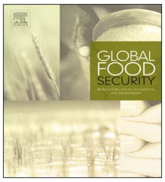
ARTICLE IN PRESS

Global Food Security ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs



# Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India

Ruth DeFries[a,*], Pinki Mondal[a,b], Deepti Singh[c], Ishan Agrawal[d], Jessica Fanzo[e], Roseline Remans[f,g], Stephen Wood[h]

[a] Department of Ecology, Evolution and Environmental Biology, Columbia University, NY, USA
[b] Center for International Earth Science Information Network, Columbia University, NY, USA
[c] Lamont-Doherty Earth Observatory, Columbia University, NY, USA
[d] Foundation for Ecological Security, Mandla, Madhya Pradesh, India
[e] Berman Institute of Bioethics, Johns Hopkins University, MD, USA
[f] Agriculture and Food Security Center, Columbia University, NY, USA
[g] Bioversity International, Addis Ababa, Ethiopia
[h] School of Forestry and Environmental Studies, Yale University, CT, USA

ARTICLE INFO

Article history:
Received 20 February 2016
Received in revised form
25 June 2016
Accepted 1 July 2016

Keywords:
Sustainable agriculture
Coarse cereals
Central India
Climate resilience
Nutritional yields
Trade off analysis

ABSTRACT

Sustainable agriculture has multiple objectives, including efficient use of land to produce nutrients for human consumption, climate resilience, and income for farmers. We illustrate an approach to examine trade-offs and synergies among these objectives for monsoon cereal crops in central India. We estimate nutritional yields for protein, energy and iron and examine the sensitivity of yields to monsoon rainfall and temperature. Rice, the dominant crop in the region, is the least land efficient for providing iron and most sensitive to rainfall variability. Sorghum and maize provide high nutritional yields while small millet is most resilient to climate variability. Price incentives are strong for rice. No single crop is superior for all objectives in this region. Instead, understanding which crops, or combinations of crops, are most suitable requires identifying household-, community-, and region-specific priorities coupled with empirical analysis that considers multiple objectives.

## 1. Introduction

Sustainable agriculture has multiple and diverse goals. Society relies on agricultural systems to provide sufficient human energy from food, a range of nutrients required in the human diet, and economic returns for farmers, businesses and others who derive livelihoods from the food system. At the same time, sustainable agricultural systems aim to adapt to climate change and variability, reduce greenhouse gas emissions and environmental impacts of agrochemicals, and use land and water efficiently. These multi-faceted, complex and sometimes competing goals have produced a healthy burgeoning of definitions and conceptualizations of sustainable agriculture (Loos et al., 2014; Velten et al., 2015).

While the concept of sustainable agriculture remains broad and ill-defined, decision-makers require pragmatic and robust approaches to navigate trade-offs and synergies among these many objectives to guide their decisions about agricultural investments and strategies (Beddington et al., 2012). A focus on increasing production of high-yielding staple cereals (rice and wheat) has dominated investments since the Green Revolution (Evenson and Gollin, 2003). While increasing production was essential to avert famine and remains an important goal, many countries are now facing multiple malnutrition burdens – undernutrition including stunting and wasting; micronutrient deficiencies; and overweight, obesity and diet-related non-communicable diseases - in different segments of their populations (Gómez et al., 2013). Moreover, agricultural systems contribute up to 30% of all greenhouse gases (Smith and Gregory, 2013), cover 38% of the Earth's ice-free land surface (Foley et al., 2011), and are one of the most vulnerable sectors to climate change (Porter et al., 2014). This growing complexity calls for a reexamination of the current paradigm that prioritizes production and economic returns over nutritional adequacy, climate resilience, and environmental consequences of agricultural systems.

Undernourishment has reduced substantially over the past 2.5 decades both in terms of prevalence 19–11%) and absolute numbers (over 1 billion to less than 800 million) (Food and Agriculture et al., 2015). However, more than two billion people are at

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.gfs.2016.07.001
2211-9124/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001

risk for one or more mineral (calcium, iodine, iron, selenium, zinc) or vitamin deficiencies (Kumssa et al., 2015; Miller and Welch, 2013). For example, iron deficiency is a common cause of anemia. Prevalence of anemia in 2007 was over 44% for children and nearly 50% for women in developing countries (United Nations Standing Committee on Nutrition, 2010). Increased production of energy-dense and nutrient-poor cereals has contributed to the irony of an abundance of calories alongside nutrient deficiencies (DeFries et al., 2015). Many countries, particularly in South Asia, have inadequate micronutrients in their food supplies to offer healthy diets to their populations, further exacerbated by problems of unequal distribution along with other social and cultural factors (Arsenault et al., 2015; Mark et al., 2016).

Low-income, subsistence-based farming households who rely predominantly on cereals for their nutrition are particularly disadvantaged by the erosion in nutritional content of cereals and unavailability of nutrient-dense foods such as animal source foods, fruits, and vegetables. For example, in 2011–12 the share of energy intake contributed by cereals for rural Indians ranged from approximately 70% for the bottom 5% of the population (by monthly expenditure) to 42% for the top 5% (National Sample Survey Organisation, 2014b). Consumption of nutritious cereals which are historically staples for the poor – sorghum (local name jowar), pearl millet (bajra), and maize – declined by more than half between 2004–05 and 2011–12, while consumption of rice and wheat from the government's Public Distribution System more than doubled (National Sample Survey Organisation, 2014a).

In addition to nutritional adequacy, sustainable agricultural systems need to be resilient to variability and projected changes in precipitation, temperature and extreme events due to both anthropogenic and natural causes. Models of the impact of future climate change on agricultural productivity agree that, without effective adaptation measures, agricultural systems in low latitudes are likely to suffer larger reductions in yield than those in higher latitudes as temperatures increase (Porter et al., 2014; Wheeler and von Braun, 2013). Projections of changes in precipitation are more uncertain and spatially variable, and the impacts on agriculture are less well understood.

Millions of small scale and low-income farmers in low latitudes, with limited means to adapt to change, are particularly vulnerable to climate change and variability. One strategy to reduce vulnerability is to grow crops that are less sensitive to climate change and variability. Crops with C4 photosynthetic pathways (e.g., maize, sorghum and millet) that evolved in arid, low-latitude conditions, for example, are generally more drought resistant, have higher optimal growing temperatures, and are less affected by reduced nutritional content from increasing atmospheric carbon dioxide concentrations than those crops with a C3 photosynthetic pathway (e.g. rice) (Myers et al., 2014). On the other hand, yields of C3 crops benefit more than C4 crops from the fertilization effect with increasing atmospheric carbon dioxide concentrations (Lobell and Gourdji, 2012).

Another constraint on sustainable agricultural systems is land availability. Declining field sizes for smallholder farmers, agricultural labor constraints as people gain employment in urban areas, and increasing dependency ratios (the ratio of non-working to working members of a household) in rural areas compel efficiency in agricultural land use.

The conceptual model for this analysis is based on the multiple dimensions of sustainable agriculture and the differing priorities of various actors in the food system. For subsistence farmers, food security and nutrition from local production are critical considerations. For market-based farmers, prices are overwhelming priorities. Resilience to climate change is paramount, particularly for the most vulnerable farmers. Environmental impacts from agriculture, e.g. greenhouse gas emissions and fertilizer runoff, are also key considerations though not addressed in this analysis. Each of these factors is relevant for sustainable agriculture but is traditionally studied by different disciplines. Decision-making, however, requires integrating across these separate disciplines.

The need to reorient agricultural systems towards more holistic goals is increasingly recognized (Beddington et al., 2012; Gómez et al., 2013). However, tools and frameworks that integrate across multiple objectives for agriculture systems are in their infancy. Nutritional yield is one metric, for example, that incorporates both nutrition and efficiency of land use to compare different crops (DeFries et al., 2015). This paper is a step further towards empirically-based, viable approaches that untangle the overwhelming complexity of incorporating myriad objectives in a single framework.

Here we present an approach to examine the synergies and tradeoffs for a subset of sustainable agriculture goals – nutrition produced with efficient use of land, resilience to climate variability, and price. We illustrate this approach for the main cereal crops grown in the monsoon season in central India, a semi-subsistence, mostly rain-fed agricultural landscape that has already experienced substantial changes in temperature and rainfall characteristics over the last fifty years (Ghosh et al., 2012; Goswami et al., 2006; Manabe et al., 2011; Singh et al., 2014).

Specifically, we address the following questions: which cereals were the most resilient to variability in temperature and precipitation on average across the region from 2000 to 2012?; which cereals on average produced the most nutrients per unit land area?; what are the trade-offs and synergies in choice of monsoon cereal crop to achieve multiple objectives for nutrition, land use efficiency, resilience to future climate change, and price? We use available data from multiple sources and mixed-effect models to examine these questions.

## 2. Study region

The study region encompasses 34 districts in central India spanning the states of Chhattisgarh, Madhya Pradesh and Maharashtra (Fig. 1), covering 25 million ha and 7.6% of the total land area of the country. The districts encompass the “central highlands” Agro-Ecological Region (AER), one of twenty defined for India (Gajbhiye and Mandal, 2000). The central highlands AER is characterized by a hot, sub-humid (dry) climate with 1000–1200 mm average total rainfall of which 70% is received during the monsoon season (July to September). Soils are generally deep and loamy. Natural vegetation is tropical deciduous forest.

Total population of the study region is 54 million of which nearly 70% is rural. Land use is primarily smallholder, rain-fed farming for subsistence. In 2011, 43% of agricultural land holdings in the region were marginal ( $<1$ ha) and 72% were marginal or small (1–2 ha) (Government of India, 2011a) (Table S1). There is little to moderate access to surface canals and shallow tanks for irrigation, with negligible but increasing access to groundwater through deep wells (Mondal et al., 2014). Crops are grown in monsoon (kharif) and in winter (rabi) season in places with sufficient water and suitable soils. Kharif crops include rice, maize, sorghum, millet, sugarcane, groundnut and pulses. Rabi crops include wheat, pulses, vegetables and oil seeds (Government of India, 2015). Farmers can sell surplus production on the open market or through the government's public distribution system (PDS), which purchases cereals from farmers at a guaranteed price and redistributes to households below the poverty line at subsidized rates (Gulati and Saini, 2015).

Although data are sparse on nutritional status of the population in this study region, micro-nutrient deficiencies including vitamin A and D, iron, iodine and zinc are pervasive throughout India

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001

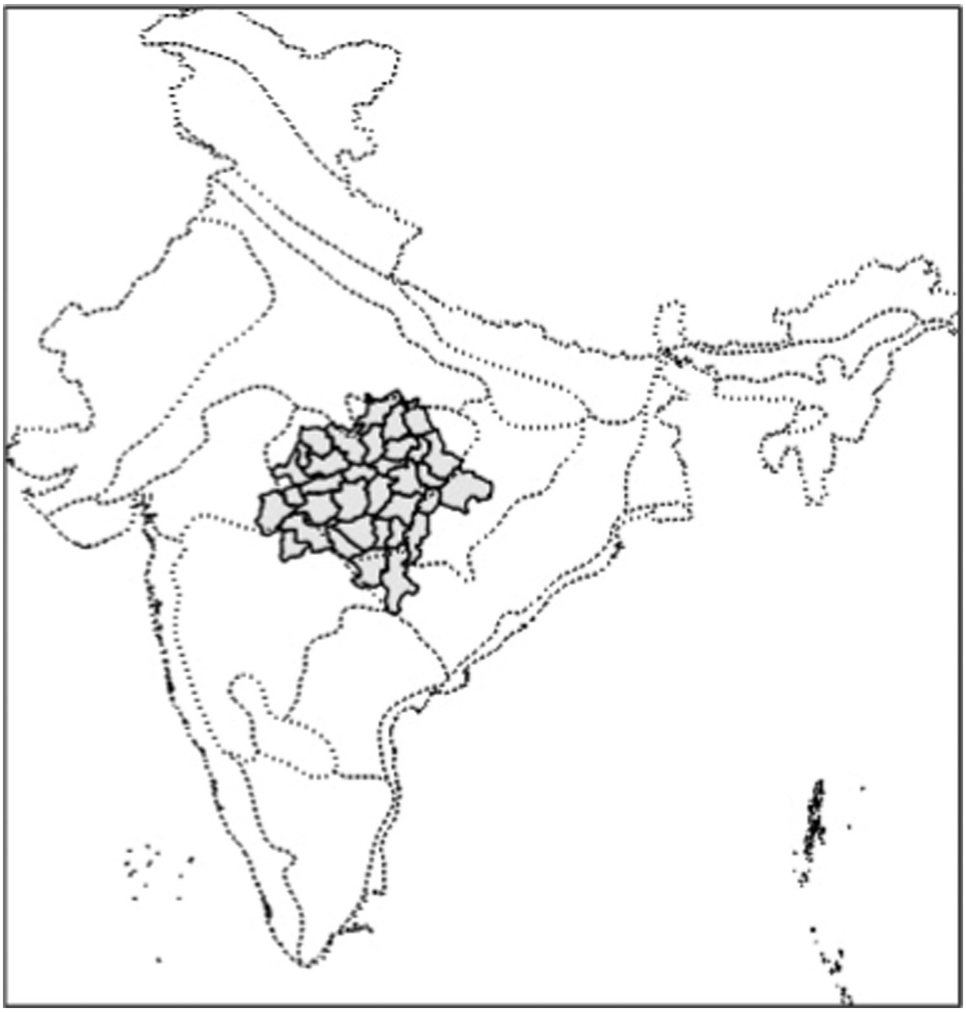


**Fig. 1.** Location of 34 districts included in study region. Dotted gray lines outline India's 20 agro-ecological regions (Gajbhiye and Mandal, 2000).

(Akhtar et al., 2013). Anthropometric indicators in the 34 districts indicate high levels of food insecurity (Table S1). In 2015, percentages of rural children under 5 with stunting (35%), wasting (32%) and underweight (36%) (Government of India, 2016c) were similar to such measures in Ethiopia (Food and Agriculture et al., Madhya Pradesh, the state with the majority of districts in the study region, the share of protein from cereals was highest (66%) of any Indian state, indicating heavy reliance on cereals for nutrition in the study region (National Sample Survey Organisation, 2014b).

Farmers and food security in the study region are highly dependent on monsoons (Government of India, 2011b). The central highlands agro-ecological zone is one of the most vulnerable in terms of climatic variability, ecological and demographic sensitivity, and socio-economic capacity (Shukla et al., 2015). Average June to August temperature over South Asia is very likely to increase in the future irrespective of the future emissions pathway (Niu et al., 2015; Stocker, 2014). By the late 21st century, the ensemble of coupled climate models show temperature increases between 1.5 and 3.0 °C for Central India under a moderate future emissions (RCP4.5) pathway relative to the present climate (Stocker, 2014). Some studies also suggest that by the end of the century, 60–80% of summer seasons will have temperatures exceeding the warmest seasonal temperature in the present climate (Diffenbaugh and Scherer, 2011).

Although climate models agree on the increase in temperature in the region, there are considerable uncertainties in the direction and magnitude of precipitation changes associated with the Indian Summer Monsoon (Sabade et al., 2011; Sharmila et al., 2015; Stocker, 2014; Stowasser et al., 2009). Amongst the global models that can suitably simulate the monsoon, a majority predict an increase in rainfall ranging from 10% to 30% over central India by the late 21st century (Sharmila et al., 2015; Stocker, 2014). However, simulations with higher resolution models that more accurately represent the processes suggest the opposite response of rainfall (Ashfaq et al., 2009; Krishnan et al., 2015; Niu et al., 2015) with some models showing significant decreases of up to 25% over central India. Despite this uncertainty in overall seasonal precipitation, models suggest robust increases in the inter-annual (~30%) and subseasonal (~13–50%) variability of precipitation (Menon et al., 2013; Sharmila et al., 2015). These changes in variability are associated with increases in the intensity of heavy precipitation events as well as increases in the frequency and duration of dry spells (Ashfaq et al., 2009; Sharmila et al., 2015; Stowasser et al., 2009). Impacts on agriculture of projected changes in rainfall variability in the region are not well known.

## 3. Data

Calculation of nutritional yields requires data on yields and nutritional content for different crops (DeFries et al., 2015). We obtain data on monsoon cereal crops from the Government of India agricultural census (Government of India, 2015; Indiastat, 2013). These data include yields per season from 2000 to 2012, area sown, and crop-wise and season-wise irrigated area for each district. In addition to rice (*Oryza sativa*), coarse cereals included in the agricultural census are sorghum (*Sorghum bicolor*, local name jowar); pearl millet (*Pennisetum glaucum*, local name bajra); finger millet (*Eleusine coracana*, local name ragi); maize (*Zea mays*); and small millets which include little millet (*Panicum sumatrense*, local name kutki), kodo millet (*Paspalum setaceum*), barnyard millet (*Echinochloa utilis*, local name sanwa), and foxtail millet (*Setaria italic*) (Government of India, 2013). The agricultural census data contains missing values for some districts in some years, mostly in more recent years. For missing irrigation data, we used the value for area irrigated closest in time to the missing year and assumed no irrigation if no data were available in any year for the district. Soil data were calculated from (FAO/Unesco, 1971) as percentage area of each soil type within each district. Main soil types in the study region are Vertisols, Cambisols, Lithosols, and Luvisols.

Data for nutritional content for monsoon cereals (energy, protein, and iron) produced in the study region were taken from the literature specific to cereals in India (Anon, 2012; Kaur et al., 2014; Saleh et al., 2013; Shobana et al., 2013). We averaged the values for nutritional content from these sources for each nutrient. For small millets, we averaged the values for the four types included under the census definition.

We used multiple sources of temperature and rainfall data to test the sensitivity of model results to different data sets. We primarily use NASA's Tropical Rainfall Measuring Mission (TRMM) satellite-based precipitation estimates (Anon, 2016a) and NCEP Climate Prediction Center's land surface air temperature (GHCN-CAMS) data in our regression model (Fan and Van den Dool, 2008). The precipitation data is available at a ($0.25° \times 0.25°$, approximately 785 km$^2$) spatial and daily temporal resolution from 2000-present. The temperature data is (available at a $0.5° \times 0.5°$, approximately 3136 km$^2$) spatial and monthly temporal resolution from 1948 to present. To assess the sensitivity of our results to the dataset, we additionally use three other precipitation datasets - Indian Meteorological Department ($1° \times 1°$, approximately 12,320 km$^2$) available at daily resolution (Rajeevan et al., 2006), Willmott-Matsuura ($0.5° \times 0.5°$) available at monthly resolution (Willmott and Matsuura, 2014), and Climate Hazards Group Infrared Precipitation with Station (CHIRPS) ($0.05° \times 0.05°$, approximately 31 km$^2$) available at monthly resolution (Funk et al., 2014); and three temperature datasets - Willmott-Matsuura ($0.5° \times 0.5°$) available at monthly resolution (Willmott and Matsuura, 2014), Berkeley Earth Surface Air Temperature ($1° \times 1°$) available at daily resolution (Anon, 2016b) and Climate Research Unit ($0.5° \times 0.5°$) available at monthly resolution (Harris et al., 2014). In addition to differences in their spatial and temporal resolutions and interpolation methodologies, there are slight differences between these datasets in terms of the number and type of observations used to create these gridded products.

To calculate prices for the cereals, we used two sources: purchaser's price in standardized local currency (FAO, 2015) and Minimum Support Price set by the Indian Government as a guaranteed price for farmers (Government of India, 2016b). These two data sets only overlapped for 2008, so we estimate prices only for that year. We were unable to include costs of labor, inputs, and other production costs due to data limitations. The analysis of price, rather than net revenue, is therefore only suggestive of the economic comparison of the crops.

## 4. Methods

### 4.1. Nutritional yields of cereal types

The method to calculate nutritional yield is defined in (DeFries et al., 2015). In summary, the metric estimates, for a nutrient, the number of adults (average for male and female between 19 and 50 years old) who can fulfill 100% of their recommended dietary reference intake (DRI) from one hectare for one year. Conversely, the inverse of nutritional yield is the number of hectares required to provide sufficient quantity to fulfill 100% of dietary reference intake for a nutrient for one adult. Nutritional yield of nutrient *i* from cereal *j* is calculated as (DeFries et al., 2015):

$$\mathrm{NY}_{ij} = \text{fraction of } \mathrm{DRI}_i/100_{gj} \times \text{tonnes}_j/\text{ha/yr x } 10^4/365$$

where fraction of $\mathrm{DRI}_i/100_{gj} = (g_i/100g_j)/\mathrm{DRI}_i$.

To calculate nutritional yields, values for grams of nutrient *i* in 100 g of cereal *j* ($g_i/100g_j$) are taken from nutrient composition data, e.g., (United States Department of Agriculture, 2015) and values for $\mathrm{DRI}_i$ are taken from recommended daily allowances, e.g. (Institute of Medicine, 2000). For example, a cereal's nutritional yield for iron is derived from the fraction of dietary reference intake for iron supplied by 100 g of the cereal (which is the grams of iron in 100 g of cereal divided by the daily dietary requirement for iron) multiplied by the yield for that cereal. In essence, the nutritional yield metric weights the conventional yield measure (tonnes/ha) by its nutritional content.

For this analysis, because nutrient composition varies with variety and growing conditions, we used average values of nutrient composition reported in the literature for cereals in India (Anon, 2012; Kaur et al., 2014; Saleh et al., 2013; Shobana et al., 2013) (Table 1). We illustrate the framework for assessing synergies and tradeoffs for energy, protein and iron. Although zinc deficiencies are a major risk factor in developing countries (Akhtar et al., 2013), we did not include this nutrient in the analysis.

### 4.2. Climate resilience of cereal types

To quantify the sensitivities of yield to variability in precipitation and temperature, we assessed statistical relationships between historical variability in yield and variability in climate parameters, an approach taken by other researchers (Lobell et al., 2014, 2011; Verón et al., 2015). Response variables were yields reported at each district level for each year available from 2000 to 2012. Fixed effects were total monsoon rainfall for each year, mean seasonal temperature for each year (either mean or mean maximum daily), soil type, and crop- and season-specific irrigation for each year (Table 2). Data for fixed effects were aggregated to the district level with grid cells weighted by their proportions falling within the district. For each of the monsoon cereal crops, we constructed separate mixed-effect models with the above fixed effects and random intercepts for district and year (model equation in Table S2). We included quadratic terms for precipitation and temperature to account for possible non-linear relationships.

Fixed-effect variables were tested for collinearity and standardized (difference from mean divided by standard deviation). We tested the sensitivity of results from the models for different precipitation and temperature data sets using marginal R squared values (variance explained by fixed effects only) and AIC to determine which data sets provide the most explanatory power. We compared standardized coefficients to assess the sensitivity of yields of the cereal crops to variability in temperature and precipitation. We also included additional variables, total monsoon days with no rainfall and Simple Daily Intensity Index (no. of rainy days with total monsoon rainfall/number of monsoon rainy days),

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001

**Table 1**
Nutrient content reported for cereal crops (per 100 g of dry weight edible portion).

| | Rice | Sorghum | Maize | Small millets | | | | Source |
|---|---|---|---|---|---|---|---|---|
| | | | | Kodo millet | Little millet | Barnyard millet | Foxtail millet | |
| **Energy (kcal)** | 345 (raw milled) | | | 309 | 341 | 307 | 331 | (Shobana et al., 2013) (Table 1.1) |
| | 361 (brown) | 329 | 358 | 353 | 329 | 300 | 351 | (Saleh et al., 2013) (Table 2) |
| | **353** | **329** | **358** | **328** | | | | |
| **Protein (g)** | 6.8 (raw milled) | | | 8.3 | 7.7 | 6.2 | 12.3 | (Shobana et al., 2013) (Table 1.1) |
| | 7.9 (brown) | 10.4 | 9.2 | 9.8 | 9.7 | 11.0 | 11.2 | (Saleh et al., 2013) (Table 2) |
| | 6.8 | 10.4 | 11.5 | 8.3 | 8.7 | 11.6 | 12.3 | (Anon, 2012) (Table 9) and (Kaur et al., 2014) (Table 1) |
| | **7.4** | **10.4** | **10.4** | **9.5** | | | | |
| **Iron (mg)** | 0.7 (raw milled) | | | 0.5 | 9.3 | 5.0 | 2.8 | (Shobana et al., 2013) (Table 1.1) |
| | 1.8 (brown) | 5.4 | 2.7 | 1.7 | 9.3 | 18.6 | 2.8 | (Saleh et al., 2013) (Table 2) and (Kaur et al., 2014) (Table 1) |
| | 1.8 | 5.4 | 2.7 | 1.7 | 9.3 | 18.6 | 2.8 | (Anon, 2012) (Table 9) |
| | **1.4** | **5.4** | **2.7** | **6.3** | | | | |

Values used in calculation of DRI/100 g to calculate nutritional yields indicated in bold.

**Table 2**
Means and standard deviations (in parentheses) of fixed-effect variables used in mixed models to predict cereal yields for 34 districts for 2000–2012.

| Variable | Source | Mean |
|---|---|---|
| Total monsoon rainfall (mm) | (Anon, 2016a) | 1062 (237) |
| Mean seasonal temperature (°C) | (Fan and Van den Dool, 2008) | 28.77 (1.19) |
| Soils: fraction vertisols | (FAO/Unesco, 1971) | 0.084 (.162) |
| Soils: fraction cambisols | (FAO/Unesco, 1971) | 0.149 (.167) |
| Soils: fraction lithosols | (FAO/Unesco, 1971) | 0.177 (.299) |
| Irrigation: fraction area sorghum | (Government of India, 2015) | 0.003 (0.015) |
| Irrigation: fraction area rice | (Government of India, 2015) | 0.107 (0.154) |
| Irrigation: fraction area small millet | (Government of India, 2015) | 0 |
| Irrigation: fraction area maize | (Government of India, 2015) | 0.009 (0.025) |

to test sensitivity of model results to precipitation variables other than total monsoon rainfall. We implemented these methods with the lmer() function in R.

### 4.3. *Assessing trade-offs and synergies*

To assess trade-offs and synergies among the four cereal crops, we compare average nutritional yields (energy, protein and iron) for all 34 districts for 2000–12, climate resilience (standardized coefficients for mean monsoon season temperature and total monsoon precipitation) and price (2008 purchaser's price and minimum support price (MSP)). We normalize values to maximum value for all cereals for nutritional yields and price (1.0 is highest nutritional yield or price relative to other cereals). For climate resilience, difference from the maximum values of standardized coefficients are normalized so that 1.0 is most resilient (least sensitive) and 0 is least resilient (most sensitive) relative to the other cereals. We plot these normalized values on a spider chart to visualize the multiple dimensions of the crops.

## 5. Results

### 5.1. *Nutritional yields of cereals*

Of the main monsoon cereal crops, rice was sown on 70% of cereal area followed by sorghum (12%), small millet (9%) and maize (8%) on average from 2000 to 2012 (Government of India, 2015) (Fig. 2a). Yields (in terms of tonnes/ha/yr) of cereals in the study region are substantially below the national average (excepting sorghum) presumably due to limited access to inputs, small landholdings and poor soils (Fig. 2b). Yields averaged 0.87, 1.09, 0.37, and 1.63 t/ha from 2000 to 2012 for rice, sorghum, small millet and maize respectively (Government of India, 2015), compared with national averages for the same time period of 3.19, 0.85, 0.96, and 2.13 t/ha (FAO, 2015).

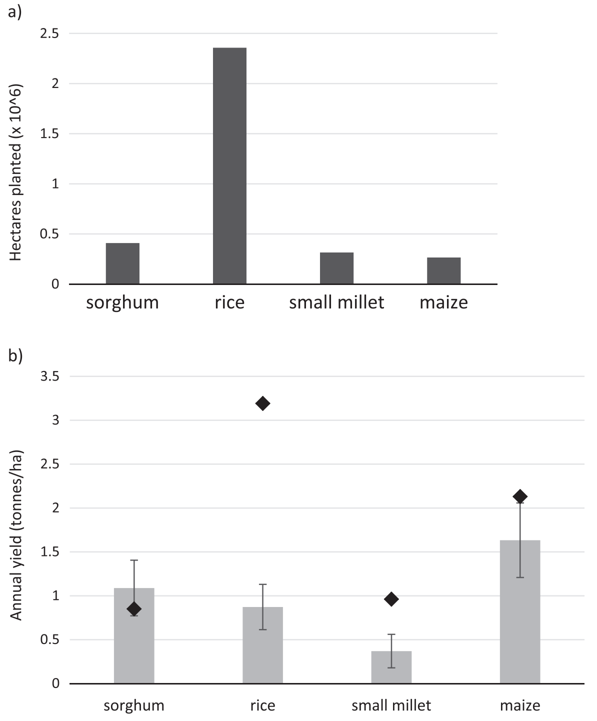


**Fig. 2.** (a) Average number of hectares planted in monsoon cereal crops in study region from 2000 to 2012 and (b) average and standard deviations of yields. Data from (Government of India, 2015). Black diamonds in (b) are national average yields for 2000–2012 for each cereal (FAO, 2015).

Nutrient content for the monsoon cereals show substantial difference for protein and iron content and similar energy content (Table 1). Rice has lowest content for both protein and iron, with sorghum the highest content for protein. Data sources vary on the iron content, with two of the four types of small millets (barnyard

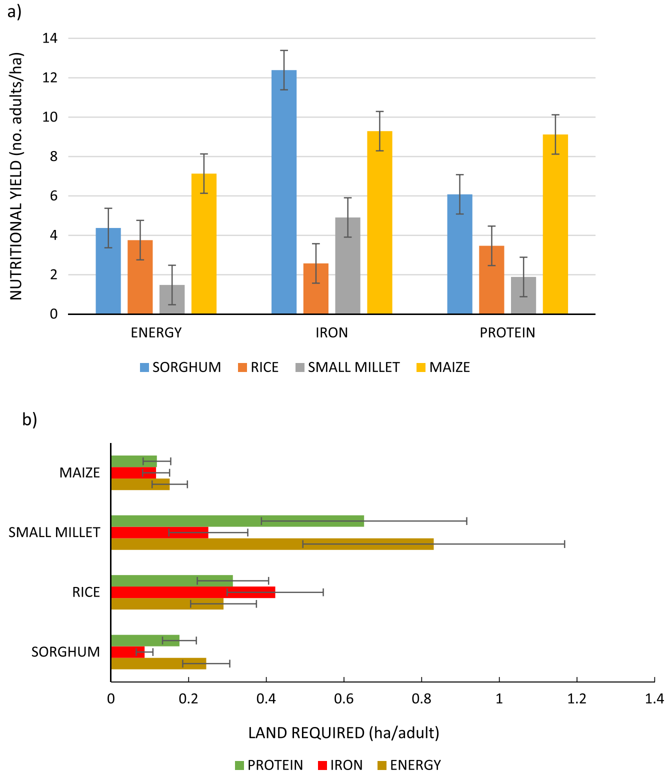


**Fig. 3.** (a) Average and standard deviation for nutritional yields in the 34 districts for 2000–2012. (b) Same data as (a) shown as land requirement to produce 100% recommended dietary reference intake per year. See Table S2 for calculations.

millet and little millet) highest in iron. Iron content for maize is relatively low. Combining yields with nutrient content, energy nutritional yields averaged for the 34 districts for 2000–2012 (Fig. 3a) do not vary substantially from conventional yield values (Fig. 2b) for the four cereals. However, iron nutritional yields are lowest for rice (2.6 adults/ha averaged across all years and all districts) and highest for sorghum (12.4 adults/ha). Small millets (averaged across all four types) have higher nutritional yield for iron (4.9 adults/ha) than rice (2.6 adults/ha) despite the relatively low yield for small millets. Protein nutritional yields are highest for maize (9.1 adults/ha) and lowest for small millet (1.9 adults/ha) (Fig. 3a).

Land required to supply one adult's 100% of dietary reference intake for the three nutrients (the inverse of nutritional yield values) reinforces that sorghum is the most land efficient cereal to produce iron (0.09 ha/adult) and maize for protein and energy (0.12 and 0.15 ha/adults respectively). Of the four cereals, rice is the only cereal that is less land efficient for producing protein and iron than for energy. Specifically, in this study region and time period, 0.29 ha of rice were required to supply one adult with sufficient energy, but 0.42 and 0.31 ha were required to supply one adult with sufficient iron and protein respectively. Maize, small millets and sorghum all require less land to supply sufficient iron and protein than energy (Fig. 3b).

### *5.2. Climate resilience*

We ran mixed effect models using four data sets for total monsoon precipitation and four temperature data sets for each of the four cereals (Table S6). Prior to running the model, we tested for collinearity among fixed effects. The test revealed that one of the soil types was co-linear and it was excluded from the model. All other variables have correlation coefficients less than 0.40 (Table S5).

**Table 3**
Standardized coefficients for fixed effects in mixed effects model to predict yields of cereal crops for 34 districts from 2000 to 2012.

| Predictor | Sorghum | Rice | Maize | Small millet |
|---|---|---|---|---|
| PRECIPITATION: TOTAL MONSOON RAINFALL | 0.06 | 0.16 | 0.14 | 0.07 |
| SOILS: VERTISOLS | 0.10 | −0.01 | 0.27 | 0.07 |
| SOILS: CAMBISOLS | 0.08 | 0.05 | 0.27 | 0.03 |
| SOILS: LITHOSOLS | −0.10 | −0.01 | 0.16 | 0.04 |
| TEMPERATURE: SEASONAL MEAN | −0.10 | −0.02 | 0.07 | 0.01 |
| IRRIGATION: FRACTION OF SOWN AREA | 0.00 | 0.12 | −0.01 | n.a. |
| PRECIP_QUADRATIC | −0.04 | 0.02 | −0.02 | −0.01 |
| TEMP_QUADRATIC | −0.02 | 0.01 | −0.01 | 0.00 |
| marginal r2 (fixed effects) | 0.26 | 0.37 | 0.29 | 0.15 |
| conditional r2 (fixed+random effects) | 0.71 | 0.74 | 0.64 | 0.72 |
| n | 277 | 294 | 280 | 216 |

Random effects are district and year. See Table 2 for variables and source data and Table S2 for model form. Table S5 provides model results using other precipitation and climate data sets. Dark yellow $p < 0.0001$, paler yellow $p < 0.01$, palest yellow $p < 0.05$, pale gray $p < 0.10$.

Comparison of mixed effect models to predict cereal yield shows that TRMM data for total monsoon rainfall provides higher explanatory power (lowest AIC and highest marginal $R^2$ values) than the other three precipitation data sets for three of the four crops (Table S6). Model results using TRMM data and the candidate data sets for temperature data (seasonal mean and mean of daily max) indicate little difference in results. Explanatory power for models for two cereals (sorghum and rice) was highest using the NOAA seasonal mean and the CRU seasonal mean temperature for the other two (maize and small millet). Consequently, we show model results using TRMM data for total monsoon rainfall and NOAA seasonal mean temperature, and we examine the robustness of results with the full range of data sets.

For all four cereals, total monsoon rainfall is significantly and positively correlated with yields after controlling for soils, irrigation and random effects (district and year) (Table 3). The standardized coefficients of rainfall are highest for rice (0.16) and maize (0.14), approximately double the coefficient for sorghum (0.06) and small millet (0.07). The quadratic term for precipitation indicates a decreasing incremental effect on yields with increasing precipitation for sorghum and an increasing incremental effect for rice.

As expected, the statistically significant ($p < 0.001$) coefficient for rice irrigation (0.12) indicates that monsoon rice yields are higher in districts and years with higher irrigated area. Percentage of monsoon rice area irrigated in the districts ranges from none to about 50%. Sorghum and maize are less widely irrigated, with maximum sown area irrigated in a district 17% and 22% respectively, so it is unsurprising that irrigation is not a significant variable for those cereals. Virtually no irrigation is reported for small millet and the irrigation variable is not included in that model.

Mean seasonal temperature is not a significant variable, except for sorghum (coefficient −0.10), indicating that the other three cereal crops are less sensitive (more resilient) to variability in temperature than to precipitation within the ranges experienced from 2000 to 2012.

Model results with other climate data sets are in general consensus with results given in Table 3 with some discrepancies (Table S6 and Fig. 4a). Precipitation is a positive and significant variable for all crops and all data sets except in a single case of maize for one of the precipitation data sets. The coefficient for precipitation is consistently highest for rice for all data sets.

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001

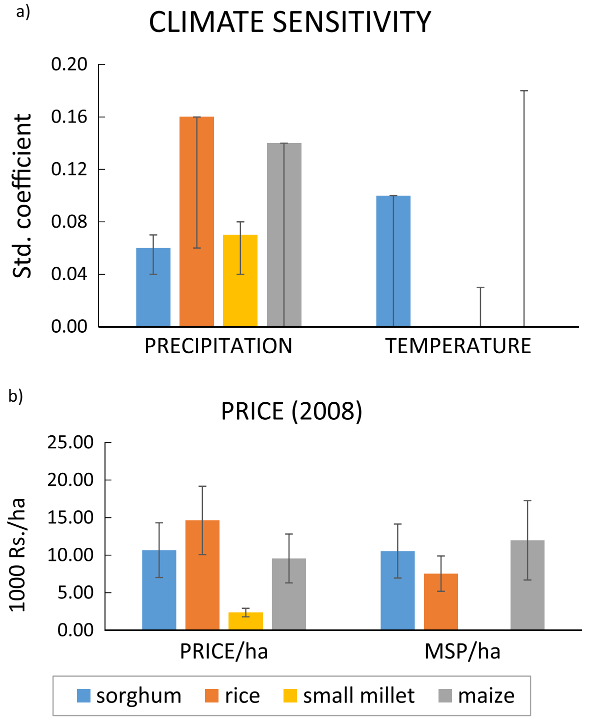


**Fig. 4.** (a) Absolute values of standardized coefficients for monsoon precipitation and temperature variables in main models (TRMM precipitation and NOAA temperature data sets) for the four cereals. Higher values indicate more sensitivity (less resilience) to climate variability. Error bars are the ranges in values of standardized coefficients for models testing sensitivity to different precipitation and temperature data sets (Table S6). Coefficients with $p > 0.10$ are considered to be zero. (b) Average and standard deviations across the 34 districts for 2008 prices per hectare for four cereals for Purchasers Price in Standardized Local Currency (FAO, 2015) and minimum support price established by the government (Government of India, 2016b). There is no minimum support price for small millets.

However, coefficients for precipitation are generally lower than the main model for rice and maize. Models with different temperature data sets give inconsistent results for sorghum, maize and small millet. Temperature is a significant variable ($p < 0.10$) for sorghum, maize and small millet in 6, 5, and 3 out of 8 models respectively. Temperature is consistently not significant across models with different data sets for rice. Additional precipitation variables, number of monsoon days with no rainfall and SDII, did not improve the models, nor does average of daily maximum temperature provide more explanatory power (Table S7).

These results generally agree with other studies that examine the sensitivity of yields to variability in precipitation in India. Yields for rice, pearl millet and sorghum are positively associated with precipitation (Fishman, 2012; Gupta et al., 2014). In agreement with this study, Gupta et al. (2014) find a negative association with temperature for sorghum yields and no significant relationship for millet yields. In contrast to this study, both Gupta et al. (2014) and Fishman (2012) find a negative association of temperature with rice yields. A larger number of observations or a wider range of temperature represented in the data might reveal a stronger temperature sensitivities.

### 5.3. Price

Average purchaser's price in 2008 was Rs. 8600, 16,780, 8400, and 8400 per tonne for sorghum, rice, millets (not differentiated by type) and maize respectively. Minimum Support Price was Rs. 8500, 8650, and 8400 per tonne for sorghum (average for two types), rice (average for two types) and maize with no MSP for small millets. Combining with yields, the average price per hectare for 2008 across the 34 districts was highest for rice and 27%, 35%, and 84% lower for sorghum, maize and small millets respectively. However, the average price per hectare based on MSP was highest for maize and 12% and 37% lower for sorghum and rice respectively (Fig. 4b). These prices do not necessarily indicate the prices that farmers receive or their net profits, but are broadly indicative of the relative prices from the different cereals.

### 5.4. Synergies and trade offs

The comparison across the four monsoon cereals indicates that each cereal has different desirable attributes (Fig. 5). Sorghum provides the highest nutritional yield for iron while maize provides the highest nutritional yields for energy and protein. Sorghum is also the least sensitive (lowest coefficient in the model indicating most resilient) to variability in precipitation but most sensitive to temperature variability. Small millets are resilient (least sensitive) to temperature and precipitation variability, but have low nutritional yields due to low overall yield despite high nutritional content. Rice compares poorly to sorghum and maize, is least resilient (most sensitive) to precipitation variability, has the lowest nutritional yields for iron, and the second lowest nutritional yields for energy. In 2008, rice had the highest price per hectare for purchaser's price. Maize and sorghum had higher prices than rice in terms of price per hectare based on Minimum Support Price. Small millets are not included in MSP.

## 6. Discussion and conclusions

The analysis provides a pragmatic approach to quantify tradeoffs and synergies among crops for disparate attributes for sustainable agriculture. Using a mainly subsistence and highly monsoon-dependent study region in central India to examine monsoon cereal crops from 2000 to 2012, the approach illustrates the choices among crop types that decision-makers – whether local farmers or national policy makers – need to confront.

Results indicate that, while rice is the dominant monsoon crop in the region, it performs poorly in comparison to the other cereals grown in the region for several attributes. Rice in the study region has low yield compared with the national average, is the least resilient of the cereals to variability in precipitation, has the lowest nutritional yields of all cereals for iron, and the lowest for energy beside very low-yielding small millet. Rice is the only cereal of the four considered in this study that supplies less of the recommended requirement for iron and protein per hectare than for energy. Overall, maize and sorghum perform well but were sown on only 12% and 9% of area used for monsoon cereals in the study region, while rice was sown on 70%. Price incentives are strong for rice in terms of purchaser's price, although maize and sorghum yield higher price per hectare than rice for minimum support prices.

Lack of milling technology, declining seed quality, and shortage of research devoted to increasing yields for coarse cereals have contributed to the predominance of rice in India despite the desirable characteristics of coarse cereals (Anon, 2012). Systematic studies are not available in the study region to assess the specific reasons for the predominance of rice above the coarse cereals. Anecdotal observations from the field suggest that agriculture extension since the Green Revolution sidelined coarse cereals and provided incentives for cultivation of rice. Association of coarse cereals as a poor man's food led to gradual decline in consumption among the local population. The market for coarse cereals, especially small millet, was not established with resulting neglect of seed quality and threshing technology. Arduous physical labor required to de-hull the grain from coarse cereals contributes to the

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001

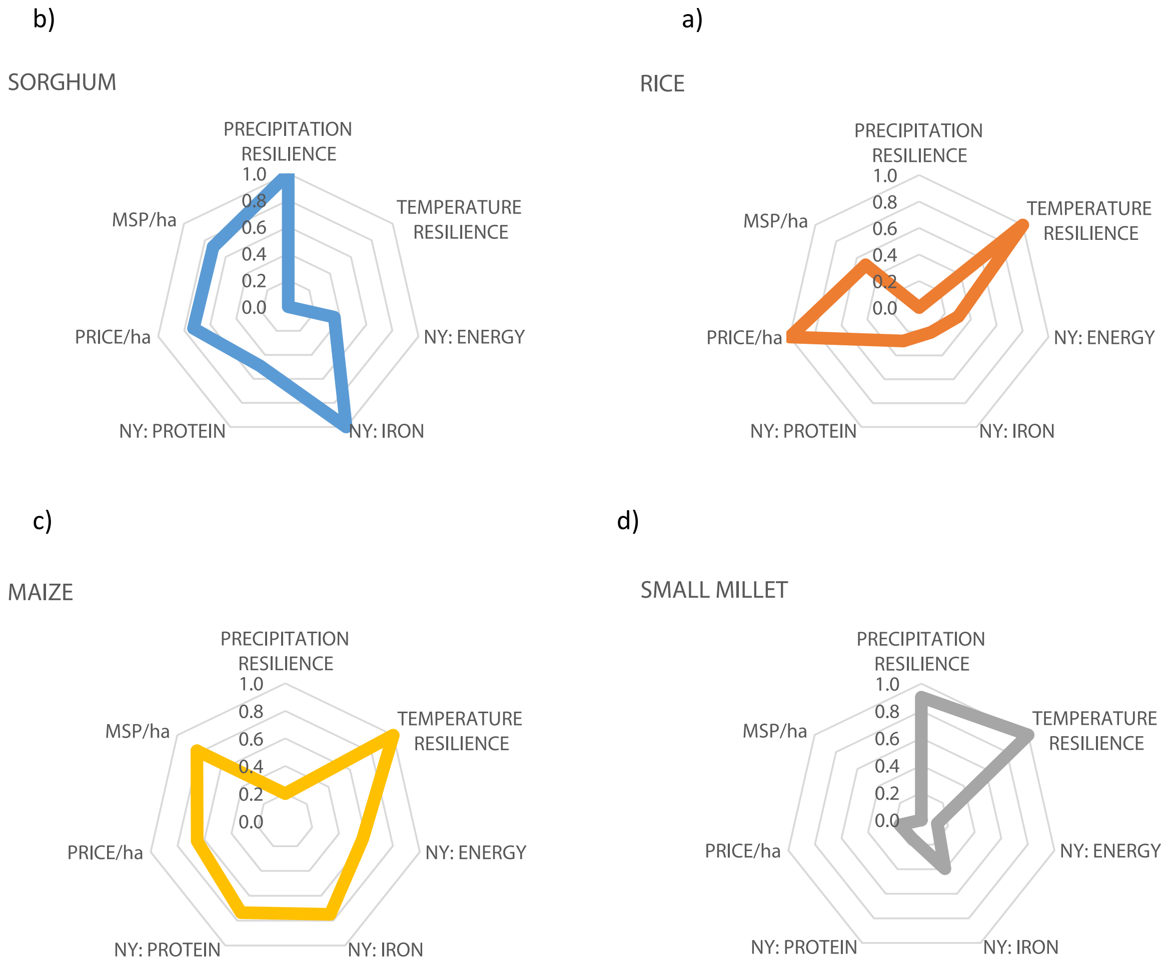


**Fig. 5.** Comparison of average nutritional yields (energy, protein and iron) for all 34 districts for 2000–12, climate resilience (standardized coefficients for mean monsoon season temperature and total monsoon precipitation) and price (2008 purchaser's price and minimum support price (MSP)) for the four cereals. Values are normalized to maximum value for all cereals for nutritional yields and price (1.0 is highest nutritional yield or price relative to other cereals). For climate resilience, difference from the maximum values of standardized coefficients are normalized so that 1.0 is most resilient (least sensitive) and 0 is least resilient (most sensitive) relative to the other cereals.

popularity of rice. Practical issues that inhibit the production of coarse cereals remain unresolved in this study region. Many have called for vitalization of research and incentives to increase production of nutritious coarse cereals, e.g. (Kaur et al., 2014). Our results support the claim that these cereals could contribute to nutrition and climate resilience in the study region if constraints are addressed.

No single cereal is superior in all attributes considered in this analysis. If the most desirable attribute is efficient production of energy and protein, the most desirable crop is maize while sorghum is most desirable for iron. Small millet is the most climate resilient, but is least land-efficient for supplying energy and protein. Maize provides the most synergies in terms of climate resilience and nutritional yields, while sorghum is the most resilient to precipitation variability but most sensitive to temperature variability in the ranges experienced from 2000 to 2012 in the study region. Trade-offs between climate resilience and yields are also apparent for small millet.

Choices of crops, crop varieties, and crop combinations need to prioritize which attributes are most desirable in a particular setting. For example, iron deficiency is likely to be widespread in the study region. An increase in sorghum consumption would use land efficiently to produce more iron per hectare than rice and help alleviate deficiencies. While we examine cereals in this study region only, the result that trade-offs among multiple attributes of sustainable agriculture are inherent in crop choice is likely to hold true in other regions.

This study focusses on a mostly subsistence-based, food insecure region with a predominance of marginal and smallholder farmers. Where farmers sell crops on the open market or to the government, economic returns become a critical factor. Increased income could provide a pathway to improved nutrition and food security if households have access to nutritious food for purchase. Notably, the MSP set by the government has increased substantially for coarse cereals (aside from small millet) although rice and wheat are the dominant cereals in the Public Distribution System (Government of India, 2016a).

Results also suggest that the specific trade-offs and synergies among crops vary in different places. In the central India study region, yields of rice are low relative to the national average while yields of sorghum are high. Consequently, the low nutritional content for rice compounded with low yields results in nutritional yields that compare unfavorably to sorghum and maize. Trade-offs and synergies among crops need to be analyzed for specific regions to support decision-making.

In this study region where subsistence farmers rely heavily on cereals to provide nutrition, attention to expanding production and increasing yields of coarse, nutritious cereals could contribute to efficient use of land to improve nutritional outcomes. In addition, as climate models robustly predict increasing variability in precipitation and increasing temperature, climate resilience is a key concern. Increasing variability in precipitation would

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001

negatively affect rice yields more than the other cereals. Increasing temperature is a robust prediction from climate models, but our results indicate a less certain impact on yields, possibly because mean monsoon temperature in 2000–2012 already exceeded optimum temperatures for yields (18–25 °C, 23–26 °C, and 25 °C for maize, rice and sorghum respectively) (Hatfield et al., 2011; Lobell and Gourdji, 2012).

In summary, our examination of three attributes of sustainable agriculture - provision of nutrients for human consumption with efficient use of land, sensitivity to climate change and variability, and price – illustrate the need for locally-specific analysis based on empirical data to guide choices about trade-offs and synergies in crop choice. Ideally, a single crop would be superior in all attributes although such an outcome is unlikely. As is apparent in the central India study region, empirical analysis highlights that traditional crops, such as sorghum and small millet, can contribute to sustainable agriculture by providing climate resilience and land-efficient nutrition, particularly with efforts to improve yields. Combinations of crops within farming systems, as well as different varieties, provide further options to optimize for multiple objectives simultaneously.

This analysis has many limitations. We consider only a subset of important attributes for sustainable agriculture. We do not consider, for example, the impact of rising atmospheric carbon dioxide concentrations on C3 cereals (Myers et al., 2014) or crop rotations as a factor in cropping decisions. We also do not assess the costs of production relative to prices, nor do we include farm-gate prices that can differ from published values. The analysis of nutritional yields does not consider bioavailability or anti-nutrients as factors in the comparison of different crops. Data on nutrient content are sparse with many sources of uncertainties, including growing conditions, variation among varieties, and effects of processing and food preparation. The average values we use from the literature may not be representative of all places. We also do not explore in depth climate variables beyond mean temperature and total precipitation, such as dry spells or daytime temperature range, which can affect crop yields. By comparing averages in yields, we do not assess the heterogeneity in trade-offs and synergies across the study region. Nor do we attempt to quantify the cultural issues related to preferences for different cereals among different segments of the population. The analysis is confined to a single agro-ecological region. Additional analysis in other regions is required to examine the robustness of the conclusions and develop region-specific support for decisions.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.gfs.2016.07.001.

## References

Akhtar, S., Ismail, T., Atukorala, S., Arlappa, N., 2013. Micronutrient deficiencies in South Asia–Current status and strategies. Trends Food Sci. Technol. 31, 55–62.

Anon, 2012. Supporting Millets in India: Policy Review and Suggestions for Action. In: Foundation, D. (Ed.), Revalorising Small Millets in Rainfed Regions of South Asia. International Development Research Centre, Canada.

Anon, 2016a. Daily TRMM and Other Satellite Precipitation Projects (3B42 V6 derived), (TRMM) (Tropical Rainfall Measurement Mission project).

Anon, 2016b. Earth B Berkeley Earth Surface Air Temperature Dataset.

Arsenault, J.E., Hijmans, R.J., Brown, K.H., 2015. Improving nutrition security through agriculture: an analytical framework based on national food balance sheets to estimate nutritional adequacy of food supplies. Food Secur., 1–15.

Ashfaq, M., Shi, Y., Tung, Ww, Trapp, R.J., Gao, X., Pal, J.S., Diffenbaugh, N.S., 2009. Suppression of south Asian summer monsoon precipitation in the 21st century. Geophys. Res. Lett., 36.

Beddington, J., Asaduzzaman, M., Clark, M., Fernandez, A., Guilou, M., Jahn, M., Erda, L., Mamo, T., Van Bo, N., Nobre, C.A., Scholes, R., Sharma, R., Wakhunga, J., 2012. Achieving food security in the face of climate change: Final report from the Commission on Sustainable Agriculture and Climate Change, in: CGIAR Research Progrm on Climate Change, A.a.F.S.C. (Ed.), Copenhagen, Denmark.

DeFries, R., Fanzo, J., Remans, R., Palm, C., Wood, S., Anderman, T., 2015. Metrics for land-scarce agriculture: nutrient content must be better integrated into planning. Science 349, 238–240.

Diffenbaugh, N.S., Scherer, M., 2011. Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries. Clim. Change 107, 615–624.

Evenson, R.E., Gollin, D., 2003. Assessing the impact of the Green Revolution, 1960 to 2000. Science 300, 758–762.

Fan, Y., Van den Dool, H., 2008. A global monthly land surface air temperature analysis for 1948–present. J. Geophys. Res.: Atmos., 113.

FAO, 2015. FAOSTAT. United Nations, Rome, Italy.

FAO/Unesco, 1971. Soil Map of the World, 1:5,000,000. United Nations Educational, Scientific, and Cultural Organization, Paris.

Fishman, R., 2012. Climate change, rainfall variability, and adaptation through irrigation: evidence from Indian agriculture. Working Paper.

Foley, J., Ramankutty, N., Brauman, K., Cassidy, E., Gerber, J., Johnston, M., Mueller, N., O'Connell, C., Ray, D., West, P., Balzer, C., Bennett, E.L., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D., 2011. Solutions for a cultivated planet. Nature 487, 337–342.

Food and Agriculture Organization, International Fund for Agricultural Development, World Food Program, 2015. The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targest: taking stock of uneven progress, Rome, FAO.

Funk, C., Peterson, P., Landsfield, M., Pedreros, D., Verdin, J., Rowland, J., Romero, B., Husak, G., Michaelson, J., Verdin, A., 2014. A Quasi-global Precipitation Time Series for Drought Monitoring. U.S. Geological Survey Data Series, Reston, Virginia, p. 832.

Gajbhiye, K., Mandal, C., 2000. Agro-ecological zones, their soil resource and cropping systems. Status of Farm Mechanization in India, Cropping Systems, Status of Farm Mechanization in India, 1–32.

Ghosh, S., Das, D., Kao, S.-C., Ganguly, A.R., 2012. Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes. Nat. Clim. Change 2, 86–91.

Gómez, M.I., Barrett, C.B., Raney, T., Pinstrup-Andersen, P., Meerman, J., Croppenstedt, A., Carisma, B., Thompson, B., 2013. Post-green revolution food systems and the triple burden of malnutrition. Food Policy 42, 129–138.

Goswami, B., Venugopal, V., Sengupta, D., Madhusoodanan, M., Xavier, P.K., 2006. Increasing trend of extreme rain events over India in a warming environment. Science 314, 1442–1445.

Government of India, 2011a. Agricultural census database. National Informatics Centre, Agriculture Census Division.

Government of India, 2011b. Madhya Pradesh development report. Planning Commission, New Delhi.

Government of India, 2013. State of Indian Agriculture 2012-13. Ministry of Agriculture, Department of Agriculture and Cooperation, New Delhi.

Government of India, 2015. Districtwise crop production statistics, Directorate of Economic and Statistics Ministry of Agriculture and Farmers Welfare.

Government of India, 2016a. Farmer's Portal. Department of Agriculture and Cooperation and Farmers Welfare, Ministry of Agriculture and Famer's Welfare, New Delhi, India.

Government of India, 2016b. Minimum support prices recommended by CACP and Fixed by Government. Commission for Agricultural Costs and Prices, Ministry of Agriculture and Farmers Welfare, New Delhi, India.

Government of India, 2016c. National Family Health Survey, India - District Fact Sheet. International Institute for Population Sciences, Mumbai.

Gulati, A., Saini, S., 2015. Leakages from Public Distribution System (PDS) and the Way Forward. Working Paper 294. Indian Council for Research on International Economic Relations. New Delhi, India.

Gupta, S., Sen, P., Srinivasan, S., 2014. Impact of climate change on the Indian economy: evidence from food grain yields. Clim. Change Econ. 5, 1450001.

Harris, I., Jones, P., Osborn, T., Lister, D., 2014. Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset. Int. J. Climatol. 34, 623–642.

Hatfield, J.L., Boote, K.J., Kimball, B., Ziska, L., Izaurralde, R.C., Ort, D., Thomson, A.M., Wolfe, D., 2011. Climate impacts on agriculture: implications for crop production. Agron. J. 103, 351–370.

Indiastat, 2013. Selected district-wise area irrigated for cereals in India, 2000–2001 to 2012–2013).

Institute of Medicine, 2000. Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium and Zinc. National Academy Press, Washington DC.

Kaur, K.D., Jha, A., Sabikhi, L., Singh, A., 2014. Significance of coarse cereals in health and nutrition: a review. J. Food Sci. Technol. 51, 1429–1441.

Krishnan, R., Sabin, T., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B., Hourdin, F., Dufresne, J.-L., Terray, P., 2015. Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. Clim. Dyn., 1–21.

Kumssa, D.B., Joy, E.J., Ander, E.L., Watts, M.J., Young, S.D., Walker, S., Broadley, M.R., 2015. Dietary calcium and zinc deficiency risks are decreasing but remain prevalent. Sci. Rep., 5.

Lobell, D.B., Gourdji, S.M., 2012. The influence of climate change on global crop productivity. Plant Physiol. 160, 1686–1697.

Lobell, D.B., Roberts, M.J., Schlenker, W., Braun, N., Little, B.B., Rejesus, R.M., Hammer, J., 2014. Greater sensitivity to drought accompanies maize yield increase in the US Midwest. Science 344, 516–519.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333, 616–620.

Loos, J., Abson, D.J., Chappell, M.J., Hanspach, J., Mikulcak, F., Tichit, M., Fischer, J., 2014. Putting meaning back into "sustainable intensification". Front. Ecol. Environ. 12, 356–361.

Manabe, S., Ploshay, J., Lau, N.-C., 2011. Seasonal variation of surface temperature change during the last several decades. J. Clim. 24, 3817–3821.

Mark, H., Houghton, L., Gibson, R., Monterrosa, E., Kraemer, K., 2016. Estimating dietary micronutrient supply and the prevalence of inadequate intakes from national Food Balance Sheets in the South Asia region. Asia Pac. J. Clin. Nutr. 25.

Menon, A., Levermann, A., Schewe, J., 2013. Enhanced future variability during India's rainy season. Geophys. Res. Lett. 40, 3242–3247.

Miller, D.D., Welch, R.M., 2013. Food system strategies for preventing micronutrient malnutrition. Food Policy 42, 115–128.

Mondal, P., Jain, M., Robertson, A.W., Galford, G., Small, C., DeFries, R., 2014. Winter crop sensitivity to inter-annual climate variability in central India. Clim. Change 126, 61–76.

Myers, S., Zanobetti, A., Kloog, I., Huybers, P., Leaky, A., Bloom, A., Carlisle, E., Diettrich, L., Fitgerald, G., Hasegawa, T., Holbrook, M., Nelson, R.F., Ottman, M., Raboy, V., Sakai, H., Sartor, K., Schwartz, J., Seneweera, S., Tausz, M., Usui, Y., 2014. Increasing $CO_2$ threatens human nutrition. Nature 510, 139–142.

National Sample Survey Organisation, 2014a. Household consumption of various goods and services in India) 2011-12. Ministry of Statistics and Programme Implementation, Government of India, Report no. 558 (68/1.0/2). (NSS 68th Round).

National Sample Survey Organisation, 2014b. Nutritional intake in India), 2011–12 NSS 68th Round, Report No. 560. (Ministry of Statistics and Programme Implementation, New Delhi).

Niu, X., Wang, S., Tang, J., Lee, D.K., Gutowski, W., Dairaku, K., McGregor, J., Katzfey, J., Gao, X., Wu, J., 2015. Projection of Indian summer monsoon climate in 2041–2060 by multiregional and global climate models. J. Geophys. Res.: Atmos. 120, 1776–1793.

Porter, J., Liyong, X., Challinor, A., Cochrane, K., Howden, M., Iqbal, M., Lobell, D., Travasso, M., 2014. Chapter 7: food security and food production systems. IPCC 2014: climate change 2014: impacts, adaptation, and vulnerability. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Final draft. IPCC AR5 WGII. Cambridge University Press, Cambridge.

Rajeevan, M., Bhate, J., Kale, J., Lal, B., 2006. High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. Curr. Sci. 91, 296–306.

Sabade, S., Kulkarni, A., Kripalani, R., 2011. Projected changes in South Asian summer monsoon by multi-model global warming experiments. Theor. Appl. Climatol. 103, 543–565.

Saleh, A.S., Zhang, Q., Chen, J., Shen, Q., 2013. Millet grains: nutritional quality, processing, and potential health benefits. Compr. Rev. Food Sci. Food Saf. 12, 281–295.

Sharmila, S., Joseph, S., Sahai, A., Abhilash, S., Chattopadhyay, R., 2015. Future projection of Indian summer monsoon variability under climate change scenario: an assessment from CMIP5 climate models. Glob. Planet. Change 124, 62–78.

Shobana, S., Krishnaswamy, K., Sudha, V., Malleshi, N., Anjana, R., Palaniappan, L., Mohan, V., 2013. Finger millet (Ragi, *Eleusine coracana* L.): a review of its nutritional properties, processing, and plausible health benefits. Adv. Food Nutr. Res 69, 1–39.

Shukla, R., Chakraborty, A., Joshi, P., 2015. Vulnerability of agro-ecological zones in India under the earth system climate model scenarios. Mitig. Adapt. Strateg. Glob. Change, 1–27.

Singh, D., Tsiang, M., Rajaratnam, B., Diffenbaugh, N.S., 2014. Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. Nat. Clim. Change 4, 456–461.

Smith, P., Gregory, P.J., 2013. Climate change and sustainable food production. Proc. Nutr. Soc. 72, 21–28.

Stocker, T.F., 2014. Climate change 2013: The Physical Science Basis: Working Group I contribution to the Fifth assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Stowasser, M., Annamalai, H., Hafner, J., 2009. Response of the South Asian summer monsoon to global warming: mean and synoptic systems. J. Clim. 22, 1014–1036.

United Nations Standing Committee on Nutrition, 2010. Sixth report on the world nutrition situation: progress in nutrition. United Nations Systems, Standing Committee on Nutrition, Geneva.

United States Department of Agriculture, 2015. National Nutrient Database for Standard Reference Release 27, in: Service, A.R. (Ed.).

Velten, S., Leventon, J., Jager, N., Newig, J., 2015. What is sustainable agriculture? A systematic review. Sustainability 7, 7833–7865.

Verón, S.R., de Abelleyra, D., Lobell, D.B., 2015. Impacts of precipitation and temperature on crop yields in the Pampas. Clim. Change 130, 235–245.

Wheeler, T., von Braun, J., 2013. Climate change impacts on global food security. Science 341, 508–513.

Willmott, C.J., Matsuura, K., 2014. Terrestrial Air Temperature and Precipitation: Gridded Monthly Time Series (1900–2014).

Please cite this article as: DeFries, R., et al., Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Global Food Security (2016), http://dx.doi.org/10.1016/j.gfs.2016.07.001