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/

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