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Sensitivity of crop cover to climate variability: Insights from two Indian agro-ecoregions

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ABSTRACT

Crop productivity in India varies greatly with inter-annual climate variability and is highly dependent on monsoon rainfall and temperature. The sensitivity of yields to future climate variability varies with crop type, access to irrigation and other biophysical and socio-economic factors. To better understand sensitivities to future climate, this study focuses on agro-ecological subregions in Central and Western India that span a range of crops, irrigation, biophysical conditions and socioeconomic characteristics. Climate variability is derived from remotely-sensed data products, Tropical Rainfall Measuring Mission (TRMM – precipitation) and Moderate Resolution Imaging Spectroradiometer (MODIS – temperature). We examined green-leaf phenologies as proxy for crop productivity using the MODIS Enhanced Vegetation Index (EVI) from 2000 to 2012. Using both monsoon and winter growing seasons, we assessed phenological sensitivity to inter-annual variability in precipitation and temperature patterns. Inter-annual EVI phenology anomalies ranged from −25% to 25%, with some highly anomalous values up to 200%. Monsoon crop phenology in the Central India site is highly sensitive to climate, especially the timing of the start and end of the monsoon and intensity of precipitation. In the Western India site, monsoon crop phenology is less sensitive to precipitation variability, yet shows considerable fluctuations in monsoon crop productivity across the years. Temperature is critically important for winter productivity across a range of crop and management types, such that irrigation might not provide a sufficient buffer against projected temperature increases. Better access to weather information and usage of climate-resilient crop types would play pivotal role in maintaining future productivity. Effective strategies to adapt to projected climate changes in the coming decades would also need to be tailored to regional biophysical and socio-economic conditions.

1. Introduction

Agriculture is the largest employment sector in India, ranging from traditional village farming to modern agriculture, with ∼55% of the working population relying directly on agriculture for sustenance and livelihoods (Government of India, 2013). Food production, and thus food security, is highly impacted by seasonal weather and long term climate change, including changes in temperature (Peng et al., 2004; Lobell and Burke, 2008; Lobell et al., 2012; Jalota et al., 2013) and precipitation (Kumar et al., 2004; Cramer, 2006; Asada and Matsumoto, 2009; Byjesh et al., 2010; Auffhammer et al., 2012; Barnwal and Kotani, 2013; Jalota et al., 2013). Indian smallholder farmers who own less than 2 ha of farmland represent 78% of the total Indian farmers and produce 41% of the country's food crops. These smallholder farmers are among some of the most vulnerable communities to climatic and economic changes due to limited access to technology, infrastructure, markets, and institutional or financial support in the case of adverse climatic events (Singh et al., 2002).

Both inter-annual and long-term climate variability affect food production in India (Selvaraju, 2003; Kumar et al., 2004; Guiteras, 2007; Revadekar and Preethi, 2012). The El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) impact differential heating of the Indian Ocean, which disrupts the typical onset of the Indian monsoon (Wu and Kirtman, 2004, Sankar et al., 2011). A warm ENSO phase results in an average agricultural loss of US$773 million, whereas a cold ENSO year leads to an average financial gain of US$437 million (Selvaraju, 2003). In addition to these episodic

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events, historical records indicate that winter precipitation has significantly increased for all of India since 1954, yet monsoon precipitation has decreased over most regions (Pal and Al-Tabba, 2011; Subash et al., 2011). Recent research indicates that a less frequent but intense monsoon could have a negative impact on crop productivity (Auffhammer et al., 2012).

Extreme precipitation events (>40 mm/day) across all of India are projected to increase in frequency in the second half of this century based on findings from the Coupled Model Intercomparison Project 5 (CMIP5) (Chaturvedi et al., 2012). Annual precipitation is projected to increase between 4% and 14% for all of India by 2080 given "business as usual" parameterizations (Chaturvedi et al., 2012). The potential benefits of any increased precipitation on water-limited crops through direct water supply and increased storage of irrigation water, however, could be offset by projected increases in temperature (Peng et al., 1995; Wheeler et al., 2000). Long-term records show that winter temperatures have increased but there have only been non-significant increases in monsoon temperatures (Pal and Al-Tabba, 2010; Subash et al., 2011). By the 2080s, annual temperatures are expected to increase by 1.7 °C–4.8 °C according to the CMIP5 models (Chaturvedi et al., 2012).

Historically, India has demonstrated the capacity to adapt new practices and technologies to increase agricultural production and decrease vulnerability to climate variability. The 'Green Revolution' benefited the Indian agricultural sector in many ways, introducing irrigation, fertilizers, and high-yielding crop varieties (Freebairn, 1995). Many argue that the benefits focused on already advantaged large-scale farmers in north-western India, while small-scale farmers in other regions only marginally benefited (Freebairn, 1973; Shiva, 1991; Das, 1999). These small-scale farmers typically rely on climate-dependent irrigation such as canal irrigation and shallow dug-wells, and do not always have access to high yielding crop varieties; they are thus at a greater risk to variations in climate (Singh et al., 2002). Excessive use of groundwater irrigation in the north-western part of India has led to severe groundwater depletion (Rodell et al., 2009), and is likely to affect future crop productivity in the absence of effective adaptation strategies, such as new drought-tolerant crop varieties, access to other forms of irrigation (e.g. canal irrigation), better and effective storage of monsoon precipitation, and access to timely weather information to inform planting strategies (Singh et al., 2002). Baseline information on agricultural sensitivity to climate variability could provide useful information for farm-level strategies and policies that promote adaption to climate variability. We must therefore first understand how, and to what degree, crops in different regions in India respond to current temperature and precipitation variability.

Crop responses to intra- and inter-annual climate variability have been widely assessed using remotely sensed vegetation indices, which can accurately capture cropping patterns, including crop phenology, crop type, and cropping intensity (Xiao and Moody, 2004; Sakamoto et al., 2006, 2009; Prasad et al., 2007; Wardlow and Egbert, 2008; Tao et al., 2008; Lobell et al., 2012). The Moderate Resolution Imaging Spectroradiometer (MODIS)-derived data products, in particular, have been used to examine several different crop pattern parameters, such as identifying cropping rotation (Morton et al., 2006; Sakamoto et al., 2006; Brown et al., 2007; Galford et al., 2008, 2010; Wardlow and Egbert, 2008), quantifying crop area coverage (Biradar and Xiao, 2011; Pan et al., 2012), documenting crop-related land use practices (Wardlow and Egbert, 2008), classifying specific crop types (Wardlow et al., 2007; Hatfield and Prueger, 2010; Ozdogan, 2010; Pittman et al., 2010), and monitoring crop phenology (Sakamoto et al., 2005, 2006; Wardlow et al., 2006). MODIS data products have been preferred for such applications due to their moderate spatial resolutions (250, 500, 1000 m), high temporal resolutions (16-day composites for the vegetation index products), and global coverage. Although the spatial resolution of MODIS presents challenges to identify crop patterns in small-scale farms (≤2 ha), the possibility of achieving moderately high accuracy and the ease of implementation at regional scales offer considerable potential for time-series analysis of crop cover (Jain et al., 2013).

India is a highly heterogeneous country in terms of environmental characteristics. Annual precipitation in India varies from a few centimeters in western Indian deserts to several hundred centimeters in the northeastern mountainous regions of India. Temperature can vary from less than −40 °C in the Himalayas to over 50 °C in western India. In addition, a highly variable topography across India has resulted in a great variety of soils. In order to identify relatively homogeneous regions in terms of soil, climate, physiography and moisture availability periods for crop growth, India has been grouped into 20 agro-ecoregions (Fig. 1) that have been further divided into 60 agro-eco subregions (Gajbhiye and Mandal, 2000).

Previous crop-modeling studies have projected changes in crop yield based on different climate model-generated scenarios (Lal, 2011). These models generally focus on bio-physical characteristics of crop responses to changing climate in a larger region. Few studies have assessed the relative agricultural sensitivity to changing climate among different agro-eco subregions that differ in their access to irrigation, source of irrigation (groundwater vs. surface irrigation), crop type (food crops vs. cash crops), and market access. Better understanding of the potential and constraints in each of these agro-eco subregions will help formulate effective strategies to adapt to a changing climate.

The aim of this study is to quantify decadal changes in seasonal crop covers and identify, compare and contrast agricultural sensitivity to inter-annual climate variability in two Indian agro-eco subregions. We use satellite-derived Enhanced Vegetation Index (EVI) to capture heterogeneity in crop cover across space and time. The term 'crop cover' in this study includes both crop greenness (a measure for crop productivity) and crop extent (or field area), since the EVI value at the pixel level can be influenced by both. We address the following questions in this study:

1. Which climate variables (precipitation and temperature) most influence crop cover for monsoon and winter crops from 2000 to 2012 in the two study regions?
2. How does the sensitivity of crop cover to climate variability vary in different agro-ecological regions with different socio-economic factors?

We first quantified seasonal peak EVI values and anomalies in crop cover at the pixel level (2000–2012). We then constructed mixed-effect models to identify the most important climate variables for crop cover for each season in each of the study sites. With these results, we discussed the relative climate sensitivity in the context of socio-economic characteristics of these two regions.

2. Materials and methods

2.1. Study sites

We selected two sites from different agro-ecological subregions in central and western India (Fig. 1) based on our long-term research experience in these regions, thus enabling us to better interpret the findings. These sites represent a variety of demographic characteristics (Table S1), cropping practices (Table S1), precipitation range (Fig. 2), irrigation access (Fig. 3), and market dependence that is typical of the Indian agricultural sector (Fan