# Assessing the sustainability of post-Green Revolution cereals in India

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Contributed by Ruth DeFries, October 11, 2019 (sent for review June 26, 2019; reviewed by Prabhu L. Pingali and Navin Ramankutty)

**Sustainable food systems aim to provide sufficient and nutritious food, while maximizing climate resilience and minimizing resource demands as well as negative environmental impacts. Historical practices, notably the Green Revolution, prioritized the single objective to maximize production over other nutritional and environmental dimensions. We quantitatively assess outcomes of alternative production decisions across multiple objectives using India's rice-dominated monsoon cereal production as an example. We perform a series of optimizations to maximize nutrient production (i.e., protein and iron), minimize greenhouse gas (GHG) emissions and resource use (i.e., water and energy), or maximize resilience to climate extremes. We find that increasing the area under coarse cereals (i.e., millets, sorghum) improves nutritional supply (on average, +1% to +5% protein and +5% to +49% iron), increases climate resilience (1% to 13% fewer calories lost during an extreme dry year), and reduces GHGs (−2% to −13%) and demand for irrigation water (−3% to −21%) and energy (−2% to −12%) while maintaining calorie production and cropped area. The extent of these benefits partly depends on the feasibility of switching cropped area from rice to coarse cereals. Based on current production practices in 2 states, supporting these cobenefits could require greater manure and draft power but similar or less labor, fertilizer, and machinery. National- and state-level strategies considering multiple objectives in decisions about cereal production can move beyond many shortcomings of the Green Revolution while reinforcing the benefits. This ability to realistically incorporate multiple dimensions into intervention planning and implementation is the crux of sustainable food production systems worldwide.**

Green Revolution | sustainable agriculture | India | cereals | tradeoffs

Global food supply has increased markedly over the past 50 y, rising to meet the demands of a growing, more affluent population and preventing widespread hunger and famine. Substantial increases in natural resource demand and greenhouse gas (GHG) emissions supported a tripling of food production (1, 2), and as a result, agriculture is now one of the most extensive activities by which humanity modifies natural systems (e.g., ref. 3). At the same time, staple crop production has shifted away from more nutritious cereals toward high-yielding cereals (4), and a triple burden of malnutrition has emerged, in which 1 in 9 people is undernourished, 1 in 8 adults is obese, and 1 in 5 people is affected by some form of micronutrient deficiency (5). Thus while efforts to increase food production have been largely successful, historical approaches have meant substantial compromises for nutrition security and the environment (6, 7).

As a result of these ever-growing human demands and their mounting pressure on natural systems, improving the sustainability of food systems means not only continuing to increase food production but also enhancing nutrition, adapting to climate change, and minimizing greenhouse gas emissions and environmental impacts (1, 2, 6). Solution-oriented science that links knowledge generation with the needs of decision makers to inform policy solutions can be used to highlight tradeoffs and synergies across multiple dimensions (e.g., refs. 8–13). Recent work focused on food system sustainability has identified opportunities to achieve improved nutritional and environmental outcomes in tandem through solutions such as improved technology and management (e.g., ref. 14), dietary changes (e.g., refs. 15 and 16), and the spatial optimization of crops (e.g., ref. 17) and input use (e.g., refs. 18 and 19). Other work has sought to identify pathways for achieving multiple sustainable development objectives through coproduction relationships in which knowledge building and decision making shape and inform one another (12, 20–23). All of these efforts point to a growing need for integrated and transdisciplinary approaches to inform food system decision making—a call to action with which scientists and policymakers continue to grapple and which emerging initiatives are only starting to address [e.g., EAT-Lancet (24), TEEBAgriFood (25)].

Many of the challenges resulting from the Green Revolution persist, and solutions tailored to local conditions are urgently needed. In India—one of the primary beneficiaries of the Green Revolution—the promotion of high-yielding varieties of rice and

## Significance

**Substantial growth in food production has occurred from a narrowing diversity of crops over the last 50 y. Agricultural policies have largely focused on the single objective of maximizing production with less attention given to nutrition, climate, and environment. Decisions about sustainable food systems require quantifying and assessing multiple dimensions together. In India, diversifying crop production to include more coarse cereals, such as millets and sorghum, can make food supply more nutritious, reduce resource demand and greenhouse gas emissions, and enhance climate resilience without reducing calorie production or requiring more land. Similar multidimensional approaches to food production challenges in other parts of the world can identify win–win scenarios where food systems meet multiple nutritional, environmental, and climate resilience goals.**

Author contributions: K.F.D., A.C., N.D.R., and R.D. designed research; K.F.D., A.C., N.D.R., D.S., S.G.-J., A.M., M.P.-C., N.P., and R.D. performed research; K.F.D., A.C., N.D.R., A.M., M.P.-C., N.P., and R.D. analyzed data; and K.F.D., A.C., N.D.R., D.S., S.G.-J., and R.D. wrote the paper.

Reviewers: P.L.P., Cornell University; and N.R., University of British Columbia.

The authors declare no competing interest.



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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1910935116/-/DCSupplemental.

First published November 21, 2019.

wheat has driven a tripling of cereal production over the past 50 y (26). As a result, rice and wheat now contribute three-quarters of the country's cereal production (44% and 30%, respectively) (26), and cereals continue to comprise much of per capita calorie consumption—60% and 70% in urban and rural households (27). For the monsoon season in particular, these trends have led to a homogenization of cereal production toward rice. Between the years 1966 and 2011, total cropped areas for monsoon cereals remained nearly constant, while harvested areas dedicated to monsoon rice increased from 52% to 67% (+7.3 Mha) (26). Owing to the increased share of monsoon cereal area dedicated to rice—often in places where agroecological conditions are not well suited (e.g., water scarcity) (28), there have been large declines in areas used for coarse cereals such as finger millet, pearl millet, and sorghum as well as dietary shifts away from their consumption (27, 29). This growing dominance of rice in monsoon croplands is due to the underlying policy regime that has made rice cultivation more profitable, expanded use of irrigation and other agricultural inputs, and focused investments in research and development (7, 28). Yet these cereals have higher nutritional quality (30) (*SI Appendix*, Table S1), greater resource use efficiencies per unit of production (31–35), and lower sensitivity to climate variability compared to rice (even after controlling for areas where rice production co-occurs with that of coarse cereals) (36). In addition, a high proportion of rice in diets is linked with incidence of anemia in women (27). Thus while the potential benefits of these coarse cereals have been demonstrated for individual dimensions, it remains unclear whether increasing the diversity of cereal production would lead to tradeoffs among nutrient supply, climate resilience, and environmental outcomes.

Here we consider 4 monsoon cereals—finger millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*), rice (*Oryza sativa*), and sorghum (*Sorghum bicolor*)—which collectively contribute 85% of cereal production for the season (years 2007 to 2011 average) (26). While rice has historically been promoted within the country, the 3 coarse cereals considered here (finger millet, pearl millet, and sorghum) are part of a recent push by the Government of India—as well as several states (e.g., Andhra Pradesh, Karnataka, Odisha, Tamil Nadu)—to encourage the production and consumption of "nutri-cereals" (37). We do not consider wheat, which is grown exclusively during the winter (rabi) season. We also hold maize production constant as the crop is not included among the nutri-cereals being actively promoted by state and federal governments under the National Food Security Mission, and a large and increasing fraction of its production (52%) is utilized for animal feed (30%) and exports (22%) (38). It is therefore unlikely that any increase in maize production would serve as a staple substitute for rice in diets. We combine crop-specific district-level data (2007 to 2011 average) on rainfed and irrigated yields and harvested areas with information on each cereal's protein and iron content (30), energy and GHG intensities (34), water use efficiency (32), and yield variations due to variability in temperature and precipitation (36). Using these data, we estimate the nutritional supply, energy and water demands, greenhouse gas emissions, and climate sensitivity of current monsoon cereal production. We then perform a series of national optimizations to assess the tradeoffs and cobenefits in these outcomes when each one is accorded highest priority: 1) maximize protein supply, 2) maximize iron supply, 3) minimize energy demand, 4) minimize GHG emissions, 5) minimize water demand, and 6) maximize climate resilience (defined as the least loss in production under an historically extreme dry year [i.e., the district-wise historical minimum monsoon precipitation from 1966 to 2011 and its corresponding temperature]). Each optimization reallocates cropped areas between cereals with the constraints that cropped area for cereals within each district remains constant, only cereals currently grown within a district can be planted there, and calorie supply cannot decrease in any state—a constraint reflecting the fact that agricultural and food security decisions are largely made and implemented by state governments as well as the reality that drastic shifts in production patterns across states may have infeasible implications for trade and employment. As a pseudocounterfactual intended to represent a continuation of current trends in monsoon cereal production, we also run an optimization to maximize national calorie production.

The constraint that harvested area can be allocated only to cereals currently grown within a district is meant to serve as a proxy for limiting cereal diversification to the places that are agroecologically suitable. However, it remains poorly quantified to what extent the biophysical envelopes of cultivation for rice and coarse cereals overlap within a given district. To better to account for the possibility that some croplands may not be suitable for cultivating all cereals, we repeat the main set of optimizations with the added constraints that 1) the area allocated to each coarse cereal within a district could not exceed the maximum historical (1966 to 2011) harvested area for that cereal in that district and 2) the total area allocated to coarse cereals within a district could not exceed the maximum historical (1966 to 2011) harvested area for coarse cereals in that district. We note that all optimizations do not address places of consumption or interstate trade. Using plot-level farmer surveys for 2 states in which data were complete for the study cereals, we also quantify how these optimized configurations of croplands may alter the inputs to production (e.g., seeds, labor, fertilizers, and manure). Such simultaneous evaluations of multiple objectives offer promise for developing interventions that achieve sustainable food production systems and provide an approach that can be readily applied to similar challenges elsewhere. We intend these simulations as thought experiments to evaluate the potential cobenefits and tradeoffs across multiple dimensions rather than recommendations for actual implementation, as the latter would involve many considerations such as markets, farmer readiness, and consumer demands.

## Results

The current configuration of monsoon (kharif) cereal production is dominated by rice, which occupies 67% of monsoon cereal area. Rice also currently contributes substantially to the supply of calories (74% of kharif cereal production), protein (70%), and iron (31%); constitutes much of monsoon resource use for cereal production (energy [80%], GHGs [90%], and water [81%]); and makes up the vast majority of calorie loss (89%) under an extremely dry year (Table 1). These statistics point to the disproportionately large contribution of rice production to resource use, greenhouse gases, and climate sensitivity relative to its share of kharif cereal calorie production. Combined with the fact that yields of coarse cereals are greater than those of rice in certain districts and comparable in many others (*SI Appendix*, Fig. S1), this highlights the potential for selective increases in the share of cereal production from coarse cereals to achieve cobenefits for the supply of key nutrients, climate resilience, and the environment.

Across all 6 optimization objectives, we observed increases in the combined share of calories contributed by coarse cereals (from 14% currently to 21% to 32%), even though rice continued to contribute the majority of calorie production (Fig. 1). In addition, the share of calories contributed by each coarse cereal increased relative to its current fraction, with the only exception being finger millet in the scenario to maximize national protein supply. Only certain states (e.g., Bihar, Gujarat, Haryana, Jharkhand, Madhya Pradesh, Tamil Nadu, and Uttar Pradesh) experienced large increases in the share of calorie production contributed by coarse cereals (*SI Appendix*, Figs. S2–S4). This reflects the localized expansion of coarse cereals from areas in which their cultivation is centered and is based on the constraint of the optimization that expansion can occur only in districts where coarse cereals are currently grown (Fig. 2 and *SI Appendix*, Figs. S5–S9). Because harvested area for cereals within each district was held constant, these collective increases in harvested area for coarse cereals meant reductions in the area cultivated for rice. In comparison,

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**Table 1. Current nutrient production, resource use, and climate resilience of monsoon (kharif) cereals**

| Characteristics | Finger millet | Maize | Pearl millet | Rice | Sorghum | % for rice |
|---|---|---|---|---|---|---|
| Harvested area, Mha | 1.4 | 7.9 | 9.4 | 43.6 | 3.1 | 67 |
| Food supply | | | | | | |
| Calories, $10^{12}$ kcal | 6.7 | 64.6 | 35.9 | 344.3 | 11.2 | 74 |
| Protein, ktonne | 149 | 1,702 | 1,131 | 7679 | 334 | 70 |
| Iron, ton | 96 | 482 | 662 | 629 | 132 | 31 |
| Resource demand and emissions | | | | | | |
| Irrigation water, $km^3$ | 0.1 | 0.9 | 0.5 | 76.7 | 0.1 | 98 |
| Energy, $10^9$ kWh | 1.1 | 15.5 | 4.7 | 94.0 | 2.4 | 80 |
| GHGs, Mtonne $CO_2$eq | 0.6 | 12.3 | 3.8 | 161.5 | 1.5 | 90 |
| Resilience, $10^{12}$ kcal loss under extremely dry year | 0.00 | 0.00 | −1.39 | −11.47 | −0.03 | 89 |

Data are an average of the years 2007 through 2011. Maize harvested area and production were not considered in our analysis.

the pseudocounterfactual optimization to maximize national calorie production led to a modest 7% increase in calorie supply, increases in harvested area allocated to rice (+3%) and sorghum (+54%), and decreases in areas for pearl millet (−19%) and finger millet (−79%). These results confirm that Indian cereal production has been developed to maximize calorie production and that rice plays a central role in achieving this end.

We also found the potential for substantial increases in iron supply, modest improvements in protein supply, reductions in water and energy demands and GHG emissions, and enhancements of climate resilience (Fig. 3 and *SI Appendix*, Tables S2–S7)—all while maintaining calorie production from cereals within each state. These results were consistent when imposing a national-level calorie constraint rather than a state-level one, when considering changes in the allocation of winter (rabi) cereal production areas or when using state as units of optimization rather than districts (*SI Appendix*, Fig. S10). We also note that because these single-objective optimizations did not produce any real tradeoffs among the dimensions that we considered (*SI Appendix*, Table S8), we did not perform any multiobjective optimizations. National iron supply from cereals could increase by 49% on average (+737 tons annually). Changes in protein supply were relatively modest in comparison (+5%) due to the overall similarity in protein content between cereals. Reductions in total water demand were also modest (−8%), while monsoon irrigation water demand could be reduced by 16 $km^3$ $H_2O$ on average (or −21%) and in many places that currently experience declining groundwater tables (*SI Appendix*, Fig. S11) (32). Energy demand reduced by an average 12%, and GHG emissions were reduced by an average 21 Mtonne $CO_2$eq (−13%). Further, by increasing areas cultivating coarse cereals, the loss of calories under an extremely dry year would reduce by 13% on average. These estimated changes are in large part a reflection of the nutritional and environmental characteristics of rice in comparison to coarse grains [i.e., comparable protein content; lower iron content (*SI Appendix*, Table S1); less efficient intensities of water use (32), energy use, and GHG emissions (34); and higher climate sensitivity (36)].

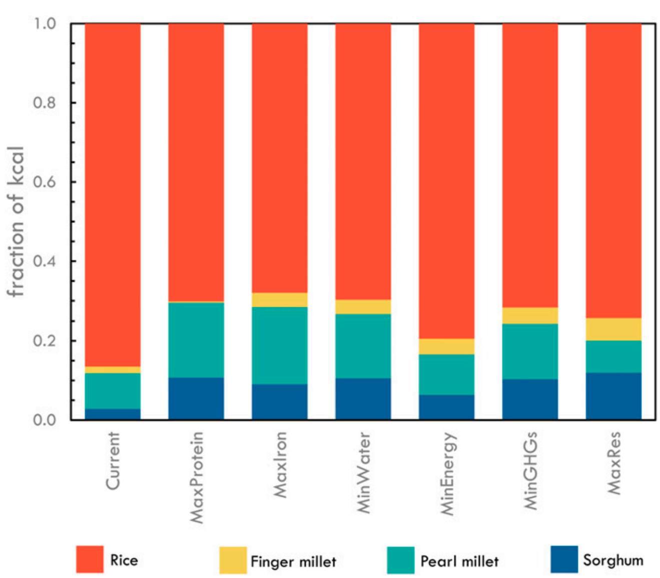


**Fig. 1.** Current and optimized shares of monsoon cereal production. These proportions include the 4 cereals analyzed in this study—finger millet, pearl millet, rice, and sorghum. Because maize production was held constant across all scenarios, its contribution to calories from monsoon cereals is not included here (Table 1).

Certain states contributed disproportionately to these benefits (Fig. 4). Across the dimensions of iron supply, water, energy, and GHG emissions, states in the central (Madhya Pradesh, Uttar Pradesh), east (Bihar, Jharkhand), and south regions (Andhra Pradesh, Tamil Nadu) were responsible for many of the improvements (*SI Appendix*, Tables S2–S7). Bihar alone contributed 33% of the improvement in climate resilience, and Bihar, Tamil Nadu, and Uttar Pradesh were responsible for greater than 50% of the benefits across all dimensions. Assam, Himachal Pradesh, Kerala, Odisha, Punjab, and West Bengal would see few or no improvements. Overall, these results suggest that targeted interventions in only a few states can produce substantial benefits for national-level nutrient supply, climate resilience, and the environment.

When we further constrained the 6 optimization objectives to allow coarse cereal expansion to occur only up to the maximum extent historically reported within each district, we found that all scenarios (except the minimization of national energy demand) still saw increases in the share of calories contributed by coarse cereals and, on average, produced cobenefits across all dimensions—+1% protein, +5% iron, −2% energy demand, −1% irrigation water demand, −2% GHG emissions, and 1% fewer calories lost under an extremely dry year (Fig. 3 and *SI Appendix*, Table S9). Not surprisingly, benefits were substantially muted (7% to 18% of those achieved above)—with the effect of the historical constraint similar across objectives—and, in certain scenarios (e.g., minimization of national energy demand), tradeoffs began to emerge. Compared to the results in which coarse cereal expansion was not constrained by historical extent, this set of optimizations points to the need for research and development to enhance coarse grain yields and to develop varieties adapted to a wider range of growing conditions to fully achieve the estimated cobenefits.

Finally, we quantified the potential changes in farmer inputs that would occur under the first set of optimizations (i.e., with no

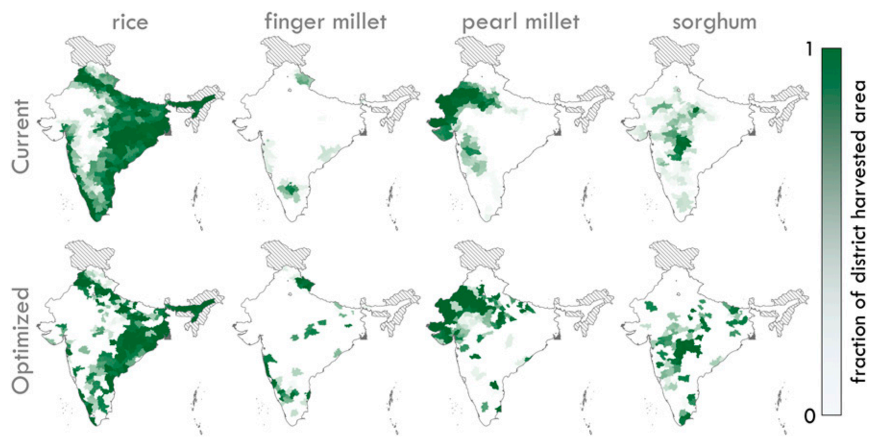


**Fig. 2.** Allocation of harvested area under current production and under scenario to minimize water demand. Maps show the fraction of each district's monsoon cereal area allocated to each crop. Areas with diagonal lines indicate places with no data. Maize maps are not shown because maize production was held constant. Maps for other optimization scenarios are shown in *SI Appendix*, Figs. S5–S9.

historical constraint on coarse cereal area within a district)—assuming current (2007 to 2011) cultivation practices—by focusing on the states of Karnataka and Tamil Nadu (for which farmer input survey data were complete) (Fig. 5). In Karnataka, we observed reductions in seed use and fertilizer use. Hours for labor, draft animal power, and machinery and irrigation pumping remained largely the same. However, manure use would need to increase across all scenarios to support the expanded roles of finger millet and sorghum in the state—assuming that current cultivation practices remained constant—with potential indirect consequences for livestock production and methane emissions. In Tamil Nadu, we estimate that increasing the share of production contributed by coarse cereals would lead to substantial reductions in seed and fertilizer use as well as hours for labor and machinery and irrigation pumping. The outcomes for manure use and draft animal power, however, depend on the optimization objective, with sorghum generally requiring more manure and pearl millet contributing to increased draft animal requirements. For these 2 states, the decreases in fertilizer demand and increases in manure demand suggest that—because current agricultural incentives typically make it a more valuable crop for farmers—rice fields tend to receive the higher-value synthetic fertilizer inputs while lower-value inputs like manure are devoted to coarse cereals. Policies that also promote the production of coarse cereals may therefore mean a shift in how farmers prioritize the use of their available inputs.

## Discussion

Food systems across the planet face the multiple challenges of increasing food supply, improving nutrition, minimizing environmental impacts, and adapting to climate change. Solutions that have multiple cobenefits (and reduce or eliminate tradeoffs) among these objectives are essential for improving food system sustainability. In the case of India, our results indicate that increasing the



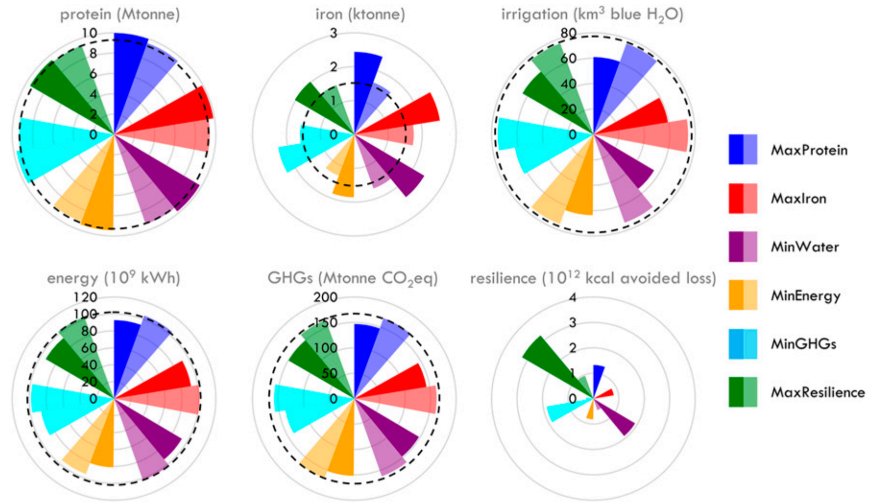


**Fig. 3.** Outcomes of optimizations for nutrient supply, environment, and climate resilience. Each color corresponds to 1 of the 6 optimization scenarios. Bold-colored wedges correspond to the optimization scenarios that do not constrain coarse cereal area within a district, and faded wedges correspond to the scenarios in which coarse cereal expansion could occur only up to the maximum extent historically reported within each district. Black dashed lines represent current nutrient supply, resource demand, and emissions. For climate resilience, a larger wedge indicates a greater benefit. Because climate resilience was calculated as the difference between the calories lost under an extremely dry year under current cropping patterns and the calories lost under an extremely dry year under optimized cropping patterns, there is no black line shown for that panel. In addition, 3 scenarios (MaxProtein, MaxIron, and MinEnergy) saw decreased resilience under the constraint to historically limit coarse cereal expansion (*SI Appendix*, Table S9) and appear as zeros in the resilience panel. All values are presented in *SI Appendix*, Tables S2–S9.

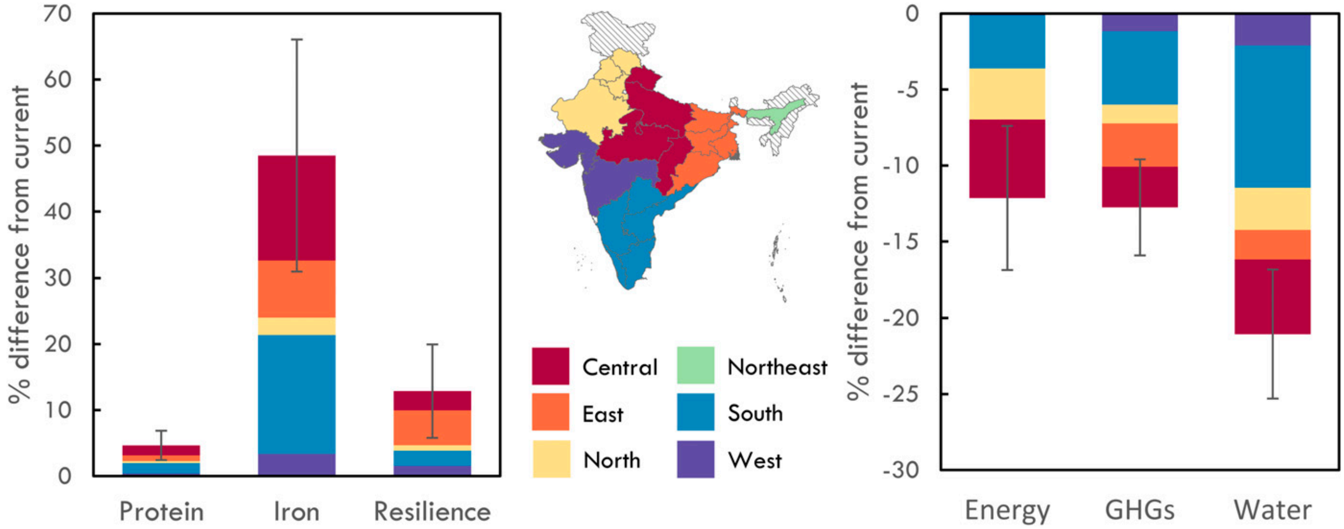


**Fig. 4.** State-level breakdown of optimization outcomes. Columns show the average outcome across the 6 optimization scenarios. Error bars represent the range of outcomes across the 6 optimization scenarios. Regions are based on those defined in Longvah et al. (30). State-level values are presented in *SI Appendix*, Tables S2–S7.

diversity of cereal production with coarse cereals (i.e., millets and sorghum) consistently improves outcomes for nutritious food supply, climate resilience, irrigated water and energy demand, and GHG emissions regardless of how these objectives are prioritized. These benefits would come without compromising calorie supply in any state or requiring increased cropland area for cereals in any district.

Our district-level analysis—which optimized national outcomes—also allowed us to account for the spatial differences in many of the variables that we considered and thereby allowed for the identification of specific parts of India where increased coarse cereal production would realize the largest benefits in states where it is currently grown. As such, the benefits of this strategy were not evenly spread across the country, with much of the improvements occurring only in certain states (Fig. 4). Given our constraint that each state must maintain its calorie production, this demonstrates, on one hand, that these states could potentially achieve the estimated benefits independent of the ability of each to coordinate with other states, as outcomes were nearly the same when the state-level calorie constraint was relaxed. On the other hand, our analysis shows that for certain states (e.g., Assam, Himachal Pradesh, Kerala) this intervention of increased coarse cereal production would provide little or no direct improvement across all dimensions unless efforts are made to improve yields of coarse cereals or to plant coarse cereals in locations where they have not historically been cultivated. However, for these states, interstate trade could still mean that they indirectly experience some of the benefits, especially in regard to improved national nutritional supply.

Increases in coarse cereal production largely occurred in or close to the places where the cultivation of these cereals is currently centered (Fig. 2). This is encouraging from a farmer perspective as the local knowledge of effective crop management practices may be more readily available. In addition, some districts in these areas (e.g., pearl millet and sorghum in central India) have coarse cereal yields that are similar to (or exceed) those of rice (*SI Appendix*, Fig. S1). Further, the dietary compositions of populations living in these baskets of coarse cereal cultivation—such as pearl millet in the northwest and sorghum in central India—tend to have higher fractions of these crops in their overall cereal consumption (*SI Appendix*, Fig. S12). Thus, the finding that drastic shifts in cropping patterns would not be required to achieve substantial benefits for nutrition supply, climate resilience, and the environment is promising from both production and consumption perspectives. At the same time, additional expansion of coarse cereals to deepen the benefits—especially in places such as Punjab where rice is particularly high yielding but where unsustainable resource use is widespread—would require investments to improve yields of coarse cereals and interventions that account for and prioritize finite resource availability (e.g., minimizing water scarcity or groundwater depletion) while still assessing outcomes across multiple dimensions.

Despite the multiple cobenefits that we observe, economic factors play a key role in determining a farmer's crop choice (39) and likely explain much of the historical shift toward the cultivation of rice and wheat—crops for which the Indian government sets guaranteed minimum support prices (MSPs) and large procurement goals to supply national food security programs (e.g., the Public Distribution System [PDS])—and away from coarse cereals which have had minimal (if any) annual procurement targets. These market distortions have made the production of coarse cereals less economically attractive until only recently when the Indian government and several state governments (e.g., Karnataka, Odisha) decided to procure selected coarse cereals at MSP—a move aimed at simultaneously incentivizing their cultivation and meeting national commitments to double farmers' income by 2022. In addition to the price offered for a crop, a farmer's profitability is determined by input costs of production—both in effort and in resources—and interventions promoting the expansion of coarse cereals must also anticipate these potential changes in input requirements (Fig. 5). Further, increasing consumption of coarse cereals in diets will depend on people's ability to pay—a barrier likely eased by the planned inclusion of coarse cereal in the PDS, their perceptions, and willingness to change (40). In this regard, it is worth noting that these cereals were consumed even more widely just a few decades ago (27), and while we do not attempt to assess it here, this expanded role of coarse cereals in the recent past may promote more extensive consumption should coarse cereal supplies increase.

A key caveat in achieving the estimated benefits of cereal diversification is the extent to which agronomic characteristics will permit switches between crops. On one hand, historical policy regimes have promoted the widespread cultivation of crops in places that may not have otherwise been agroecologically suitable

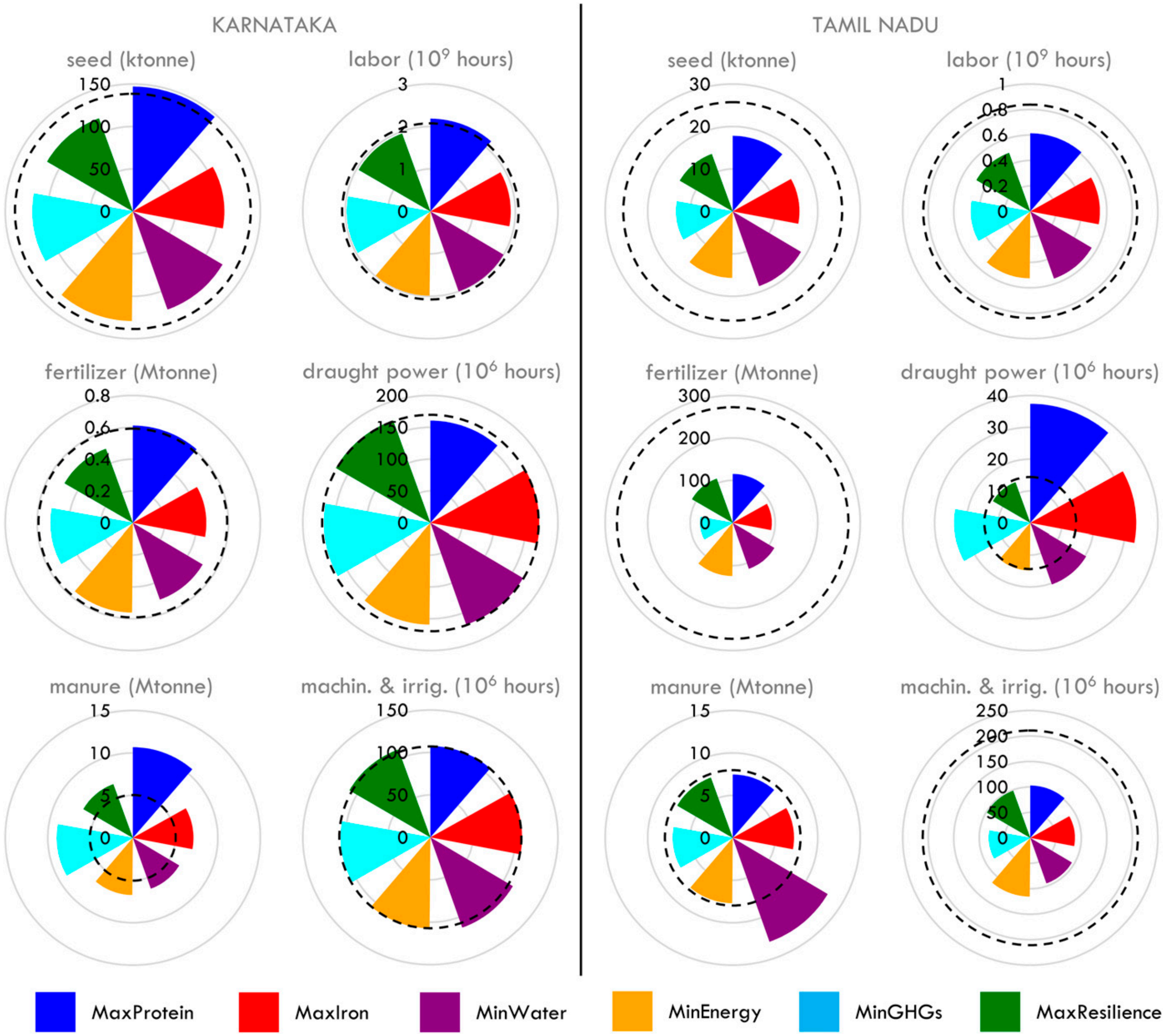


**Fig. 5.** Outcomes of optimizations for farmer inputs in Karnataka and Tamil Nadu. Each color corresponds to 1 of the 6 optimization scenarios. Black dashed lines represent current levels of inputs.



or sustainable (e.g., rice in northern India). On the other hand, certain areas where rice is currently grown (e.g., low-lying floodplains) may not be able to support the cultivation of coarse cereals. Assessments quantifying the range of biophysical conditions that can support the cultivation of each cereal will therefore be essential for understanding the potential magnitude of cobenefits from increased coarse cereal production. Other aspects not considered in this analysis include the bioavailability of certain nutrients from cereals (e.g., iron) and farmer willingness, as well as implications of altered crop production mixes for processing and supply chains (41). There are also opportunities for extending our approach to consider not only changes in the allocation of cropped areas between cereals but also a reallocation of all croplands (including those used for cash crops as well as other food groups) to meet different food security and sustainability objectives.

For all of this analysis, we note that, while these outcomes provided benefits across all of the dimensions considered in this study, the magnitude of these benefits varied by scenario and, in some instances, led to "soft" tradeoffs between the dimensions (Fig. 3 and *SI Appendix*, Table S8). For instance, the scenario to minimize energy demand provided minimal benefits for climate resilience and the lowest amount of additional iron. Similarly, the scenario to maximize climate resilience provided some of the smallest benefits for iron supply and reductions in water and energy demands as well as GHG emissions. Depending on the outcomes that are of greatest priority to decision makers and stakeholders in a particular place, other dimensions may also be improved, but the magnitude of those cobenefits may be muted.

The growing homogenization of Indian cereal production is a hallmark example of the mixed outcomes and stark tradeoffs of the Green Revolution, where the country's food supply has increased substantially at the cost of eroded nutritional quality of its cereal basket (4), unsustainable resource use (e.g., ref. 32), and greater vulnerability to climate variability (36). By adopting a multidimensional perspective this study identifies concrete opportunities for replacing rice with coarse cereals in a manner that reduces or eliminates many of the tradeoffs between food production, supply of nutrients, climate resilience, and resource requirements. This approach also provides the necessary flexibility to be adapted to a variety of situations and priorities that decision makers may face in their efforts to realize more sustainable food systems.

Strategies to enhance the sustainability of food systems require the quantification and assessment of tradeoffs and cobenefits across multiple dimensions. This analysis addresses cereal production during the monsoon season in India, one of the major countries that benefited from Green Revolution technologies. As countries continue to grapple with the challenges of increasing food production, enhancing the climate resilience of production systems, addressing micronutrient deficiencies, and reducing environmental impacts, assessments that account for multiple dimensions will offer the most promise for maintaining the benefits of the Green Revolution while moving beyond its shortcomings. Such a multidimensional perspective, based on the cultural, climatic, and ecological setting of each country, provides an effective approach for assessing the current state of food production systems across a suite of outcomes and for informing decisions to enhance their sustainability.

## Methods

We performed an array of national optimizations to assess opportunities for the diversification of cereal production through increased shares of coarse cereals (i.e., finger millet, pearl millet, and sorghum) and to assess to what extent this could improve selected objectives related to nutrition, environmental sustainability, and climate resilience. We then quantified the outcomes of these optimizations across 6 dimensions—protein supply, iron supply, energy demand, greenhouse gas emissions, water demand, and hit to production under an historically extreme climate year. For 2 states (Karnataka and Tamil Nadu) for which data on farmer inputs were complete, we also quantified how these optimizations may influence farmer input requirements.

**Datasets.** Crop-specific district-level data on rainfed and irrigated production and harvested area for the period 2007 to 2011 were taken from Davis et al. (36) and derived from the International Crops Research Institute for the Semi-Arid Tropics Village Dynamics in South Asia (VDSA) mesoscale dataset (26). These data currently cover 593 of India's 707 districts and 87% of the country's land area. Following Davis et al. (32), we assume that all production of rice, finger millet, and pearl millet occurs during the monsoon (kharif) season. This assumption is supported by crop production data reported by season from the Directorate for Economics and Statistics (42), which shows that millet production during the winter (rabi) season is negligible and that only for selected states (for example, rice in Andhra Pradesh, Odisha, Tamil Nadu, and West Bengal) is winter (rabi) production substantial for rice. The VDSA dataset reports sorghum statistics as disaggregated between monsoon (kharif) and winter (rabi) seasons. National nutrient content values for calories, protein, and iron came from the Indian Food Composition Tables (30). Average crop-specific district-level data on rainfed and irrigated crop water requirements (mm $H_2O \cdot y^{-1}$) for the period 2000 to 2009 came from Davis et al. (32). Crop-specific district-level data on rainfed and irrigated greenhouse gas emission intensities (g $CO_2$eq·kg·crop$^{-1}$) and energy intensities (kWh·kg·crop$^{-1}$) for the year 2010 came from Rao et al. (34). National crop-specific coefficients of the sensitivity of irrigated and rainfed crops to interannual variability in temperature (ton·ha$^{-1}$·°C$^{-1}$) and precipitation (ton·ha$^{-1}$·mm$^{-1}$) were taken from Davis et al. (36). Climate data used for assessing the district-wise extremely dry year (i.e., the district-wise minimum monsoon precipitation and its corresponding temperature) were the Indian Meteorological Department daily rainfall dataset (0.25 °C; 1966 to 2011) (43) and the University of East Anglia's Climate Research Unit (CRU) v3.24 daily mean temperature dataset (0.5 °C; 1966 to 2011) (44).

Plot-level agricultural input data for seed (kg·ha$^{-1}$), fertilizer (kg·ha$^{-1}$), manure (kg·ha$^{-1}$), labor (h·ha$^{-1}$), animal labor (h·ha$^{-1}$), and machine and irrigation pump use (h·ha$^{-1}$) came from the Government of India's Cost of Cultivation Surveys (45). These data were separated into rainfed and irrigated observations, where any observations that reported a value greater than zero for either irrigation pumping hours or canal fees were categorized as irrigated. We then used these plot-level data to calculate an average irrigated input ($pi_{j,s}$) for crop $j$ in state $s$ across the years 2007 through 2011, with the state-level irrigated input for crop $j$ in year $t$ calculated as

$$pi_{j,s,t} = \frac{\sum(ci_{x,j,s,t} pi_{x,j,s,t})}{\sum(ci_{x,j,s,t})}, \qquad [1]$$

where $pi_{x,j,s,t}$ is the amount of input $p$ in plot $x$, and $ci$ is the plot $x$ cluster weight—a value provided within the Cost of Cultivation dataset to calculate representative values at the state level. This process was repeated for each input considered in the study. State-level rainfed inputs for each crop ($pr_{j,s}$) were calculated in the same way using information from rainfed plot-level observations.

**Optimizations and Constraints.** We considered 6 different optimization objectives for monsoon cereal production: 1) Maximize national protein supply, 2) maximize national iron supply, 3) minimize national energy demand, 4) minimize greenhouse gas emissions, 5) minimize water demand, and 6) minimize the decline in cereal production under an historically extreme climate year. Optimizations were performed using the General Algebraic Modeling System (GAMS) software.

District-level harvested area for cereals was used as the decision variable within all optimizations. The main set of results presented here incorporates the following conditions. We also provide a brief justification with each condition: 1) Calorie production within each state must be approximately equal to current state calorie production (no less and no greater than 1%). This was to prevent any production shortfalls and assumed that each state acts independent of the others, which is reasonable as most interventions are developed and enacted at the state level in India. We also considered scenarios where only national calorie production must be maintained, although the outcomes of the optimizations saw little change (*SI Appendix*, Fig. S10*A* and Table S10). 2) Harvested area for cereals within each district must remain constant. This constraint was used to prevent any agricultural expansion within the optimizations and to limit outcomes to currently cultivated lands for cereals. 3) Only cereals currently grown within a district could be allocated harvested area with that district. This accounted for soil and climate characteristics which may prevent an expanded geographical range for any of the cereals and confined the cereal production to districts where local knowledge is in place. 4) Maize harvested area remains constant. Maize area was held constant within each district because this crop is not included among the nutri-cereals (i.e., millets and sorghum) that the Indian government has recently promoted to improve nutrition, and it is unclear what portion of additional maize production would contribute to direct human consumption and what fraction would be used for animal feed. We also considered scenarios that allowed maize harvested area to vary (*SI Appendix*, Fig. S10*B* and Table S11).

For the scenario to minimize water demand, we also imposed the constraint that irrigation (blue) water demand could not increase in any district to avoid configurations that led to further depletion of surface and groundwater resources. We also considered scenarios that allowed winter (rabi) production areas for wheat and sorghum to vary, but this provided little difference from the main set of results, as winter cereal production is dominated by high-yielding wheat and offers little opportunity for sorghum to potentially replace it (*SI Appendix*, Fig. S10*C* and Table S12). Finally, we also performed optimizations at the state level using state average values for yields, crop water requirements, greenhouse gas emission intensities, and energy intensities and found these to be consistent with the main set of results (*SI Appendix*, Fig. S10*D* and Table S13). Also, because our optimizations did not produce any real tradeoffs among the dimensions that we considered, we did not perform any multiobjective optimizations.

**Data Availability.** All data used in this study are either publicly available through the references provided or available upon request from the corresponding author.

**ACKNOWLEDGMENTS.** K.F.D. was supported by Columbia University's Data Science Institute and The Nature Conservancy's NatureNet Science Fellows program. N.D.R. was in part supported by the European Research Council Starting Grant 637462.

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