Achieving nutritious diets for planetary health requires more public agricultural investment toward minor commodity crops and increased collaboration between public health, nutrition, agriculture, and environmental sectors.

Keywords: investment, research, orphan crops, commodities, legumes, coarse grains, USDA

TWENTIETH CENTURY AGRICULTURAL DEVELOPMENT AND CURRENT TRENDS

Global agricultural production was transformed by twentieth century technologies. In the United States, research and development (R&D) funding was structured to boost productivity of a select few cereal crops, and these trends carried over to impact production in other countries as well (due in part to globalization/global politics) (Cullather, 2013). Notable developments during this period included high-yielding seed varieties and the industrial production of synthetic, nitrogenous fertilizers and other inputs—technologies that catalyzed unprecedented calorie production per acre (Evenson and Gollin, 2003). These technological changes nearly tripled crop yields (Pingali, 2012; Gordon et al., 2017), and as adoption increased, native seed and crop varieties were increasingly phased out from crop rotations (DeFries et al., 2015).

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Shifting agricultural focus toward higher yields, net farm returns, and access to global markets has encouraged more homogenous cropping systems (Welch and Graham, 2000) centered around a select few major commodity crops, namely maize, wheat, rice and later soybean (Eiselen and Webb, 2009). The percentage of global cereal area occupied by maize, wheat, and rice rose from 66 to 79% between 1961 and 2013, while land area devoted to barley, oats, rye, millet, and sorghum (all minor commodity grains) declined from 33 to 19% (DeFries et al., 2015). A diverse variety of minor commodity legumes and vegetables were also supplanted by shifts in the production landscape. India's post-colonial agricultural development, for example, was primarily characterized by the wide expansion of rice and wheat production, thereby decreasing the prevalence and diversity of coarse grains and pulses (Davis et al., 2019). Within the Philippines, farmers' adoption of intensive rice cultivation displaced a variety of nutrient-dense, leafy green vegetables (Cagauan, 1995). In the United States, major commodities were already planted over large areas by the 1960's, but their production increased over the next five decades (Figure 1A), far exceeding that of minor commodities, such as grain legumes and coarse grains (Figure 1A, see Table 1 for included crop species).

These developments have led to a substantial decrease in total crop diversity in the global food supply (Khoury et al., 2014). Despite the 7000+ plant species that have been cultivated for food production over the course of human history, 66% of total crop production in 2018 was accounted for by just nine crop species (FAO, 2019). In this analysis, we explore how these trends are underscored in part by systematic disparities in research funding for major and minor crop groups.

IMPACT OF CURRENT AGRICULTURAL SYSTEMS ON HUMAN HEALTH AND THE ENVIRONMENT

Despite successfully increasing yields, global agriculture's increased crop homogeneity, both in species and variety, has nevertheless impacted the health of both humans and the environment (Weis, 2007; Pingali, 2012; Gordon et al., 2017). While production and consumption patterns vary among countries, the current agricultural landscape has serviced higher intakes of refined grains, starches, and carbohydrates; vegetable oils; and meat (Kearney, 2010; Popkin et al., 2012; Tilman and Clark, 2014). Twentieth century gains in public health due to increased calorie availability have thus been partly offset by shifts toward unhealthy diets that lack nutritional diversity [Remans et al., 2014; Research Institute (IFPRI), 2017]. Furthermore, rates of chronic non-communicable diet-related diseases, including coronary heart disease, stroke, and type 2 diabetes, continue to rise (Hu, 2011; Zhou et al., 2016; Willett et al., 2019).

Mounting evidence shows that modern agriculture is also a major driver of global environmental change (Stevenson et al., 2013; Campbell et al., 2017). Agriculture and related land use, combined with post-production food system activities, are responsible for 21–37% or more of total net anthropogenic GHG emissions (IPCC, 2019; Clark et al., 2020; Tubiello et al.,

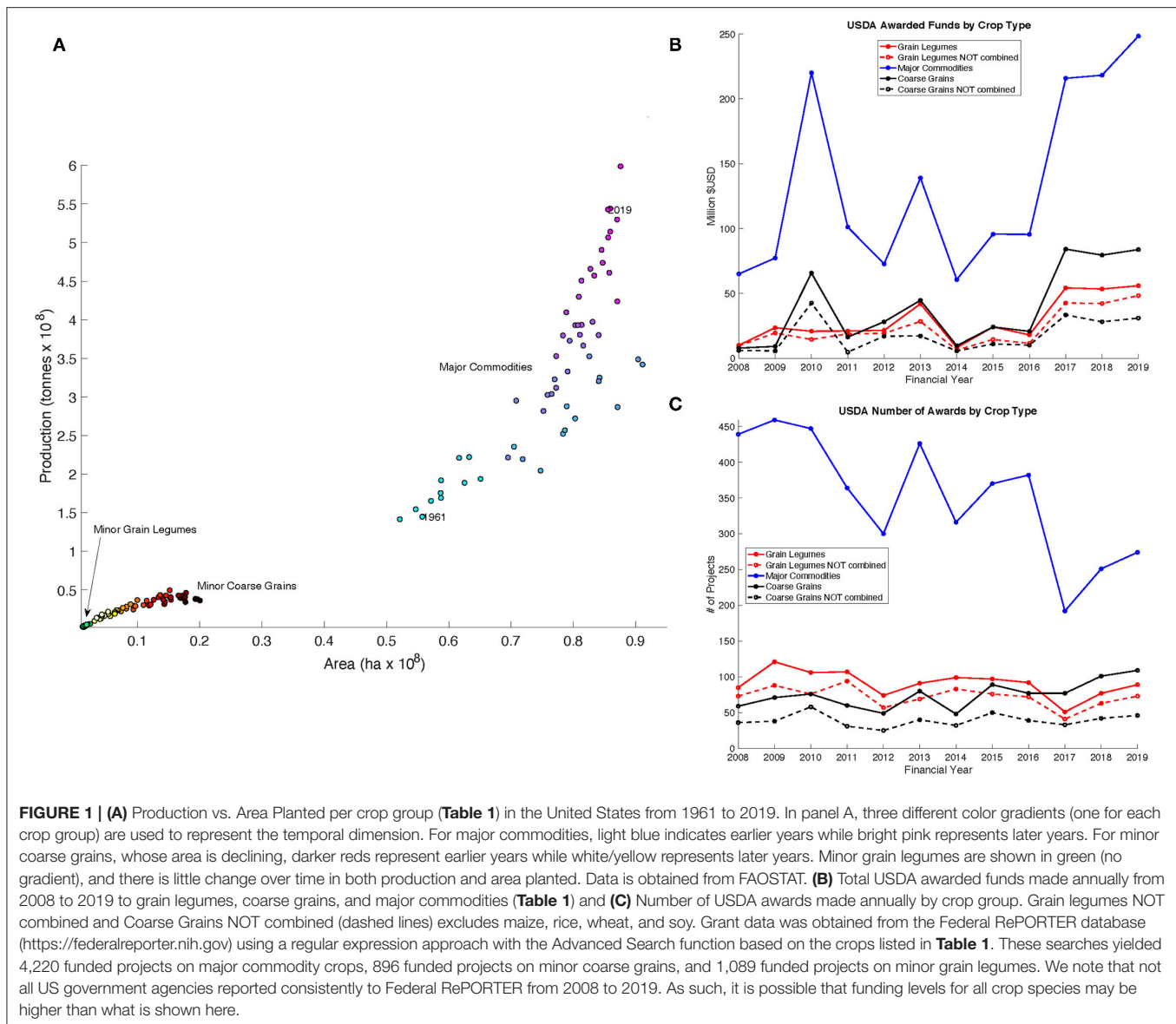
2021). Additionally, agriculturally-driven land use and land cover change, resulting partly from expanding a few major commodities, is a leading driver of nutrient pollution, habitat loss and degradation, and biodiversity loss (Campbell et al., 2017; Tilman et al., 2017; Henry et al., 2019).

NEEDS FOR A “GREAT FOOD TRANSFORMATION”

Addressing human and environmental health consequences of industrial agriculture demands agroecosystems that prioritize multiple goals inclusive of food and nutrition security, environmental and biodiversity protection, and improved ecosystem services (Cassidy et al., 2013; IPCC, 2019; Willett et al., 2019). In early 2019, the EAT-Lancet Commission, a coalition of 37 scientists studying the intersection of nutrition and agriculture, called for a global food transformation that supports human health and the environment simultaneously and sustainably into the future: a “diet for planetary health” (Willett et al., 2019).

Key to achieving these goals is the increased diversification of cropping systems as well as the consumption of a greater variety of plant-based foods in nutritious diets (Willett et al., 2019). Minor commodity legumes and coarse grains (e.g., Table 1) are generally much more nutrient dense than the dominant major commodity varieties, particularly after processing by industrial methods (Meng et al., 2005; Ortiz-Monasterio et al., 2007). Legumes (e.g., lentil, peas and cowpeas) contain approximately three times more zinc, five times more iron and magnesium, and six times more calcium than maize, wheat, and rice (Longvah et al., 2017). Other coarse grains (e.g., sorghum, millet, and barley) also have similar, higher micro-nutrient values (Longvah et al., 2017). There also exist thousands of varieties (traditional and wild) of maize, rice, and wheat, with potential to provide both higher nutrient content and adaptation to local growing conditions (Mammadov et al., 2018). However, cultivation of these varieties has also declined with the advent of higher-yielding crops (Hellin et al., 2014; Eliazar-Nelson et al., 2019; Rathna Priya et al., 2019).

Expanding minor commodity grain legume and coarse grain production also aligns with climate change adaptation and mitigation goals (Foyer et al., 2016; Tamburini et al., 2020). Many species of grain legumes and coarse grains display natural propensities for drought and heat tolerance, conditions that occur frequently in sub-tropical and semi-arid regions, where some nations are experiencing disproportionate food insecurity and climate change impacts (Cagauan, 1995; Foyer et al., 2016; Cullis and Kunert, 2017). Furthermore, these crops' relatively low water demand also facilitates conserving increasingly limited water resources (Cagauan, 1995; Davis et al., 2018; Clark et al., 2019). While their efficacy can vary regionally (Palm et al., 2001), grain legumes (e.g., see Table 1) in particular may also reduce nitrous oxide emissions and nutrient runoff (Piotrowska-Dlugosz and Wilczewski, 2012; Xie et al., 2016). Moreover, these same characteristics, particularly if further improved, can also contribute to climate change mitigation (Foyer et al., 2016).



Integrating grain legumes into conventional rotations of a single commodity crop (e.g., maize) may significantly increase soil carbon sequestration potential (Lal, 2010; Minasny et al., 2017; Stagnari et al., 2017) and, as a fresh food source, they also exhibit relatively low global warming potential (0.51 kg CO₂ eq kg⁻¹) compared to more commonly produced cereals (1.10 kg CO₂ eq kg⁻¹) across the lifecycle of their production (Clune et al., 2017).

However, while these minor commodity crop groups have many valuable characteristics, they are generally less productive than major commodity grains (Ramakrishna et al., 2000; Joshi and Rao, 2017), and farmers may lack effective management options, particularly related to pests, diseases, and weed pressure, specific to these crops (Siddique et al., 2012; Rubiales et al., 2015; Farooq et al., 2017). These production and adoption gaps

persist partly because these minor commodity crops have not been a focus of twentieth century R&D, and therefore have not received the same systematic support to boost productivity that major commodities have received. Indeed, some institutions are committed to the breeding and improvement of such crops, e.g., the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the International Center for Agricultural Research in the Dry Areas (ICARDA), and the Indian Institute of Pulses Research. However, particularly in industrialized countries like the United States, there remains a large gap in the current scale and coordination of R&D directed at these minor commodity crops compared to what major commodity crops receive (Tadele, 2019). To fully harness the potential of these minor commodity crops for improved planetary health, greater public investment into research dedicated to improving these

TABLE 1 | Crop group classifications, and yield and area harvested per crop in the United States.

Crop name	Crop group	2019 Yield (kg/ha)	2019 area harvested (ha)
Maize	Major Commodities	105,323	32,950,670
Rice	Major Commodities	83,735	1,000,390
Wheat	Major Commodities	34,748	15,039,090
Soy	Major Commodities	31,890	30,352,150
Sorghum	Minor Commodities—Coarse Grains	45,845	1,891,930
Barley	Minor Commodities—Coarse Grains	41,809	883,030
Oats	Minor Commodities—Coarse Grains	23,078	334,270
Rye	Minor Commodities—Coarse Grains	21,507	125,450
Millet	Minor Commodities—Coarse Grains	20,016	188,180
Peanuts	Minor Commodities—Grain Legumes	44,264	563,210
Peas, dry	Minor Commodities—Grain Legumes	23,809	425,730
Beans, dry	Minor Commodities—Grain Legumes	19,797	470,890
Chickpea	Minor Commodities—Grain Legumes	17,304	163,490
Lentil	Minor Commodities—Grain Legumes	14,012	174,420

Data obtained for the United States from FAOSTAT. We selected maize, wheat, soy, and rice as the major commodities as those have been identified as the top four commodity crops at a global level (Lobell et al., 2013).

crops, and their application to diversified cropping systems, is needed (Foyer et al., 2016; Stagnari et al., 2017).

CROP RESEARCH AND DEVELOPMENT INVESTMENT GAPS IN THE UNITED STATES

Agricultural R&D investment is a key means of improving crops and agricultural systems across a range of measures, including productivity, climate change resilience, and environmental impact (Pingali, 2012; Pardey et al., 2014). R&D investments, alongside other mechanisms such as subsidies and crop insurance, also play an important role in determining not only which crops and agricultural systems prevail, but also how those crops and systems change over time (Alston et al., 2011; DeLonge et al., 2016; Pimbert and Moeller, 2018; Biovision Foundation for Ecological Development IPES-Food, 2020). Public R&D funding, as opposed to private sector-driven research, is especially important because such investments can be directed to serve planetary health goals and the public good more broadly (Lehner and Rosenberg, 2018).

It has been well-established that agricultural R&D investments are economically beneficial by way of enhancing crop production via improved varieties, multifactor productivity, and pest/disease/weed resistance (Steenland, 2019; International Food Policy Research Institute, 2020; Baldos and Blaustein-Reito, 2021; Ortiz-Bobea et al., 2021). A large body of work exists to understand and quantify the role of (public) agricultural R&D in twentieth century crop improvements (Alston et al., 2000; Evenson, 2002; Baldos et al., 2018; Steenland, 2019), and it is now widely accepted that such investments were a primary

driver of these gains (Alston et al., 2000, 2009; Baldos et al., 2018; Steenland, 2019). Due to the close relationship between public R&D investment and crop productivity, there are calls to increase such investments across the world to improve food security outcomes (Andersen and Song, 2013; Baldos and Blaustein-Reito, 2021).

Despite proven payoffs, public agricultural research funding within the United States has declined in recent decades, and there is concern that these declining investments will reduce domestic productivity (Pardey et al., 2006, 2012; Clancy et al., 2016). Furthermore, critical areas needed for food system transformation are lacking in existing public investments. In particular, an analysis of United States Department of Agriculture (USDA) research investments and projects totaling nearly \$300 million discovered that <15% of total funding was distributed to projects that incorporated any element of agroecology, while the largest portion of funds was allocated toward projects aiming to boost crop productivity (DeLonge et al., 2016). A similar analysis showed how investments in “sustainable nutrition science”—research and education at the intersection of food production, climate and environment, and nutrition—reached only \$15.7 million between FY2016 and FY2019 (Reinhardt, 2021). Important areas of agricultural research, like diversified cropping systems, have not had an equal opportunity to reap the benefits that transpire from consistent governmental funding and support (Miles et al., 2017).

In our review of research funding between 2008 and 2019, minor commodity grain legumes and coarse grains (see Table 1 for included species) systematically received far less research funding from the USDA, both in the total dollars spent and in the number of grants funded, than the major commodity crop group (Figures 1B,C). Averaged over this decade, the major commodities received nearly quadruple the number of grants and 4.5 times more funding than the minor commodity grain legumes group and nearly 5 times as many grants and 3 times more funding than the minor commodity coarse grains group. While the number of major commodity crop awards has actually declined (459 grants in 2009 down to 274 grants in 2019, Figure 1C), the awarded funds have increased since 2016 (Figure 1B). The amount of funding issued per grant for major commodities has risen from a mean of \$148,000 in 2008 to \$906,000 in 2019 (sd = \$321,500—relative to 2019 mean). Minor commodity coarse grains and grain legumes similarly saw increased funding since 2016, although their overall funding levels remain low in comparison to the major commodities. The amount of funding issued per grant for grain legumes has risen from a mean of \$118,000 in 2008 to \$629,000 in 2019 (sd = \$281,000—relative to 2019 mean) and for coarse grains it has gone from a mean of \$133,000 to \$768,000 (sd = \$311,500—relative to 2019 mean). Despite per-project funding increases for minor commodity crop groups, they are still underrepresented in terms of area planted, production (Figure 1A) and overall funding in US agriculture, and thus require additional investment in order to maximize their contributions to planetary health.

DISCUSSION: TOWARD A “GLOBAL FOOD TRANSFORMATION”

Given the crop and agricultural system advancements that result from dedicated R&D investment, the current USDA funding distribution, which favors major commodity crops, is an important barrier to the improvement of minor commodity crops and their utility to planetary health. Overcoming this barrier is crucial, particularly in the context of declining agricultural investments (Clancy et al., 2016) and the growing call for food production that better supports both human health and the environment. Diverse agricultural landscapes and diets with a variety of minor commodity crops could help fulfill the multi-fold goals of providing food and nutrition security, environmental restoration, and climate mitigation and adaptation. However, this shift requires (1) a major re-orientation of public agricultural investment toward minor commodities and (2) increased collaboration across public programs designed to promote food security and meet environment, climate, and conservation goals.

Reorienting Public Agricultural Investment

Public research investment into minor commodity crops must increase in order to meet the full potential of these crops to serve human and planetary health. This repurposing of agricultural production support is essential so that measures that are typically unsustainable can be replaced with those that lead to diversification toward more nutritious foods (FAO et al., 2021). A portion of this research funding should target crop-specific improvements to advance these crops' roles in improving agroecosystem resilience to climate shocks, profitability, and delivering human nutrition. Research is also needed to develop these minor commodities' roles in climate mitigation inclusive of improved total factor productivity and overall yield, which can lead to potential beneficial reductions in their required land area (when combined with deliberate, conservation-oriented land use policy and planning) (Lobell et al., 2013). As seen in **Figure 1A**, an exponential increase in production for major commodities aligns with high levels of investment in R&D, thus suggesting that minor commodities could undergo a similar transformation if invested in more heavily. Furthermore, public research spending should also expand beyond crop improvements alone to investigate the potential for these crops to serve various ecosystem services and nutritional benefits—e.g., enhanced nutrient cycling, soil health, biodiversity, and increased micronutrient content—as part of more diverse cropping systems (DeLonge et al., 2016; Foyer et al., 2016; Tamburini et al., 2020).

Achieving these multiple, convergent research aims falls within the purview of the National Institute of Food and Agriculture's Agriculture and Food Research Initiative (AFRI). For example, the AFRI Sustainable Agricultural Systems (SAS) program “promote[s] the sustainable supply of abundant, affordable, safe, nutritious, and accessible food, while enhancing and improving the long-term health and well-being of all Americans” (NIFA, 2021). In its third year, this program has seen its budget rise from an initial \$99 million in 2019 to ~\$150 million in 2021. However, only one out of the 17 research

projects funded during the program's first 2 years focused on minor commodity crops (e.g., Kernza grain) or approaches for improved human nutrient consumption (NIFA, 2019, 2020). Research funding, such as in SAS and other AFRI programs, should prioritize projects that serve both human and planetary health (Ingram, 2011; Carlisle and Miles, 2013; Bilali et al., 2019; Rosenzweig et al., 2020). This should be done alongside a consistent annual increase in funding from Congress for both this program and NIFA's Sustainable Agriculture Research and Education (SARE) program, the only USDA-competitive grants program that focuses exclusively on sustainable agriculture (Lehner and Rosenberg, 2018).

Furthermore, US R&D programs would benefit from knowledge exchanges with international research institutions. This could take the form of programmatically-funded field work and modeling on minor commodities performed in partnership between the USDA, the US Agency for International Development and institutions such as the Consultative Group's ICRISAT, ICARDA, and the International Center for Tropical Agriculture; the African Center for Crop Improvement; and other agricultural universities and national breeding organizations (e.g., Indian Institute of Pulses Research). Recommendations advanced by the 2016 International Year of Pulses (Calles et al., 2019) provide a model for the kinds of exchanges that would help to kickstart R&D on minor commodities and sustainable cropping systems for planetary health. These include: formal and structured consultation with international producers, trade organizations, and decisionmakers; the development of awareness-raising campaigns; and the creation of publicly-accessible databases.

Beyond research, there exists a mismatch between the intended goals of the Farm Bill conservation programs and the USDA's operationalization of these programs. For example, while federal crop insurance premiums are technically coupled to conservation compliance as of the 2014 Farm Bill, improvements are needed to ensure positive outcomes, including avoiding planting in environmentally sensitive areas (Ristino and Steier, 2019; NIFA, 2021). Further, incorporating soil data into the Federal Crop Insurance Program could strengthen the program and improve outcomes (Woodard, 2016). Crop insurance premiums have also largely benefitted producers of major commodity crops, the production of which may incur environmental damages that the same Farm Bill's conservation provisions aim to mitigate (Ristino and Steier, 2019).

Similarly, payments made by key federal agricultural conservation programs are also subject to mis-alignment between conservation goals and actual implementation. A review of disbursed funds by the National Resources Conservation Service's Environmental Quality Incentives Program (EQIP) from 2009 to 2018 found that only 2–27% of EQIP funding has been used to support practices conveying the highest levels of environmental benefits, such as diversified farming systems (NSAC, 2015) that move beyond the prime focus of major commodity crops. In 2015, for example, over \$88M in obligated EQIP payments was used to support activities that may not be additively contributing to enhanced conservation goals as much as remediating environmental

pollution (Basche et al., 2020), such as waste storage, animal mortality, and manure management in concentrated feedlot operations (NSAC, 2015). The USDA must provide additional incentives to expand the use and improvement of diverse minor commodity crops, as well as improve the execution, monitoring, and enforcement (where applicable) of existing conservation programs to achieve combined human and environmental goals.

Increasing Collaboration Among the Agricultural, Nutrition, and Environmental Sectors

Research and decision-making on food and nutrition security, agriculture, and the environment should not be conducted in isolation from each other (Reinhardt, 2021). Until recently, the discourse on food system sustainability and agriculture-related policies was largely siloed from discussions centered around food and nutrition security (Bilali et al., 2019). However, research at the intersection of human and environmental health will be integral for increasingly convergent agriculture and environmental policies. For example, a recent executive order mandates "... federal programs to encourage adoption of climate-smart agricultural practices that produce verifiable carbon reductions and sequestrations and create new sources of income and jobs for rural Americans" which demonstrates convergent thinking around agriculture and the environment (Exec Order No. 14008. 86 FR 7619, 2021). Missing from this Order is that any resulting programs should also benefit public health and food security. This broader approach could enable increased development and integration of minor commodities into whole farming-system approaches.

An example entry point to link public health to agricultural and environmental outcomes are initiatives like the Interagency Committee on Human Nutrition Research (ICHNR), charged with improving coordination across federal agencies engaged in funding and conducting nutrition research over 2016–2021 (Fleischhacker et al., 2017). Among their research priorities were the "[development of monitoring systems and data systems]... to evaluate change in nutritional and health status, as well as in the food supply, composition, and consumption" and "... interdisciplinary research [to] identify effective approaches to enhance the environmental sustainability of healthy eating patterns" (Fleischhacker et al., 2017). To the extent that this

committee can facilitate inter-agency coordination, their work should continue into the foreseeable future and also consider how current federal agricultural spending, research and otherwise, may be redistributed to enhance these lines of research and build new emphases on crops and cropping systems for planetary health.

Ultimately, public agricultural R&D will continue to play a critical role in the trajectory of our food systems. There is large potential for the USDA to implement principles of planetary health—intersecting human and environmental security—by increasing funding support to the integration and improvement of minor commodity legumes and coarse grains into a more diverse agricultural landscape. A global food transformation can start through changes in priorities of currently funded programs.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AB and SM conceived the manuscript ideas and concept, undertook data analyses, and wrote the manuscript. MH and MS reviewed the manuscript and contributed edits, comments, and ideas. DM undertook data analyses. MD contributed to manuscript conceptualization and ideas and manuscript writing/editing. All authors contributed to the article and approved the submitted version.

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