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STELLENBOSCH, SOUTH AFRICA
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BACKGROUND PAPERS

TRADE-OFFS AND SYNERGIES AMONG CLIMATE RESILIENCE, HUMAN NUTRITION, AND AGRICULTURAL PRODUCTIVITY OF CEREALS – WHAT ARE THE IMPLICATIONS FOR THE AGRICULTURAL RESEARCH AGENDA?

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KEY POINTS

The following is a summary of key points:

- New challenges have arisen since the successes of the Green Revolution which dramatically increased rice and wheat production and alleviated famines, particularly in South Asia. One new challenge is the prevalence of hidden hunger (micro-nutrient deficiencies). Chronic hunger (insufficient calories) has reduced substantially, but hidden hunger is estimated to affect more than 2 billion people and stubbornly persists even with economic growth. Improved micro-nutrient content of cereals through increased consumption of nutrient-rich, coarse cereals (e.g. sorghum and millet) and/or enhanced micro-nutrients in major cereals (rice, maize, wheat) could help alleviate hidden hunger, particularly in low-income countries where people rely heavily on cereals for their nutrients.

- Climate change is a second challenge that was not on the agenda at the beginning of the Green Revolution. Climate change is projected to negatively affect agriculture in low latitudes through high temperatures, variable precipitation, and vulnerability of small-scale farmers. Climate change takes many forms, including increased frequency and severity of droughts and floods; pests that become more abundant or move into new habitats; changes in length of growing season; and exacerbated water shortages. With uncertainties about climate predications and mechanisms through which climate change affects cereal production, cereal production systems need to be resilient to increased temperatures and variability in precipitation.

- Coarse cereals generally have lower yields than rice, maize and wheat but have higher content of micronutrients such as iron and zinc. Moreover, because many coarse cereals are C4 grasses, they use water more efficiently and are less susceptible to decreasing nutrient content with increasing atmospheric carbon dioxide than C3 grasses. Decisions about which cultivars are appropriate in different locations need to consider the range of trade-offs and synergies across multiple dimensions of production, nutrition, and climate resilience. A case study in India indicates that replacement of rice with coarse cereals in some places could improve production of micronutrients, save water, and enhance climate resilience without sacrificing overall production in terms of calories or tonnes.

- The underlying need is re-evaluation of the decision-making process about priorities and investments in CGIAR to incorporate multiple dimensions such as nutrition and climate resilience. As the international, public agricultural research organization, CGIAR has the opportunity to set the agenda and implement decision-making processes that maximize synergies and minimize trade-offs. Steps towards that goal could include: involvement of experts outside of traditional agricultural research in decision-making at all levels; identification and monitoring of metrics across multiple dimensions of production, nutrition, and climate resilience; and institutional arrangements that maximize flexibility and ability to adapt to new information.

- The paper considers productivity, nutrition, and climate resilience as key dimensions for cereal production systems in low income countries. Other important dimensions beyond the scope of this paper and not addressed here include: greenhouse gas emissions, runoff of excess nitrogen, and other environmental factors; distributional equity from cereal production; gender aspects of production; and dietary and cultural preferences. The paper also does not address in detail the many factors in addition to dietary intake that affect nutrition, including underlying health status, income, and education, as well as the many factors besides climate that affect yield stability in farming systems, including chemical inputs, pests, management, and incentives.

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1.0 INTRODUCTION

CGIAR's contribution to the Green Revolution is a flagship achievement. The Green Revolution was enormously successful in developing and diffusing semi-dwarf, photoperiod insensitive, high-yielding modern varieties of wheat and rice. Combined with inputs from irrigation, fertilizer, and mechanization, the Green Revolution made it possible for globally-averaged per capita production of rice and wheat to increase at an even greater pace than population (see section 2.1). Recurrence of famines has greatly reduced and food has become more affordable with the dramatic increase in rice and wheat production enabled by the Green Revolution (Pingali, 2012).

Nearly fifty years have passed since the beginning of the Green Revolution. Global calorie production is more than sufficient for the current world population, although people in some places, particularly in sub-Saharan Africa and South Asia, have a deficit of calories. In addition, new challenges have arisen to achieve a healthy and equitable food system. This paper addresses two such challenges, with respect to cereals, that have come to the fore in the last few decades: the need for diets sufficient in micro-nutrients as well as energy from calories, fat and protein; and the need for cereal production systems that are resilient to climate variability and change. Other challenges not addressed in this background paper include equitable access to nutritious cereals across all segments of the population; and environmental impacts of cereal production such as greenhouse gas emissions, runoff from overuse of fertilizer, and habitat loss. In particular, the paper focusses on the potential contribution of agrobiodiversity within cereals to help resolve the challenges from micro-nutrient deficiencies and climate variability. The paper is offered in the spirit of Norman Borlaug, father of the Green Revolution, who viewed the effort to supply the human population with sufficient and nutritious food as an on-going process. Borlaug saw the Green Revolution as "a temporary solution, a breathing space, in man's war against hunger and deprivation" (Borlaug, 1970).

Several of the Sustainable Development Goals, adopted by the United Nations in 2015, relate directly or indirectly to the two aspects of cereal production addressed in this paper, namely nutrition and climate resilience (Table 1). As a major component of diets (see section 3.2), nutrition from cereals is highly relevant to SDG2 (zero hunger) and SDG3 (good health and well-being). The ability for farmers, particularly small-scale farmers, to maintain production in the face of climate variability is relevant to SDG1 (no poverty), SDG10 (reduced inequality) and SDG8 (decent work and economic growth) in addition to SDG2 and SDG3.

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Table 1. *Sustainable Development Goals and some targets relevant to improving nutrition and climate-resilience of cereal production systems*

SDG	**RELEVANT TARGETS**
SDG1: NO POVERTY	1.5 Build the resilience pf the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters
SDG2: ZERO HUNGER	2.1. End hunger and ensure access by all people to nutritious and safe food all year round
	2.2. End all forms of malnutrition
	2.3 Double the agricultural productivity and incomes of small-scale food producers
	2.4 Ensure sustainable food production systems and implement resilient agricultural practices
	2.5 Maintain the genetic diversity of seeds, cultivated plants and farmed and domestic animals and their related wild species
SDG3: GOOD HEALTH AND WELL-BEING	
SDG8: DECENT WORK AND ECONOMIC GROWTH	8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation
SDG10: REDUCED INEQUALITY	10.1 Progressively achieve and sustain income growth of the bottom 40 percent of the population

This paper first provides background information on trends in production, consumption, and agrobiodiversity of cereals since the Green Revolution; status of diets and nutrition in low income countries; and interactions between climate and cereal production. It then examines existing knowledge about the contributions of different cereals to nutrition and climate resilience, followed by methodological approaches to consider multiple dimensions in decisions about research investments, breeding priorities, and other CGIAR activities. We present a case study of historical trends in production and consumption of cereals in India and consequences of several scenarios for cereal production across multiple dimensions. The focus of the paper is cereal production in developing countries of the Global South.

The underlying premise of the paper is the need to operationalize multi-objective decision-making, including dimensions of nutrition and climate resilience, in CGIAR decisions. Such a need is identified in CGIAR's strategy framework for 2016-2030, but approaches to operationalize this goal have yet to be routinely incorporated (CGIAR, 2016).

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2.0. TRENDS IN PRODUCTION, CONSUMPTION AND AGROBIODIVERISTY OF CEREALS SINCE THE GREEN REVOLUTION

2.1 Production and yields of major staples and other cereals

In the Global South, production of major cereals (rice, maize and wheat) increased dramatically since the Green Revolution (Figure 1). Yields of these cereals increased with the package of Green Revolution technologies: improved cultivars, expansion of irrigated land, mechanization, and increased use of fertilizer. The greatest increase in yields occurred for the major cereal staples (rice, wheat, and maize) but yields also increased for the coarse cereals crops (sorghum and millets), although in some cases area harvested declined for coarse cereals. Impressively, increases in total cereal production outpaced population growth on a global scale, with per capita cereal production increasing from 0.29 to 0.39 tonnes per person between 1971 and 2014 (Ramankutty et al., 2018).

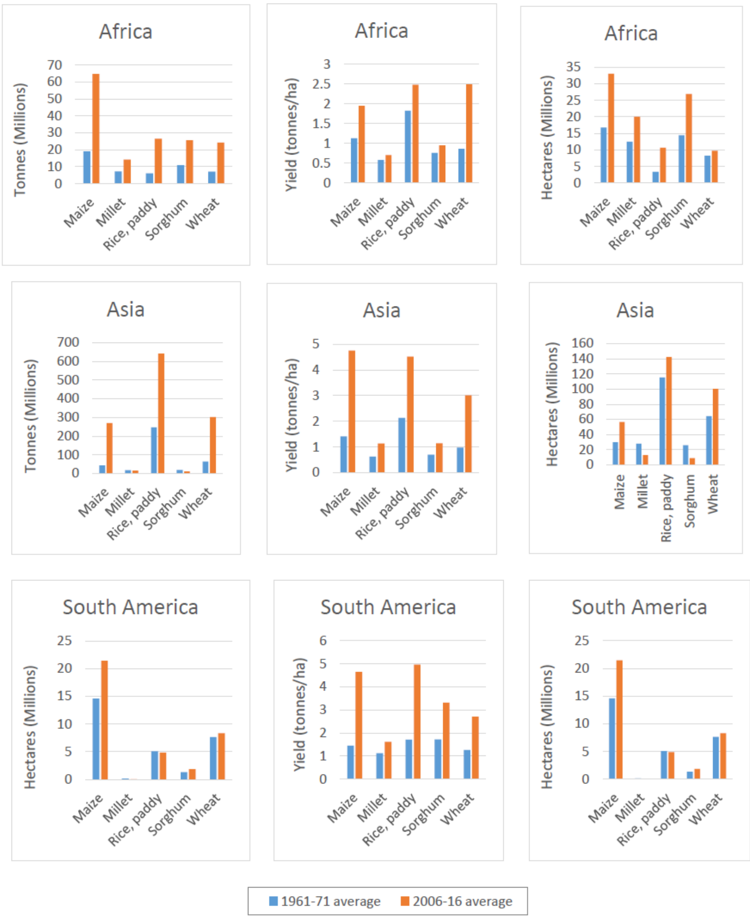

Figure 1. 1961-71 and 2006-16 average for production, yield, and area harvested for cereal types worldwide and three continents of the Global South. Data from (FAO, 2016).

A recent compilation for 55 countries of production related to farm size indicates that small farms (less than 2 ha) currently supply 28-31% of total crop production on 24% of gross harvested area (Ricciardi et al., 2018). More than 85% of production on small farms is cereals, with a decreasing percentage in larger farm sizes (see Figure 5 in (Ricciardi et al., 2018)). Smallholder farmers are generally poor, food insecure, rely on their own production and local markets for their household consumption, and have a large proportion of cereals in their diets. Consequently, the ability to produce abundant and nutritious cereals is essential to improve the well-being of smallholder farmers in combination with income-generating opportunities and access to markets that would enable purchase of a diverse, nutritious diet.

2.2 Trends in yield stability and stagnation

Many studies have reported stagnation in the overall pattern of increasing cereal yields in some parts of the world (see (Ray et al., 2012) and other references cited in (Lobell and Asseng, 2017). Stagnation results from declining rates of increase in yields, plateaus in linear or quadratic increasing trends, or absolute declines. Stagnation could be attributable to a ceiling in the biophysical limit of yield improvements, weather patterns, land degradation, shifts to more marginal lands, or policies on the use of fertilizer and irrigation (Grassini et al., 2013).

Ray et al. (2012) report that globally grain yield increases are continuing in 61-76% of areas harvested in maize, rice, wheat, and soybeans, but for the top-three global rice-producers (China, India, and Indonesia) grain yield gains are not occurring across 79, 37, and 81 percent of their rice cropland areas respectively. For wheat, the top-three producers of China, India and the United States are not witnessing grain yield increases in 56, 70, and 36 percent of their wheat cropland areas, respectively. Maize grain yields have stagnated across approximately 31 and 52% of maize-growing areas in India and China, with continuing grain yield increases in the "Corn Belt" of the United States and in the southern cone of South America. Grassini et al. (2013) similarly report plateauing yields in 33% of global rice and 27% of global wheat production areas.

In addition to grain yield, its stability (or conversely variability) is a major concern for global and national food supplies as well as household-level food security. Through nationally-disaggregated analysis based on satellite data, Izumi et al. (2014) conclude that globally maize production became more stable in 1994-2006 relative to 1982-1993 (with increasing variability in Central and South America and Southeast Asia). Conversely, variability of rice and wheat grain yields increased in the later time period. In particular, low and mid-latitudes in the Southern Hemisphere experienced significant increases in year-to-year variability in maize, rice, and wheat grain yields in 1994-2006 relative to 1982-1993. Globally, climate variability accounts for approximately one-third of observed yield variability. In South Asia, variability in precipitation explains more grain yield variability for rice, while in Southeast and East Asia temperature explains more of the variability. For wheat, precipitation explained more variability in China, while in India variability in temperature and precipitation were equally important (Ray et al., 2015). The non-climate related variability is presumably attributable to year-to-year variations in management, pest damage, cultivars, and use of fertilizers and other inputs.

Yield gaps reflect the potential to increase yields with crop and soil management given existing climate and other biophysical conditions (van Ittersum et al., 2013; Van Oort et al., 2017). Although spatially-explicit data on yield gaps are uncertain, in general yield gaps are lower in high-income countries relative to low-income countries and for irrigated cereals relative to rain-fed cereals. For rain-fed cereals, relative yield gaps (difference between potential and actual yield normalized to potential yield) range from 0.48 for wheat to 0.77 for sorghum (Van Oort et al., 2017). High yield gaps indicate the potential to improve yields through management and bred-cultivars.

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2.3 Trends in agrobiodiversity of cereals

Trends in cereal production since the Green Revolution indicate a substantial change in the mix of cereals in favor of rice, maize and wheat. They collectively increased from 66% to 79% of all cereal area, while other cereals such as barley, oats, rye, millet, and sorghum collectively declined from 33% to 19% (DeFries et al., 2015). Similar trends occurred in all continents to varying degrees.

In terms of diversity of cultivars, the general trend is an increase in modern cultivars and a decrease in local cultivars and landraces. More than 8,000 modern cultivars were released for 11 major crops by 2000 (Evenson and Gollin, 2002). Genetic erosion from loss of landraces appears to be greatest for cereals relative to other crop types (30 countries reported genetic erosion of cereals compared to 18 countries for vegetables and 17 countries for food legumes, see Table 1.3 in (FAO, 2010)). Landraces are adapted to local climatic conditions and pests and disease. For example, Ashraf and Lokanadan (2017) report more than 200,000 rice cultivars historically cultivated in India. Loss of local cultivars and landraces goes hand-in-hand with loss of local knowledge on their beneficial traits and which cultivars would be most adaptable to climate change (Dwivedi et al., 2016; Upadhya et al., 2016). (See background paper on agrobiodiversity and genetic diversity of crop species by Melinda Smale).

2.4 Summary of section on production trends

In summary, trends in production of cereals since the Green Revolution led to dramatic increases in availability of high-yielding rice, maize and wheat bred-cultivars. Simultaneously, diversity of cereal production systems declined across cereal species and within species. Agrobiodiversity underlies the ability to alter current production systems towards a mix of crops and bred-cultivars that are climate-resilient, pest-resistant, and nutritious. Stagnating edible yields in some parts of the world indicate that new approaches and technologies are needed for sustained increases in production.

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3.0 CEREALS NEED TO BE MORE NUTRITIOUS TO ALLEVIATE HIDDEN HUNGER

3.1 Trends in multiple forms of hunger

SDG 2 calls for ending hunger in all forms. Hunger is multifaceted. "Chronic hunger," which currently affects about 821 million people, reflects inadequate supply of calories. Chronic hunger has dropped precipitously in the last several decades with increasing incomes and access to affordable food. However, in the last few years a rise in hunger has run counter to the general trend and indicates that the world is not on track to eradicate hunger by 2030 (FAO, 2018b; FAO et al., 2017).

"Hidden hunger," so named because the effects are less visible than chronic hunger, refers to deficiencies of micronutrients (minerals and vitamins). The human body requires more than twenty micronutrients (Gregory et al., 2017). An oft-cited statistic is that 2 billion people in the world suffer from hidden hunger, although accurate assessments are difficult due to multiple types of deficiencies and lack of indicators. Approximately 1.6 billion people, which includes almost 50% of pre-school children, suffer from anemia related to iron-deficient diets as well as infection and disease. At least one-third of the global population is estimated to be at risk of zinc deficiency, which in children is one of the factors associated with stunting (defined as height-for-age z-score less than -2) (Barrett and Bevis, 2015; Kumssa et al., 2015). Other common deficiencies are vitamin A, iodine, and folate (Bailey et al., 2015).

On the other end of the scale, malnourishment in all of its forms also includes overweight and obesity from an excess of calories and insufficient physical activity. About 2.1 billion people are overweight or obese, slightly higher than the number suffering from hidden hunger (the two can co-occur in the same individual) (Beal et al., 2017). The rise in the prevalence of overweight and obesity people is high in the Global South as well as in the industrialized world (Popkin et al., 2012; Unicef, 2018).

To compare the contributions of chronic and hidden hunger to disability-adjusted life years (DALYs), Gödecke et al. (2018) estimated DALYs to quantify trends and respective burdens from the two types of hunger. The combined burden of chronic and hidden hunger has reduced by more than half since 1990. In 2010, Sub-Saharan Africa had the highest burden of chronic hunger and South Asia has the highest for hidden hunger. The burden of chronic hunger fell more than 50% between 1990 and 2010 while the burden of hidden hunger fell less sharply by 30%.

Economic growth was the key determinant of hunger at a country level, with significant effects of other variables including urbanization, food diversity, female schooling and access to improved sanitation. Economic growth at a national level was more closely associated with a decline in DALYs from chronic hunger than for hidden hunger, suggesting that policies and diet shifts rather than economic growth alone are required to tackle the problem of hidden hunger (Gödecke et al., 2018). This conclusion is reinforced by a lack of association in African countries between stunting (partially attributable to hidden hunger) and per capita income but a significant negative association between wasting (weight-for-height z-score less than 2, an indicator of chronic hunger) and per capita income (Barrett and Bevis, 2015).

Another measure of hidden hunger is the Hidden Hunger Index (HHI) as a composite index of deficiencies in iron, zinc, and vitamin A. Improvements in HHI were attributable to reductions in zinc and vitamin A deficiencies while anemia from iron deficiency did not reduce and may have increased (Ruel-Bergeron et al., 2015). Countries with highest HHI were all in Africa with the exception of Afghanistan (see (Ruel-Bergeron et al., 2015) for country rankings). Other metrics of hidden hunger include the Prevalence of Inadequate Micronutrient Intake (PIMII) for 14 micronutrients and Micronutrient Density Index (MDI), which measures the density of the food supply for 14 micronutrients. These metrics indicate improvements in hidden hunger in East and Southeast Asia in the last 50 years, with weaker improvements in South Asia and sub-Saharan Africa (Beal et al., 2017).

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3.2 Contributions of cereals to diets and nutrition in the Global South

The well-established "nutrition transition" is a double-edged sword for combatting hidden hunger. A nutrition transition, whereby people reduce consumption of starchy foods and increase consumption of animal source foods as income rises, is occurring throughout the Global South especially related to urbanization (Popkin et al., 2012). On one hand, a nutrition transition increases dietary diversity and can supply high-quality, bioavailable protein and iron from animal sources foods (as well as from a host of other nutrient-rich foods, including fruits, vegetables, nuts and seeds, aquatic products, legumes, etc.). On the other hand, a nutrition transition is also associated with negative aspects for nutrition. Consumption of fats and sugars generally increase leading to overweight and obesity and associated non-communicable diseases. In addition, the shift often goes hand-in-hand with replacement of nutritious, traditional coarse cereals with less nutritious polished grains and refined cereals (Barrett and Bevis, 2015).

People in low-income and low middle-income countries are generally at the beginning stages of a nutrition transition. As a reflection of the progress in alleviating chronic hunger, energy (calories) in the food supply is sufficient to meet requirements for the population (based on the unrealistic assumption of equal distribution) in 60% (50 out of 83) of low and middle-low income countries and protein is sufficient in all countries. Only 35% of countries have sufficient iron in their food supplies, with zinc more abundant with 67% of countries sufficient (Figure 2 based on (Wood et al., 2018)). The large number of countries with insufficient iron mirrors the high prevalence of iron deficiency noted above.

On average, cereals provide at least half of energy in food supplies, more than 40% of protein and zinc, and 30% of iron in low and middle low income countries, indicating the large role of cereals in nutrition in lower income relative to higher income countries (Table 2). In terms of other micro-nutrients, cereals supply up to 13% of calcium and 27% of folate and essentially no vitamin B12, vitamin A, or vitamin D. In general, there has been a global trend towards increasing importance of Green Revolution major cereals in diets and declining diversity in food systems (Khoury and Jarvis, 2014).

Because people in low-income and low middle-income countries obtain a large proportion of their macro- and micro-nutrients from cereals, the nutritional content of cereals takes on particular importance (see (Wood et al., 2018) for list of countries within income categories). With the dominance of the major Green Revolution cereals, the nutrient density of the cereal supply has declined (DeFries et al., 2018; DeFries et al., 2015). To the extent that countries produce rather than import cereals for domestic consumption (which varies from countries which imported all cereal to net exporters), the nutritional content of cereals domestically produced could play a substantial role in combatting hidden hunger. Multiple prongs to reduce hidden hunger are essential and need to be assessed for potential effectiveness, tractability, and costs. Such approaches include, along with improved nutrient content of cereals, fortification of staples, diet diversity, less cereal-based diets, maternal education, and improved health systems.

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Figure 2. *Fraction of population with potential to meet requirement for food supply for macro and micro-nutrients and proportion from cereals and other food groups in low and middle-low income countries. Calculated from methods described in (Wood et al., 2018). Fractions do not account for within-country distribution.*

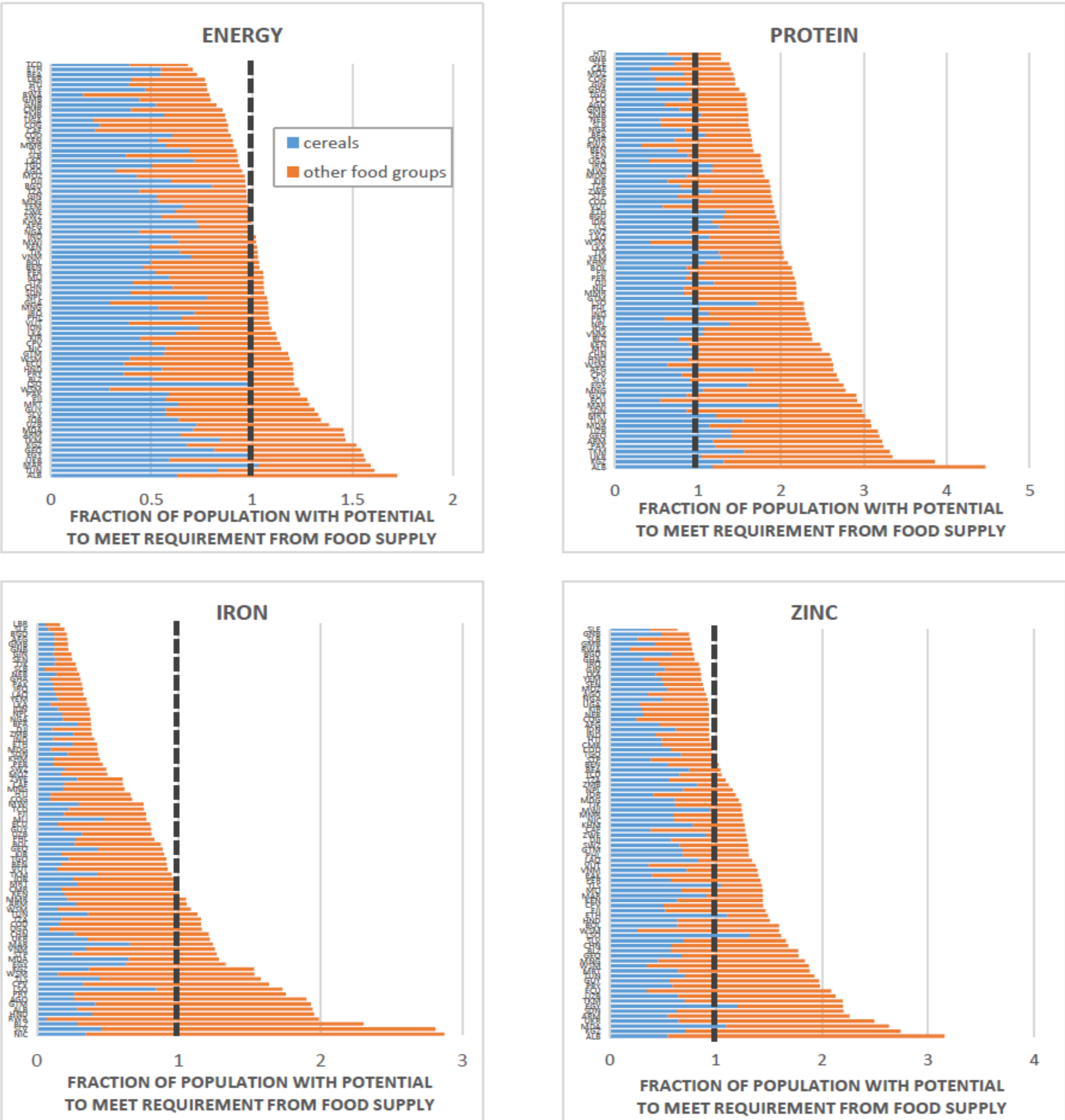

Table 2. *Average proportion of macro- and micro-nutrients supplied by cereals in the total food supply by income category. Estimates are based on calculations following methods in (Wood et al., 2018).*

Income category	**No. of countries**	**Energy**	**Protein**	**Iron**	**Zinc**
Low	36	0.55	0.50	0.36	0.53
Lower middle	46	0.49	0.43	0.30	0.42
Upper middle	40	0.40	0.32	0.23	0.30
High	45	0.31	0.22	0.18	0.18

3.3 Do higher yields decrease nutrient content?

Some evidence exists for a "yield dilution effect," whereby plants bred with the objective of high yields sacrifice nutrient content (Gregory et al., 2017). A dilution effect is a secondary factor to shifting dietary patterns for nutrient intake (Davis et al., 2004). Although data is sparse, nutrient content of fruits and vegetables has apparently declined over time with high-yielding cultivars. Side-by-side experiments of different cultivars confirm the link between increased edible yields and lower nutrient content (Davis, 2009; Davis et al., 2004).

In relation to a dilution effect in cereals, Andanan et al. (2011) found a significant, negative relationship between grain yield and content of iron and zinc in a study of 202 rice genotypes. Content of iron and zinc was significantly higher in traditional than in improved genotypes (mean iron content was 14.06 mg/kg and 10.95 mg/kg and mean zinc content was 21.58 mg/kg and 11.03 mg/kg for traditional and improved genotypes respectively). Similar effects for wheat are summarized in Davis (2009), thus suggesting a broad phenomenon. Reported average rate of decline was significant for four mineral nutrients (iron, zinc, phosphorus, selenium) in wheat cultivars in the Great Plains (based on cultivars grown between 1873 and 1995) and ranged from 22% to 33% over a 100-year period. Similar effects are reported for maize. Fan et al. (2008) found that concentrations of iron, zinc, copper and magnesium for archived wheat grains from the Broadbalk Wheat Experiment remained stable between 1845 and the mid-1960s, but decreased significantly (by 19 to 28%) with the introduction of semi-dwarf, high-yielding cultivars. The dilution effect could be counteracted by carefully-utilized fertilizers with high mineral content (Barrett and Bevis, 2015; Gregory et al., 2017) or biofortification to explicitly factor nutrient content among plant breeding target traits. The magnitude of a dilution effect and potential solutions requires additional experimentation and analysis.

3.4 Does changing atmospheric composition alter nutrient content?

Decline in nutrient content in cereals with increasing concentration of atmospheric carbon dioxide is another secondary factor that could increasingly affect hidden hunger in the future. Many studies report that elevated atmospheric concentration is associated with declines in nutrient content of grass species with the C3 photosynthetic pathway (e.g., rice, wheat) but not in C4 grasses (e.g., sorghum, millet, maize). Most experiments are conducted in semi-controlled settings rather in open-field plots. A compilation of these experiments appears in Dietterich et al. (2015). A decline in nutrient content potentially increases risk of micronutrient deficiencies particularly where people rely heavily on plant species for nutrients (Myers et al., 2015).

In an analysis of 40 genotypes grown under current and elevated carbon dioxide concentrations expected in the middle of the century, Myers et al. (2014) conclude that zinc, iron, and protein decreased significantly in C3 grass species (wheat, rice). Responses varied across rice cultivars. No effect was found for C4 grasses (sorghum, maize), except iron in maize. The difference between C3 and C4 grasses is consistent with the differences in photosynthetic pathways, whereby C4 plants concentrate carbon dioxide internally and are less sensitive than C3 plants to ambient carbon dioxide concentrations.

A recent, though non-replicated, study concluded that over a longer-term 20 year time frame, plant species with the C3 photosynthetic pathway have a greater increase in biomass than C4 plants with elevated carbon dioxide (Reich et al., 2018). This result is counter to previous observation over shorter time periods and theoretical understanding of plant physiology. The implications for nutritional content of cereals over the long term with increasing concentrations of atmospheric carbon dioxide concentration are unclear at this point.

Cultivars with high nutrient content and promotion of C4 grasses could reduce vulnerability to reduction in nutrients from rising atmospheric carbon dioxide concentrations.

3.5 Nutrient content across major and minor cereals

Estimates of nutrient content for the suite of cereals vary across different data bases, e.g. (FAO, 2018a; Longvah et al., 2017; Smith, 2018; United States Department of Agriculture, 2015) (Table 3). In general, all of the major and minor cereals have fairly comparable densities in terms of energy (kcals). Nutrient content also varies with growing conditions, processing (e.g. whole vs milled), soil, and management, as well as across cultivars within a cereal type. Millets contain exceptionally high density of iron with brown rice and refined cereals (milled rice and refined wheat) relatively low density. Zinc is more comparable across cereals with refined products containing low densities. However, refined cereals have low densities of the anti-nutrient phytate (although high ratios due to the low micro-nutrient content).

Phytate and other anti-nutrients, e.g. polyphenols, bind with minerals to inhibit absorption of non-heme (plant-sourced) iron and other mineral micronutrients and reduce bioavailability (Cilla et al., 2018). For example, bioavailability of heme-iron from animal sources is 12-25% and less than 5% for non-heme iron (Bailey et al., 2015). A second disadvantage of coarse cereals is their relatively low grain yield (FAO, 2016).

Table 3. *Nutrient content of macronutrients (energy and protein), two micronutrients (iron and zinc), and anti-nutrient phytate with molar ratios for cereals. The range is taken from two sources for nutrient content (Longvah et al., 2017; United States Department of Agriculture, 2015). Note the variation across the same cereal with different processing (brown vs. milled rice and whole vs. refined wheat).*

		GREEN REVOLUTION CEREALS					COARSE CEREALS		
		Brown rice	Milled rice	Whole wheat	Refined wheat	Maize	Sorg-hum	Pearl millet[1]	Finger millet[1]
CONTENT (per 100 g dry weight)	Energy (kcal)	354-357	356-370	320-332	352-364	334-365	329-334	348	320
	Protein (g)	7.14-7.81	6.81-7.94	9.61-10.57	10.33-10.36	8.80-9.42	9.97-10.62	10.96	7.16
	Iron (mg)	1.02-1.71	0.65-1.60	3.71-4.10	1.17-1.77	2.49-2.71	2.26-3.95	6.42	4.62
	Zinc (mg)	1.68[2]	1.20-1.21	2.85-2.96	0.70-0.88	2.21-2.27	1.67-1.96	2.76	2.53
	Phytate (mg)[2]	742	266	632	123	646	549	485	306
	Phytate:iron molar ratio[3]	45.99	20.02	13.69	7.08	21.02	12.71	6.39	5.60
	Phytate:zinc molar ratio[3]	43,75	21.87	21.55	15,42	28.57	29.96	17.41	11.98

[1] The USDA data base does not distinguish between different millets. The values given for "millets" are 378, 11.02, 3.01, and 1.68 for energy, protein, iron and zinc respectively. The values in the table are from (LONGHVAH REF)
[2] Phytate for all cereals and zinc for brown rice are not reported in the USDA data base. The values in the table are from

(Longvah et al., 2017).
[3] Molar ratio is the molar weight of phytate divided my molar weight of iron or zinc. Molar masses of phytate, iron, and zinc are 660.04, 55.85, and 65.39 g/mol respectively. Values used for iron and zinc are midpoints of the range in estimates. The critical thresholds are 1 and 15 for the phytate:iron and phytate:zinc ratios respectively.

The effect of phytate on the bioavailability of minerals depends not only on the total phytate content in foods but on the relative proportions between phytate and minerals in those foods. Phytate- to-mineral molar ratios are used to predict the inhibitory effect of phytate on the bioavailability of minerals (Ma et al., 2007). In a meal, a phytate-to-iron molar ratio greater than one significantly decreases iron absorption (Hallberg et al., 1989). For zinc, a molar ratio of 15 is considered to decrease absorption (Kumssa et al., 2015). Bioavailable zinc can also be calculated from the Miller equation, which accounts for zinc and phytate content (Miller et al., 2007). While a high relative amount of phytate indicates a negative effect on absorption, in recent decades a positive effect of phytate has been emphasized for its anticancer property, antioxidant activity, and reduction of blood glucose and cholesterol (Schlemmer et al., 2009).

3.6 Summary on links between nutrition and cereal production

At the beginning of the Green Revolution, hunger was conceived as a problem of insufficient calories and protein. This target has largely been satisfied by increasing production of high-yielding but relatively micro-nutrient poor cereals. The Green Revolution was less successful in expanding the per capita supply of micronutrients, which today is manifested in the prevalence of micronutrient deficiencies under the guise of "hidden hunger". Iron deficiency is the most prevalent and persistent micro-nutrient deficiency.

Dietary shifts away from nutritious minor cereals and towards polished grains and refined cereals contribute to hidden hunger. Two other factors may secondarily contribute to declining nutrient content in cereals: a "dilution effect" of nutrient density as plants are bred for high grain yield and reduced nutrient content with increasing concentrations of atmospheric carbon dioxide. As cereals continue to supply a large proportion of diets in the Global South, improved micronutrient content of cereals could help alleviate the burden of hidden hunger. Promotion of coarse cereals (generally C4 species) provide one avenue to increase nutrient content of cereals and reduce nutrient loss with increasing atmospheric carbon dioxide concentrations, but requires efforts to overcome low yields and low bioavailability of mineral nutrients. Efforts to increase availability of other nutrient-dense food groups, promote diverse diets, and reduce dependence on high-cereal diets are other important avenues to address hidden hunger.

4.0 CEREAL PRODUCTION NEEDS TO BE RESILIENT TO CLIMATE VARIABILITY

4.1 Climate projections for cereal production in the Global South

Climate change affects cereal production through multiple pathways: heat stress through increases in temperature; increasing frequencies of extreme weather events such as droughts and floods; reduced precipitation in some places and increased precipitation in other places; changes in the length of the growing season; increasing spread of pests and disease with high temperatures; and fertilization effects from increasing atmospheric carbon dioxide. It is beyond the scope of this paper to review the vast literature on climate impacts on agriculture or future climate projections.

The literature estimates climate impacts on production through either empirical, statistics-based analysis of historical yields and weather parameters or process-based crop models linked with climate models to project future impacts under climate change scenarios (see (Lobell and Asseng, 2017) for a review of these approaches). At a very general level, results from these analyses indicate strong negative effects of climate change for major cereals, especially at low latitudes and at all latitudes for higher levels of warming (Rosenzweig et al., 2014). Climate change is already reducing global grain yields of some cereals although overall production continues to increase (Lipper et al., 2014).

Model inter-comparisons from the AgMIP project show model agreement on negative impacts in maize and wheat grain yields at low latitudes by the end of the century with a moderate emissions scenario. Models agree less for rice (Rosenzweig et al., 2014). Statistical models based on observations are generally consistent with model results with respect to the effect of increasing temperature. Exceeding critical physiological limits in temperature can sharply reduce grain yields. For impacts of changes in precipitation, results are less easily projected (Lobell and Asseng, 2017). In addition, variability in climate and extreme events may be a larger influence on food security than average changes in temperature and precipitation (Thornton et al., 2014).

Climate projections indicate increasing temperatures and increasing frequencies of heat spells, higher nighttime temperatures, change in diurnal temperature range, generally increasing precipitation but with large differences across regions, and increasing variability in precipitation. The degree of uncertainty is high, suggesting that prudent decisions about breeding and dissemination of cereal crops will emphasize cereals that can adapt to varying conditions (Burke et al., 2015). Existing genetic variability across cereals provide an opportunity to develop adaptable cultivars (see (Reynolds et al., 2016) for important traits of different cereals and cultivars).

4.2 Effects of atmospheric carbon dioxide on cereal production

A major uncertainty in models projecting impacts of climate change on cereal yields is the response to increasing carbon dioxide concentrations through the fertilization effect. Models have tended to overestimate the effect with less consideration on constraints imposed by nitrogen and other plant nutrients, water shortage, weeds, or pests (Long et al., 2006). Based on the physiology of C3 and C4 cereals, yields of C3 cereals can benefit from increasing atmospheric carbon dioxide. Increasing carbon dioxide concentrations do not confer comparable benefits for C4 crops. Experimental evidence is consistent with this prediction and indicate that atmospheric carbon dioxide concentrations of 550 ppm would on average increase C3 yields by 10-20% and C4 crops by 0-10% (Gornall et al., 2010). Experimental results from Reich et al. (2018) call into question the generality of this response over decadal time scales.

Counter to the disadvantage of C4 cereals for enhanced yields with increasing atmospheric carbon dioxide, cereals with the C4 pathway have the advantage of greater water-use efficiency at elevated carbon dioxide concentrations than C3 plants. C4 plants evolved in semi-arid conditions and are adapted to water stress. Stomata in C4 plants do not need to stay open as long as in C3 plants to obtain a required amount of carbon dioxide and could consequently conserve water with increasing carbon dioxide concentrations (Gornall et al., 2010).

4.3 Summary on cereals and climate resilience

Impacts of climate change on cereal production have already been observed and are very likely to be substantial in the future. Predictions of climate change generally indicate increasing temperature and more variability in precipitation but are highly uncertain. Predictions of impacts on cereal production are further compounded by the many pathways through which impacts can occur such as pests and extreme events. Yields of C3 cereals (e.g. wheat, rice) can benefit more from a carbon dioxide fertilization effect than C4 cereals, but C4 cereals can be more water efficient. This complex and uncertain landscape indicates that climate-smart agriculture for cereals needs to focus on adaptability to varying climate and extreme events. Breeding to develop cultivars with traits for adaptability and resilience to varying temperature and precipitation could contribute to future food security.

5.0 SYNERGIES AND TRADE-OFFS BETWEEN NUTRITION, CLIMATE RESILIENCE, AND PRODUCTION ACROSS CEREAL TYPES

5.1 Comparison of cereal types

Decisions about which traits to prioritize in plant breeding and which crops and cultivars to promote in different places involve multiple dimensions, including edible yield, climate resilience, and nutrient content among many other factors. Trade-offs between desirable characteristics are common, for example the trade-off between edible yields and nutrient content, as highlighted above. The prevailing paradigm has been to prioritize the traditional yield metric over other dimensions. Implicit, non-transparent assumptions about the relative importance of different dimensions have guided decision-making. With rising importance of combatting hidden hunger and climate-resilient agricultural systems (along with other environmental dimensions not addressed in this paper), explicit information is needed to quantify trade-offs and synergies across multiple dimensions. Trade-offs are undoubtedly necessary. Explicit and transparent evaluation across relevant dimensions will reduce likelihoods of negative unintended consequences and promote holistic production systems that help achieve food security.

Within the dimensions considered in this paper, synergies and trade-offs exist across cereal types (Table 4). The Green Revolution cereals generally have higher grain yields by traditional metrics (although not everywhere, see case study) which trades off with high nutrient-content of coarse cereals, particularly for rice. A clear synergy exists across water use efficiency, climate resilience, and nutrient content in C4 cereals (sorghum and millet). Low bioavailability of nutrients in coarse cereals tempers the contribution to alleviating hidden hunger, but could be reduced through breeding and processing (Hurrell, 2004).

In summary, coarse cereals have several desirable qualities that are overshadowed if grain yields are the single dimension for decision-making. To the extent that the negative characteristics, namely low grain yields and bioavailability, can be improved through research and breeding, coarse cereals can contribute to healthy, productive, and climate resilient cereal production systems (see case study for discussion of other factors such as cultural acceptance). With molecular techniques, desirable characteristics from coarse cereals could be incorporated in major cereals.

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Table 4. *Relative benefits of cereals in multiple dimensions of production, nutrient content, and climate resilience. Darker shades are more beneficial.*

	GREEN REVOLUTION CEREALS			COARSE CEREALS	
	RICE (milled)	WHEAT (whole)	MAIZE	SORG-HUM	MILLETS
PHOTOSYNTHETIC PATHWAY	C3	C3	C4	C4	C4
PRODUCTION:					
Yield	high	high	high	low	low
Increase biomass from CO_2 increase	high	high	low	low	low
NUTRIENT CONTENT:					
Energy	mid	mid	mid	mid	mid
Protein	mid	mid	mid	mid	mid
Iron	low	mid	mid	mid	high
Zinc	low	high	high	mid	high
Phytate[1]	low	high	high	mid	mid
Sensitivity of nutrient loss from CO_2 increase[1]	high	high	low	low	low
CLIMATE RESILIENCE:					
Water use efficiency	low	low	high	high	high
Yield stability	?	?	?	?	?

[1] low is beneficial and high is harmful

5.2 Systems approaches to decision-making

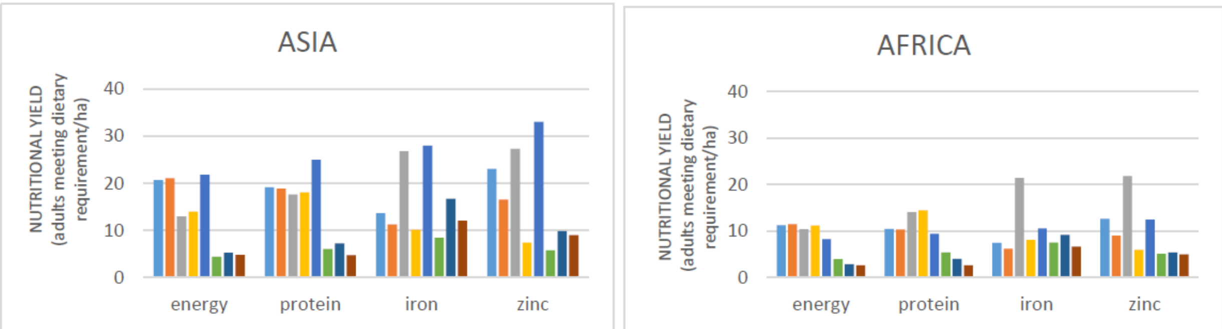
Borlaug's quote that the Green Revolution was "a temporary solution" underscores the reality that food security is a "wicked problem". Wicked problems have no clear-cut panacea; there is no single solution; and solutions often lead to unforeseen consequences (DeFries and Nagendra, 2017; Rittel and Webber, 1973). Such is the case with a focus on improved bred-cultivars to increase edible yields. Consequences on hidden hunger and the problem of climate change were not apparent at the time. The approach to address wicked problems is multi-fold: 1) to the extent possible, adopt a systems approach to assess consequences across multiple dimensions and 2) design systems that are flexible and adaptable as unintended consequences become clear and conditions change.

In the current institutional setting, forces generally act against a systems approach appropriate for wicked problems. There are many obstacles (see Table 2 in (DeFries and Nagendra, 2017)): "stove-piped" administrative structures that are dis-incentives to decisions across multiple dimensions; lack of clear authority and incentives for managers to consider multiple dimensions; lack of clear multi-dimensional metrics for decisions and monitoring; and inflexible bureaucracies.

It is beyond the scope of this paper to assess the institutional setting in CGIAR and its ability to be flexible and adaptable. However, incorporation of metrics and methods to implement and monitor decisions about new programs, breeding, and dissemination activities could encourage consideration of multiple dimensions and could promote flexibility and adaptation as new information becomes available.

5.3 Methods and evaluation tools for decision-making across multiple dimensions

Metrics are essential to assess synergies and trade-offs across multiple dimensions in decisions about investments and priorities. Metrics to assess the contribution of cereals to alleviating hidden hunger include consumption-related metrics (anthropometric measures of stunting, wasting, and undernutrition in a population), dietary surveys, and biomarkers indicating nutritional deficiencies such as blood tests for hemoglobin (King et al., 2015; Lynch et al., 2018). Production-related metrics include the nutrient density of the cereals basket (Table 3) and "nutritional yield" (DeFries et al., 2015). Nutritional yield combines nutritional content of each nutrient and computes yields in terms of nutrients (iron, zinc etc.) per hectare rather than tonnes per hectare and weights according to daily recommended dietary intake to allow comparison across nutrients. The nutrient yield for iron, for example, provides a measure of the number of adults who could receive a sufficient amount of iron from production on a hectare of land.



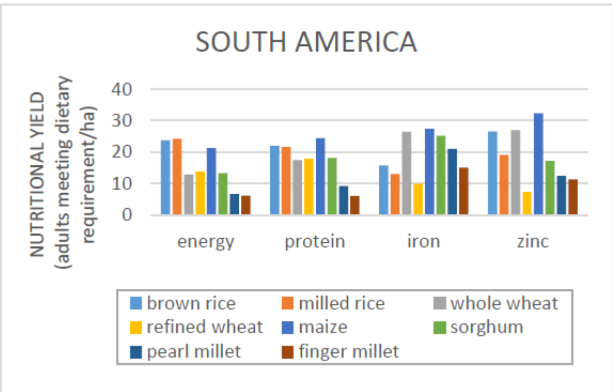


Figure 3. *Nutritional yields (number of adults who can satisfy their dietary requirements for nutrients per hectare of production of cereal). Yields are taken from (FAO, 2016) and nutrient content from Table 3. See (DeFries et al., 2015) for method to calculate nutritional yield and for dietary requirements.*

Nutritional yields for macro-nutrients are much higher for major cereals due to their higher yields and comparable energy and protein (Table 3). However, because minor cereals have higher iron content than rice in particular, the nutritional yields for iron are more comparable despite the lower yields (Figure 3).

Multiple measures of diversity from the ecological literature (Remans et al., 2011; Remans et al., 2014; Wood et al., 2015) can be applied to agrobiodiversity to measure diversity of crop types and diversity of cultivars. For climate resilience, measures of sensitivities to variability in precipitation and temperature (coefficient of variation of yields or statistical sensitivity to climate anomalies) can be determined with statistical analysis of historical data or through experiments. Experimentally measured water use efficiency and response to temperature changes are also metrics of climate resilience (see Figure 4 for summary of metrics across multiple dimensions).

Many decision support tools are available to provide input to decision –making processes. Methods range from qualitative approaches to assess priorities from different stakeholders to quantitative cost-benefit analyses and multi-criteria decision analysis (see (Kaim et al., 2018) for a review of these methods and a structured approach for assessing suitable methods). In cases in which synergies between multiple dimensions are present, such as the synergy between climate resilience and nutrient content in coarse cereals, the obvious objective is to make decisions that maximize the synergies within institutional constraints. In cases in which trade-offs are present, such as the trade-off between yield and nutrient content, the decision-making process is less obvious. Pareto frontiers (also called efficiency frontiers and production possibility frontiers), to the extent that relationships between metrics can be quantified, are useful to make trade-off decisions explicit and to guard against sub-optimal decisions (Polasky et al., 2008).

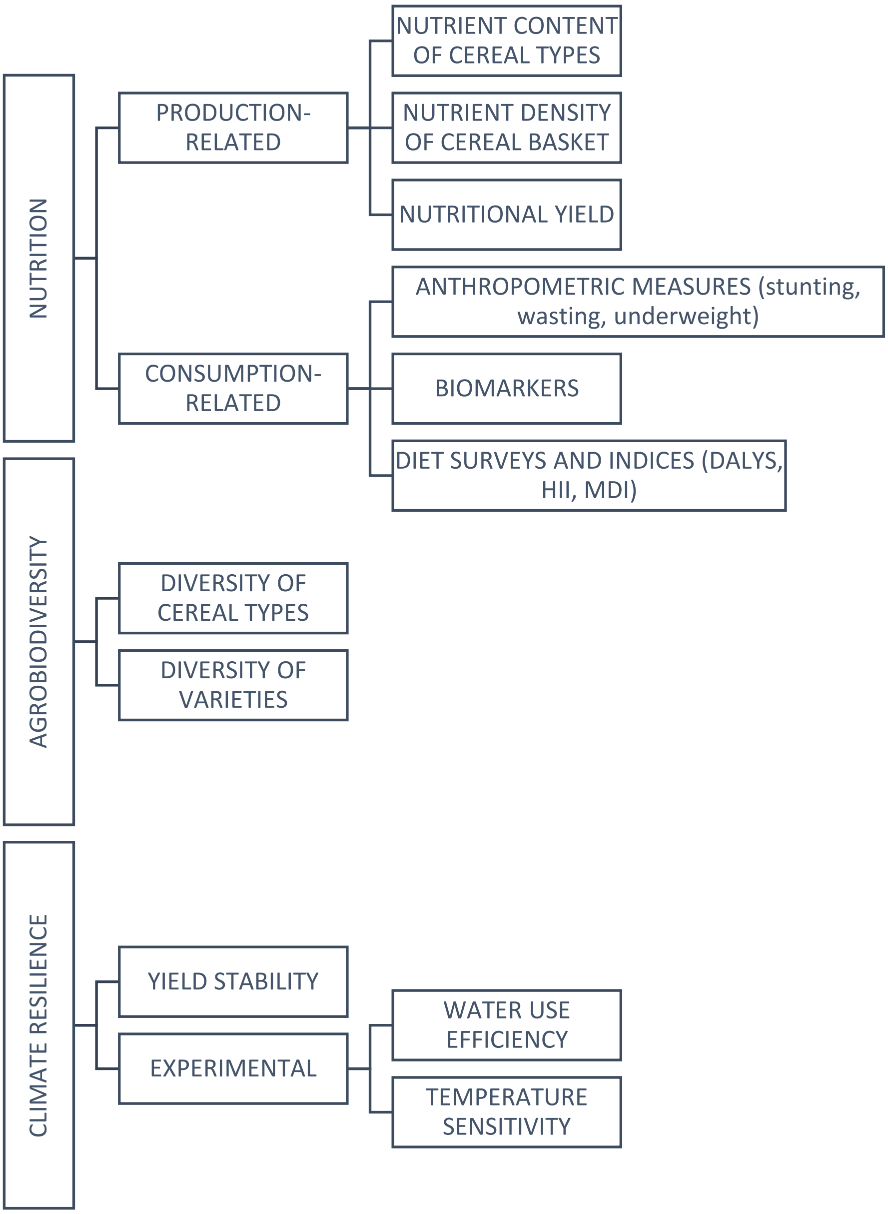


Figure 4. *Possible metrics for multiple dimensions of cereal production systems*

When the number of dimensions is high and relationships between them unclear, scenarios of alternative decisions are a straightforward approach to communicate trade-offs (see case study below for scenario analysis). Approaches to visualize trade-offs and synergies to support decisions include: plots of Pareto frontiers; comparison of multiple scenarios across dimensions relevant to stakeholders; and spider diagrams that allow comparison across multiple dimensions (e.g., (Chaudhary et al., 2018) to compare national food systems across environmental, nutrition, and economic dimensions and (DeFries et al., 2016) to compare production, climate sensitivity and nutrition from alternative cereals).

Quantitative tools and algorithms can be helpful to make trade-offs and synergies explicit and transparent, but cannot substitute for subjective judgments about the relative importance of different dimensions.

5.4 Summary of trade-offs and synergies across multiple dimensions for cereal production

Metrics are essential to incorporate multiple dimensions of production, nutrition, and climate resilience in decisions about which cereals and cultivars are suitable in different places. In general, synergies exist between climate resilience and nutrition for coarse cereals, but their grain yields are generally low relative to the Green Revolution cereals. Research and breeding focused on species, varieties, and traits of bred-cultivars that maximize synergies and overcome tradeoffs could contribute to improved nutritional outcomes. In addition, analysis of trade-offs and synergies could help decisions about which cereals to promote in different places. Many methods exist to aid decision-making across multiple dimensions. However, quantitative methods cannot substitute for subjective judgments about the relative importance of different dimensions for cereal production systems.

6.0 CASE STUDY ON CEREALS IN INDIA

India is one of the main success stories of the Green Revolution. Periodic famines no longer occur, cereal production increased 2.3-fold, and India has transformed from a rice-importing to a rice-exporting country. With the Green Revolution, rice and wheat became more dominant in the cereal production system (Figure 5). Traditional cereals were less widely-consumed.

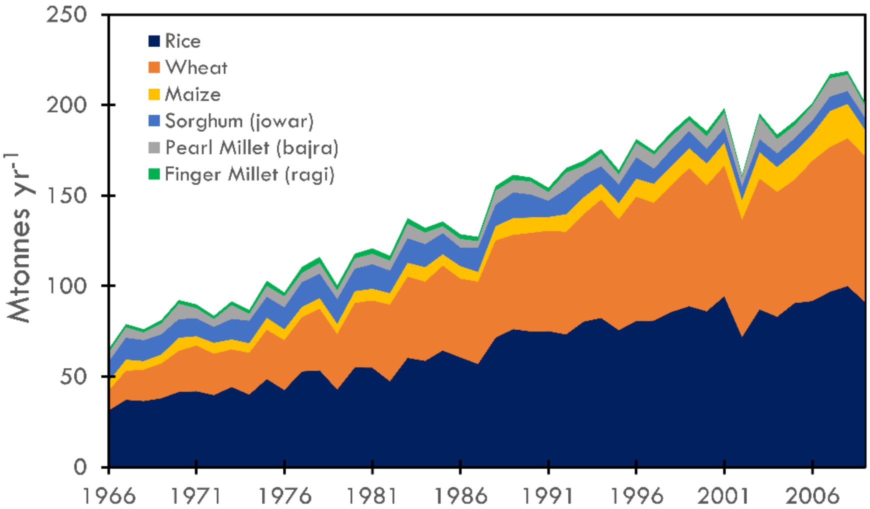


Figure 5. *Change in production of cereals in India from 1966 to 2009. Jowar (sorghum) is combined for monsoon (kharif) and winter (rabi) seasons. From (DeFries et al., 2018).*

The trend continues in recent decades. The proportion of calories from sorghum and millets in Indian diets reduced from 23% to 6% in rural households (10% to 3% in urban households) between 1983 and 2011. The loss of high-micronutrient traditional cereals in diets has reduced iron intake from cereals without compensation from other food groups (Figure 6 – bottom panel), while calorie consumption declined only slightly (Figure 6 - top panel). The prevalence of hidden hunger is high in India; anemia affects more than half of all women and children under five (DeFries et al., 2018). More than two-thirds of Indians consume insufficient micronutrients to meet requirements (Rao et al., 2018).

A major factor in India's success in the Green Revolution was due to increasing irrigation and cropping intensity. Depletion of groundwater is an urgent problem in the northwestern rice bowl and breadbasket of the country (Rodell et al., 2018). As C4 grasses, crop water requirements for traditional cereals are substantially lower than for rice or wheat (see Table 1 in (Davis et al., 2018)). Furthermore, India is a hotspot of vulnerability of climate change with increasing variability of temperature and precipitation (Bathiany et al., 2018; de Sherbinin, 2014).

Previous research shows that consumption of nutritionally-dense coarse cereals has declined in India since 1983 and increased consumption of other food groups has not compensated the loss of nutrients from cereals (DeFries et al., 2018) (Figure 6); replacing rice with alternative cereals (maize, finger millet, pearl millet, or sorghum) with lower water requirements could reduce demand for irrigation water by 33% while increasing production of protein, iron, and zinc with only a modest reduction in calorie production (Davis et al., 2018); and Indian households could overcome nutrient deficiencies within their food budgets by diversifying their diets towards coarse cereals, pulses, and leafy vegetables and away from rice (Rao et al., 2018). Additional research quantifies reduced sensitivity of alternative cereals relative to rice in central India (DeFries et al., 2016) and nationally (Davis et al., in prep).

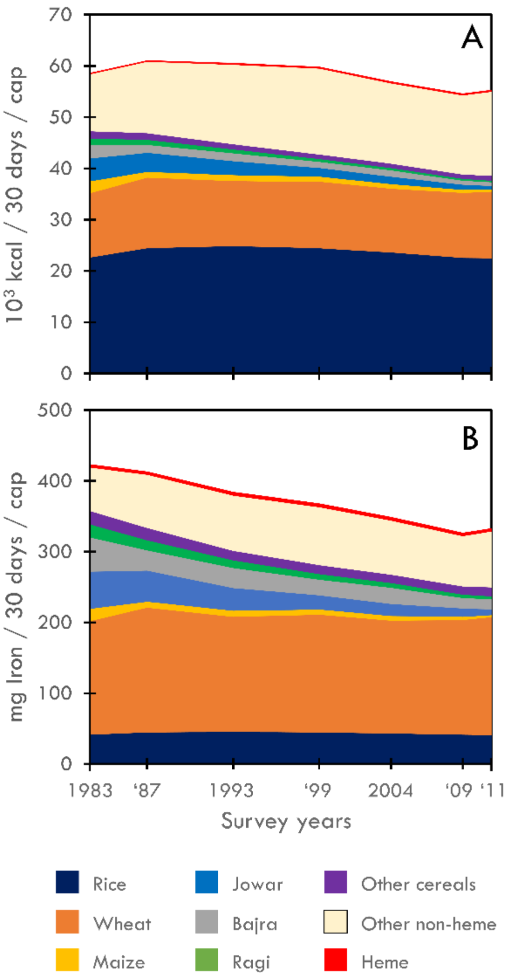


Figure 6. *Contributions of cereals, other non-heme food groups, and heme sources (meat and fish) to per capita consumption of calories (top) and iron (bottom) averaged nationally for rural households in consumption surveys from 1983 to 2011. From (DeFries et al., 2018).*

In the context of the urgent need to reduce micro-nutrient deficiencies, increase water use efficiency for cereals, and improve resilience to climate variability, while providing adequate production, we optimized the spatial allocation of cereal production across districts in India for three scenarios (analysis conducted by Narasimha Rao, IIASA; Kyle Davis, Columbia University; and Ashwini Chhatre, Indian School of Business in addition to the author*):* maximize iron production; minimize water use; and maximize climate resilience. To quantify climate resilience, we compare the loss of production in the most extreme dry year (year of minimum precipitation since 1970) relative to current production (average 2007-11) for different cereals. Additional scenarios, not shown here, include minimizing greenhouse gases and minimizing energy use.

To construct the scenarios and respect historical, regional preferences for different cereals, we imposed the following constraints: overall production of cereals must be at least equal to current (average 2007-11) amounts and calorie production within 1% of current level; total area for cereal production remains at current level; and traditional cereals can replace rice only in districts where the traditional cereal is currently produced. The scenarios are able to maintain production because yields of coarse cereals are higher than yields of rice in some districts (Figure 7).

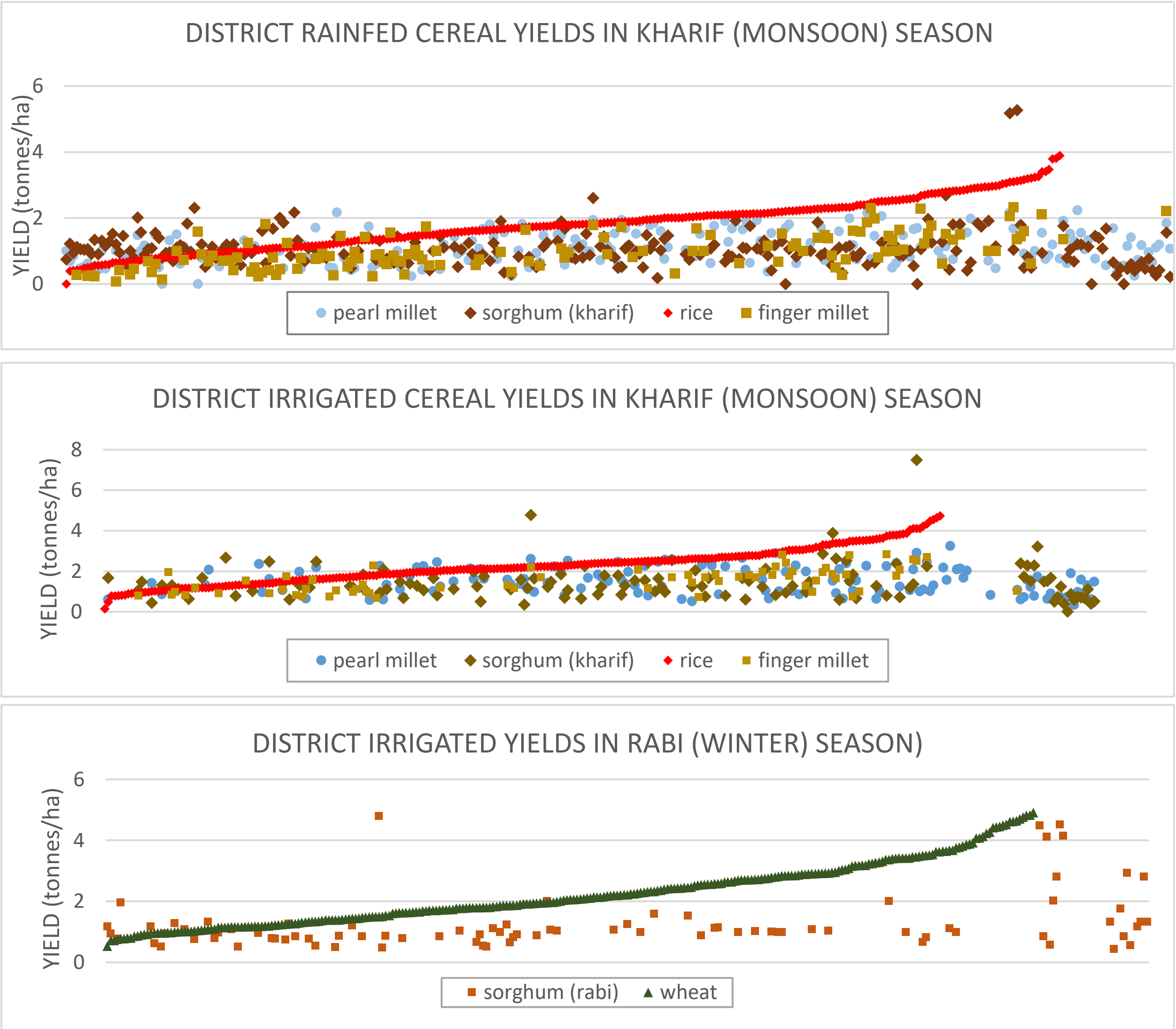


Figure 7. *District yields for cereals in order of low to high yield for rice (monsoon season) and wheat (winter season). Yield data from VDSA data base (available through ICRISAT) and apportioned between irrigated and rainfed based on India agricultural census yield data. Points above the rice (monsoon) and wheat (winter) line indicate that yield of an alternative cereal are higher than rice (monsoon) and wheat (rabi) for that district.*

With each scenario, the mix of cereal production in districts varies. For example, Figure 8 illustrates increased production of pearl millet in northwestern districts and sorghum in central India to maximize production of iron while maintaining overall production quantities. Each scenario has a different mix of cereals (Figure 8).

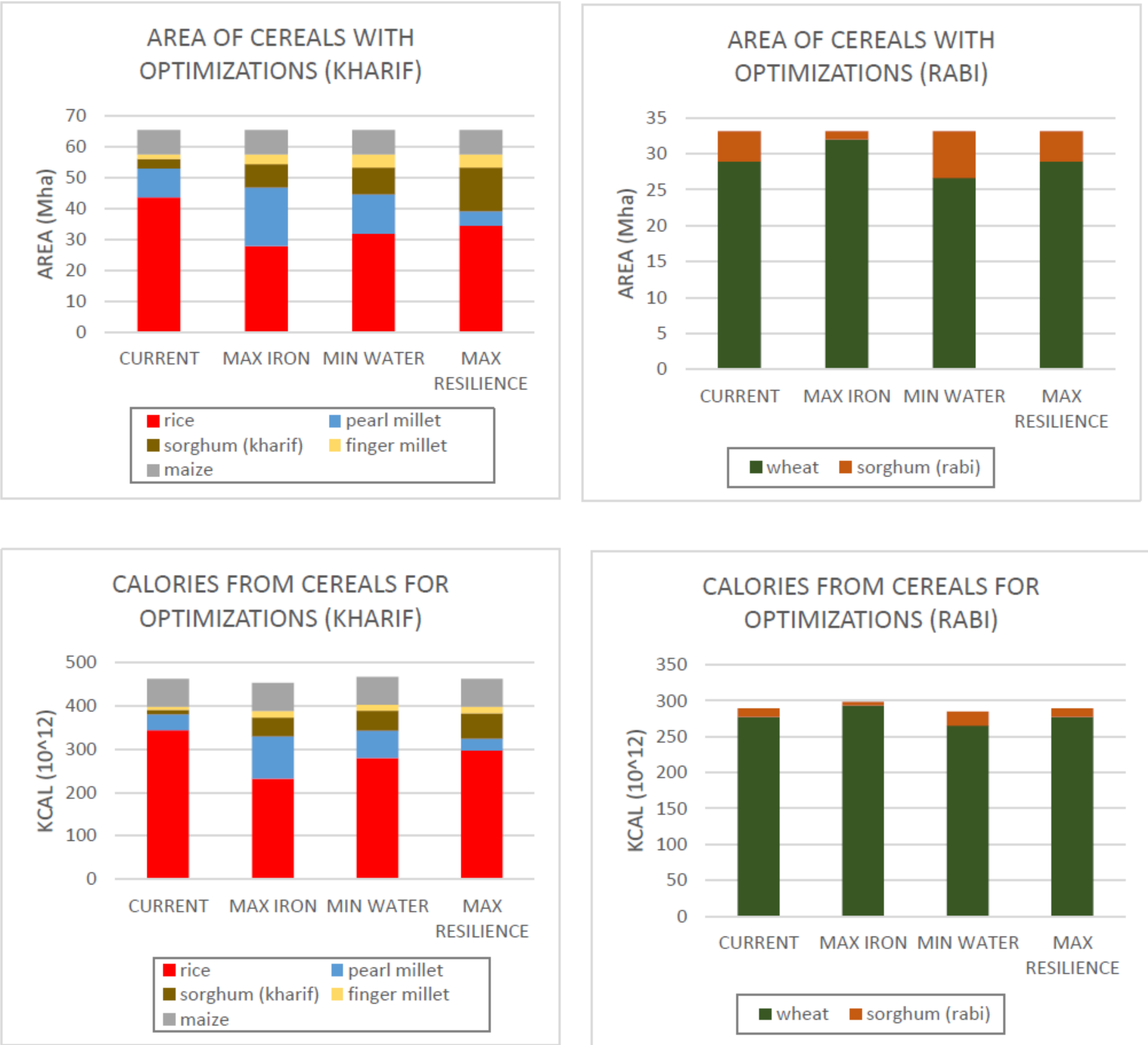


Figure 8. *Proportions of cereal production for three scenarios (maximum iron production, minimum water requirement, and maximum climate resilience) based on allocation of rice, pearl millet, finger millet, and sorghum for kharif (monsoon season) and rabi (winter season).*

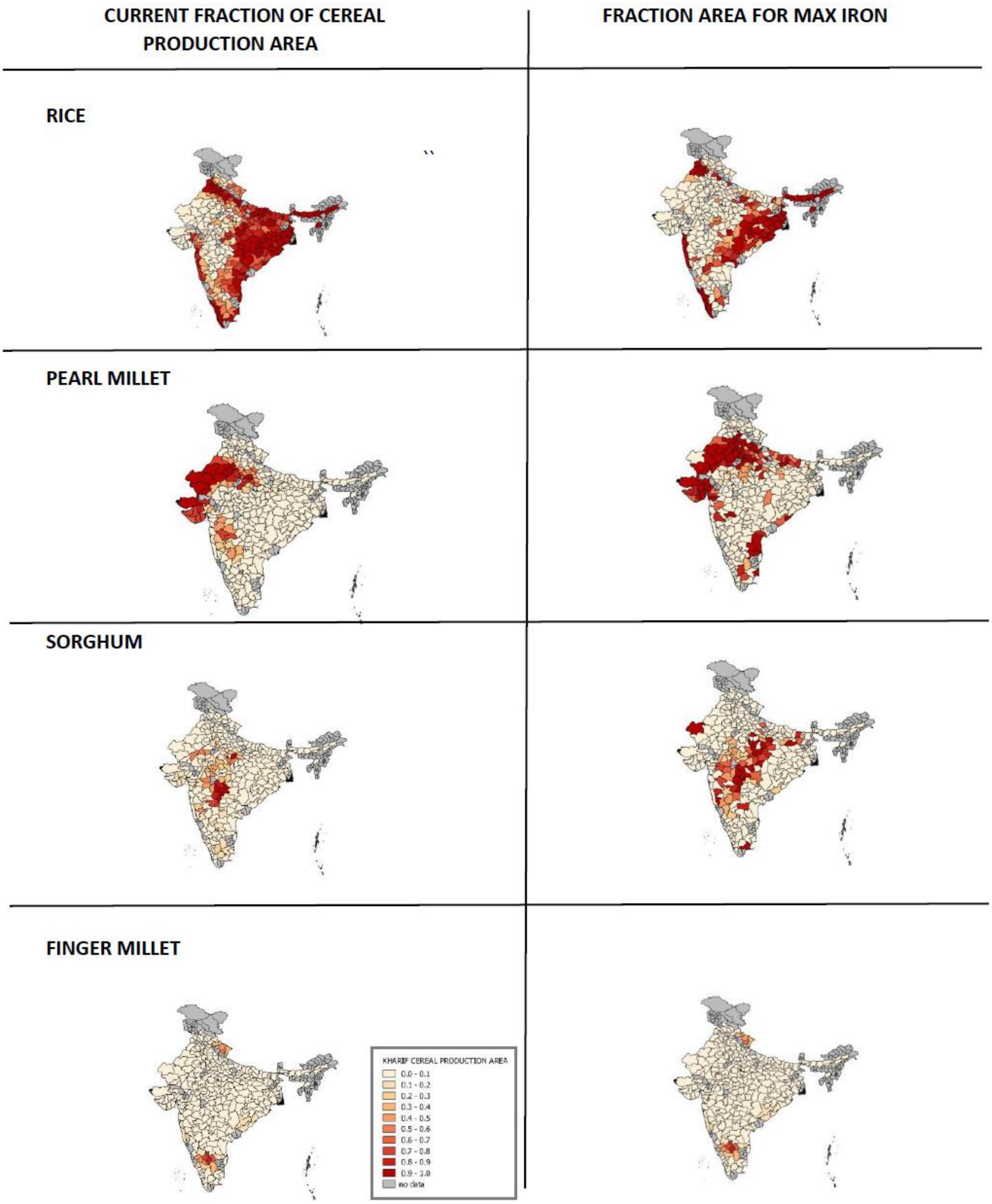


Figure 9. *Allocation of cereal production area across districts in kharif (monsoon) season for current and maximized production of iron.*

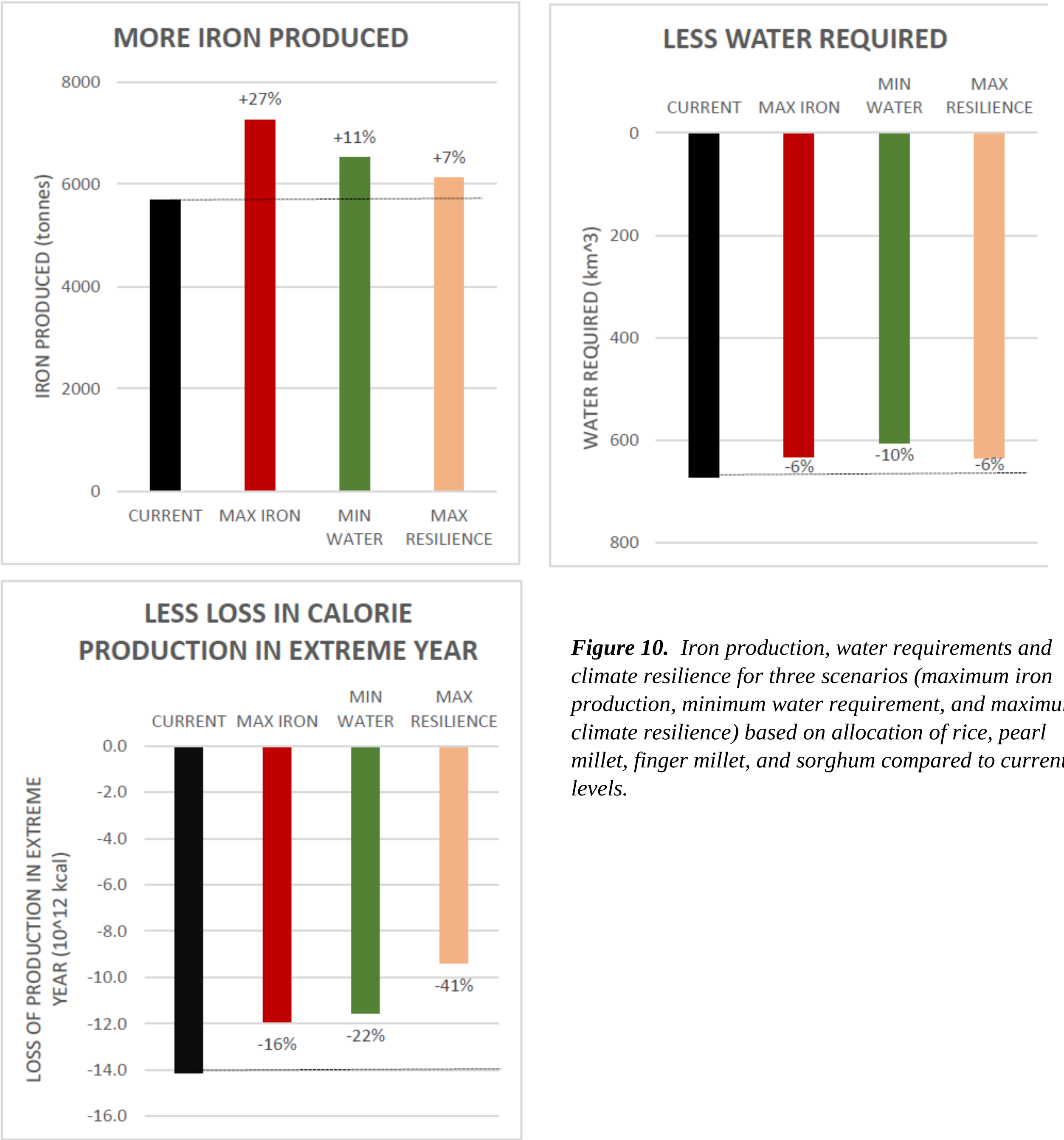


Figure 10. *Iron production, water requirements and climate resilience for three scenarios (maximum iron production, minimum water requirement, and maximum climate resilience) based on allocation of rice, pearl millet, finger millet, and sorghum compared to current levels.*

We find that all scenarios simultaneously achieve increased iron production, reduced water demand, and increased climate resilience to varying degrees (Figure 10). The case study illustrates that traditional cereals can contribute to meeting objectives of providing micronutrients, reducing water demand, and climate resilience without sacrificing production or increasing cropped area, if the locations and replacement cereal are selected carefully. Cultural preferences, market access, and processing capacity are primary considerations that require further empirical data. Increasing popularity of traditional cereals, government attention on "nutri-cereals," and recent cultural memory of traditional cereals in diets suggest an opportunity for increased consumption of traditional cereals.

Improvements of minor cereals would increase their utility further. Further synergies exist with increased focus on coarse cereals, particularly for greenhouse gas emissions due to methane emissions from rice.

In summary, India currently faces urgent challenges of hidden hunger, water shortages, and increasing climate variability. These challenges could be addressed through re-alignment of the cereal production system to increase diversity of cereals. Increased production and consumption of coarse cereals that were more commonly consumed in recent decades could make a major contribution to improved nutrition, decreased water use, and climate resilience without sacrificing production or increasing cropped area.

7.0 IMPLICATIONS FOR INTERNATIONAL AGRICULTURAL RESEARCH AND PRACTICE

The main message of this paper is the need to incorporate dimensions that were not apparent at the beginning of the Green Revolution into decisions about research and investment on cereal production. These dimensions include increased micronutrient production to help combat hidden hunger and climate resilience to reduce vulnerability to climate change. As the international, public organization for agricultural research and implementation, CGIAR plays a pivotal role in setting the agenda and pursuing achievable, practical solutions to these pressing problems. Decision-making processes that incorporate multiple dimensions often face obstacles in large, dispersed organizations such as the CGIAR. Possible mechanisms to foster processes that account for trade-offs and synergies across multiple dimensions include:

- Experts on nutrition and climate interacting with traditional research to incorporate multiple dimensions in evaluation of desirable characteristics for cultivars
- Modes of interaction across programs to minimize stovepipes focused on individual cereals and to realign around crop systems
- Measurable and practical metrics to quantify multiple dimensions of interest related to the Sustainable Development Goals
- Monitoring uptake and outcomes from introduction of cereal cultivars based on multi-dimensional metrics
- Institutional arrangements that provide flexibility to adapt to required changes based on information from monitoring and re-evaluation
- Investment in coarse cereals to maximize advantages for nutrition and climate resilience

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