Global Environmental Change 31 (2015) 98–109

Contents lists available at ScienceDirect

Global Environmental Change

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

Understanding the causes and consequences of differential decision-making in adaptation research: Adapting to a delayed monsoon onset in Gujarat, India

Meha Jain [a,*], Shahid Naeem [b], Ben Orlove [c], Vijay Modi [d], Ruth S. DeFries [b]

[a] Department of Environmental Earth System Science, Stanford University, Stanford, CA 94305, USA
[b] Department of Ecology, Evolution and Environmental Biology, Columbia University, New York, NY 10027, USA
[c] School of International and Public Affairs, Columbia University, New York, NY 10027, USA
[d] Department of Mechanical Engineering, Columbia University, New York, NY 10027, USA

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 4 December 2014
Accepted 15 December 2014
Available online

Keywords:
Adaptation
Monsoon variability
India
Agriculture
Vulnerability
Decision-making

ABSTRACT

Weather variability poses numerous risks to agricultural communities, yet farmers may be able to reduce some of these risks by adapting their cropping practices to better suit changes in weather. However, not all farmers respond to weather variability in the same way. To better identify the causes and consequences of this heterogeneous decision-making, we develop a framework that identifies (1) which socio-economic and biophysical factors are associated with heterogeneous cropping decisions in response to weather variability and (2) which cropping strategies are the most adaptive, considering economic outcomes (e.g., yields and profits). This framework aims to understand how, why, and how effectively farmers adapt to current weather variability; these findings, in turn, may contribute to a more mechanistic and predictive understanding of individual-level adaptation to future climate variability and change. To illustrate this framework, we assessed how 779 farmers responded to delayed monsoon onset in fifteen villages in Gujarat, India during the 2011 growing season, when the monsoon onset was delayed by three weeks. We found that farmers adopted a variety of strategies to cope with delayed monsoon onset, including increasing irrigation use, switching to more drought-tolerant crops, and/or delaying sowing. We found that farmers' access to and choice of strategies varied with their assets, irrigation access, perceptions of weather, and risk aversion. Richer farmers with more irrigation access used high levels of irrigation, and this strategy was associated with the highest yields in our survey sample. Poorer farmers with less secure access to irrigation were more likely to push back planting dates or switch crop type, and economic data suggest that these strategies were beneficial for those who did not have secure access to irrigation. Interestingly, after controlling for assets and irrigation access, we found that cognitive factors, such as beliefs that the monsoon onset date had changed over the last 20 years or risk aversion, were associated with increased adaptation. Our framework illustrates the importance of considering the complexity and heterogeneity of individual decision-making when conducting climate impact assessments or when developing policies to enhance the adaptive capacity of local communities to future climate variability and change.

1. Introduction

Weather variability poses a significant risk to agricultural production, since crop yields are directly tied to the rainfall and temperature experienced in a given year (Lobell et al., 2011; Schlenker and Roberts, 2006). Climate change is likely to increase the risk of crop failure and lower production in some regions, particularly in the tropics, with studies estimating up to a 30% reduction in the yields of staple crops including wheat and rice in some regions, like South Asia, by mid-century (Lobell et al., 2008; Ortiz et al., 2008; Hijioka et al., 2014). These risks are predicted to increase in the latter half of the 21st century (Porter et al., 2014). Farmers may be able to reduce some of the impacts of weather variability on yields by adapting, or adjusting their cropping strategies in response to weather stimuli (Adger, 2003; Mendelsohn et al., 1996; Porter et al., 2014). For example,

* Corresponding author at: Department of Environmental Earth System Science, Stanford University, 473 Via Ortega, Stanford, CA 94305, USA. Tel.: +1 509 396 8700.
E-mail addresses: mehajain@stanford.edu (M. Jain), sn2121@columbia.edu (S. Naeem), bso5@columbia.edu (B. Orlove), modi@columbia.edu (V. Modi), rd2402@columbia.edu (R.S. DeFries).

http://dx.doi.org/10.1016/j.gloenvcha.2014.12.008

farmers may shift to more drought-tolerant crops during low rainfall years (Smit et al., 1996). However, not all individuals may respond to weather variability in the same way. In order to more accurately estimate future climate impacts on crop production, it is important to develop a mechanistic and predictive framework for understanding how, why, and how effectively farmers may adapt to weather variability. In so doing, we can better identify which populations may be best able to cope with and adapt to future climate variability and change, and which populations may be the most in need of targeted adaptation policies (Vincent, 2007).

With this aim, many studies have documented how farmers shift their cropping practices in response to current weather parameters (e.g., Laube et al., 2011; Mertz et al., 2009; Thomas et al., 2007) and some research has identified which socio-economic and biophysical factors are associated with those farmers who decide to adapt (e.g., Below et al., 2012; Deressa et al., 2009). Our study builds on this previous research in three main ways to develop a process-based framework for understanding farmer decision-making in response to weather shocks. This framework may contribute to a mechanistic understanding of which farmers may adapt to future weather variability and why (Fig. 1; Section 2). First, previous studies on individual-level adaptation have been limited because they often assume that any coping strategy, or change in behavior in response to weather, is adaptive, or beneficial to the decision-maker (Jain et al., in review). However, without considering the outcomes of decision-making, such as the yield or profit of a given crop, it is impossible to know whether a change in behavior (e.g., switching crop type) actually confers some benefit (Section 2.2). Second, previous studies have shown that decisions to adapt are complex, and are influenced by multiple social, economic, biophysical, and perceptional factors (Below et al., 2012; Deressa et al., 2009). Yet a majority of studies on individual-level adaptation rarely consider multiple factors that influence decision-making simultaneously (Jain et al., in review); we suggest that this breadth is necessary to understand the relative importance of different factors and to develop a more mechanistic understanding of which individuals may be more likely to adapt to future changes in weather (Section 2.1). Finally, not all individuals in a given community or region decide to cope with weather variability in the same way. Examining differential decision-making across individuals is an important step in developing a process-based and predictive understanding of who may adapt to future weather variability and why (Burton et al., 2002; Eriksen and Kelly, 2006; Fazey et al., 2007). To examine differential decision-making, we suggest that separate analyses should be conducted for sub-groups of the population that likely face different constraints when making decisions about how to cope with weather variability (e.g., irrigated versus non-irrigated farmers; Section 2.3). This will allow us to assess the differential ability of these groups to adapt to weather variability and how adaptation policies may more effectively target each of these heterogeneous sub-groups.

To illustrate the utility of this framework, we apply it to understand how farmers cope with weather variability in Gujarat, India. Agricultural production in India is particularly sensitive to weather variability, as a large proportion of its agriculture is rain-fed and a majority of farmers are smallholders and may not have access to the technologies needed to ameliorate the impacts of adverse weather conditions (Fishman, 2012; Kumar and Parikh, 2001; Morton, 2007). Our study focuses on the monsoon season, which spans from late May until mid-November (Ministry of Agriculture, 2010), because it is the main growing season in this region and also because production during this season is directly tied to the quality, quantity, and timing of monsoon rains in a given year (Kumar et al., 2004; Mall et al., 2006; Vermeulan and Wynter, 2014). We specifically examine how farmers respond to a delayed monsoon onset, one of the predominant weather stimuli farmers use to inform cropping decisions in this season. In this region, rains typically arrive by June 15; however, there is high inter-annual variability in monsoon onset date (Fig. 2), and farmers state that they alter their cropping strategies if the monsoon rains are delayed. We asked farmers how they generally responded to a delayed monsoon onset, and then we applied our framework to examine specific cropping decisions in 2011, when the monsoon onset was delayed by three weeks (Fig. 2). Specifically, we asked the following questions:

(1) What are the range of coping strategies farmers employ to respond to a delayed monsoon onset?
(2) Are these coping strategies adaptive, considering yield and profit?
(3) Which biophysical, economic, social, and cognitive factors are associated with different decisions to cope with a delayed monsoon onset?
(4) How does the importance of these different decision-making factors vary across farmers in this region?

Understanding the answers to these four questions can help us better identify which farmers may be better or worse able to adapt to weather variability and which factors drive decisions to adapt, which can contribute to a more mechanistic understanding of who may adapt to future weather variability and why (Vincent, 2007).

2. Framework to examine decision-making

In this section, we develop a framework for assessing farmer decision-making in response to weather variability. Our framework consists of identifying which biophysical, economic, social, and cognitive factors are associated with decisions to cope with weather variability, as well as the outcomes of these decisions (e.g., yield and profit) to examine if these coping strategies are adaptive

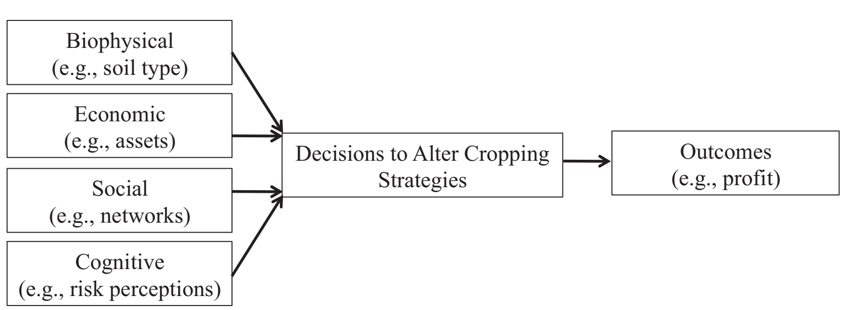

Fig. 1. Decision-making framework. We consider a variety of different biophysical, economic, social, and cognitive factors that have been shown to be important for agricultural decision-making in the previous literature. We also quantify the outcomes (e.g., yields and profits) of cropping strategies to identify if alterations were adaptive in the year of our study.

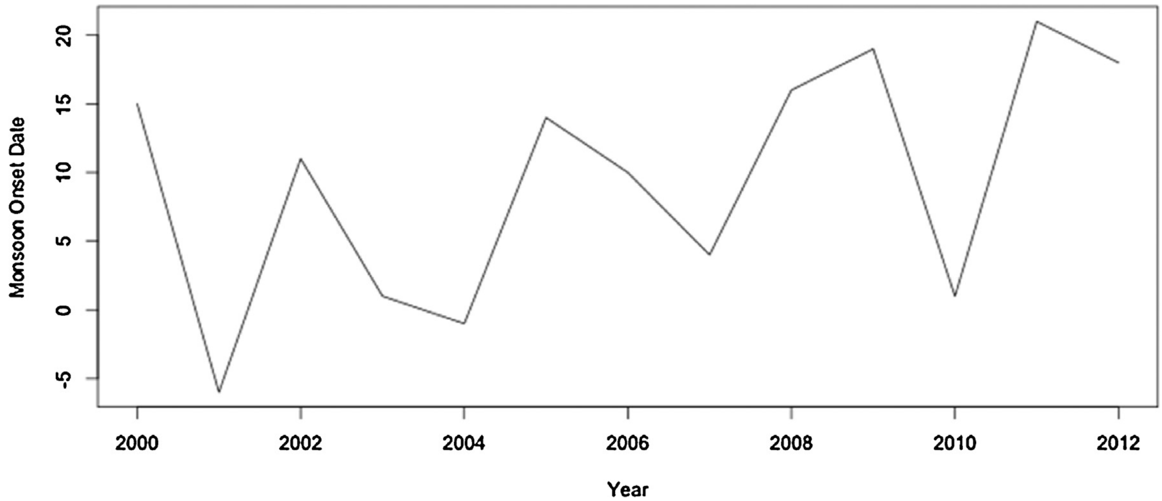

Fig. 2. Monsoon onset date from 2000 to 2012. Monsoon onset date was calculated as the first wet day (>1 mm daily rainfall) that is not immediately followed by a 10 day dry spell (<10 mm total rainfall; Mondal et al., 2014). Each date is standardized to the mean arrival date (June 15) of the monsoon in this region.

(Fig. 1). Without considering the outcomes of decision-making, it is possible that some strategies do not confer any benefit or may in fact be mal-adaptive (Barnett and O'Neill, 2010). By identifying which factors drive decisions to adapt, we can develop a more predictive understanding of which farmers may be more likely to adapt to future change or identify factors that should be targeted by policies to enhance adaptation. For example, if we find that the factors most associated with decisions to adapt are perceptions of climate change, then one way to enhance decisions to adapt in the future may be to increase knowledge about climate change and its predicted impacts via educational campaigns or weather forecasts (Cooper et al., 2013; Balaji and Craufurd, 2014).

2.1. Factors associated with decisions to alter cropping strategies

Many studies have examined if there are particular socio-economic or biophysical variables that are associated with individuals' cropping decisions in response to weather variability and change (e.g., Below et al., 2012; Deressa et al., 2009; Wood et al., 2014). The factors that have been shown to be important across the broad, inter-disciplinary literature on this topic include a range of biophysical, economic, social, and cognitive factors. Below we enumerate variables that have been associated with individuals who adapt in previous studies and may be considered within the framework we propose. However, we recognize that this is not an exhaustive list of all variables that may be important for decision-making and future work should target which specific variables are considered within a given study based on knowledge of decision-making within the system of interest. This may be assessed via time spent in the field, conducting focus groups of farmers within the communities of interest, speaking to local experts, or developing hypotheses based on previous literature.

2.1.1. Biophysical

Biophysical factors may influence cropping decisions (Kurukulasuriya and Mendelsohn, 2008). For example, soil type may constrain the types of crops that a farmer can plant on his or her field, reducing the ability of farmers to adopt certain coping strategies in response to fluctuations in weather. Furthermore, the amount and type of irrigation farmers have access to may place important constraints on the types of crops or management strategies that farmers can adopt. For example, those with more secure access to irrigation may be able to plant a wider suite of crops, consider a wider range of sowing dates, and also buffer production against periods of low rainfall by increasing the amount of irrigation used (Fishman, 2012; Mendelsohn and Seo, 2007).

2.1.2. Economic

Studies have examined the impact of economic variables on the ability of farmers to adapt to changes in weather. Previous studies have suggested that farmers who have increased assets or access to capital are more likely to adopt new cropping strategies given that they are able to invest in new adaptive technologies (Matuschke et al., 2007; Shiferaw et al., 2008). Similarly, those with diversified income sources may be more likely to adapt because they mitigate the risks of adapting by earning income from other non-farm sources or may have more access to capital that allows them to adapt (Reardon et al., 1992; Kelly and Adger, 2000). Other studies have suggested that farmers with larger landholdings are more likely to adopt new cropping strategies; these farmers may be more willing to take risks associated with new cropping strategies since they may be able to devote only a portion of their land to new strategies (Erenstein and Laxmi, 2008; Morduch, 2002).

2.1.3. Social

Many social factors have been shown to influence cropping decisions. For example, farmers who have stronger social networks have been shown to be more likely to alter cropping strategies because they receive more goods (e.g., new seed varieties) or information (e.g., weather information) through social ties than those who are less connected (Matuschke and Qaim, 2009; Vasilaky, 2013). Furthermore, social status within a given community, such as caste, has been shown to be associated with changes in cropping strategies, given that certain groups may be better connected within a given community and receive more information or economic aid to adapt (Fishman et al., 2013). Finally, institutional factors, such as how effectively institutions govern local resources including irrigation, have been shown to affect individual decision-making (Jain et al., 2014; Tompkins and Adger, 2004).

2.1.4. Cognitive

Other studies have shown that cognitive factors, such as perceptions of weather or perceptions of one's ability to adapt, are some of the strongest factors associated with decision-making (Mertz et al., 2009). For example, an individual's perceived adaptive capacity has been linked to the probability that a given individual adapts to fluctuations in weather (Grothmann and Patt, 2005). Furthermore, perceptions of risk have also been shown to be associated with cropping decisions, with more risk-averse farmers typically less willing to adopt new agricultural technologies (Feder and Umali, 1993; Marra et al., 2003; Sheikh et al., 2003).

2.2. Outcomes of decision-making

As noted above, many studies on adaptation assume that any change in cropping behavior, such as switching crop type or shifting planting date, is adaptive. However, in order to understand how well farmers are truly able to adapt to fluctuations in weather, it is important to consider the outcomes of the cropping decisions that farmers make. By considering the outcomes of decision-making, it is possible that certain coping strategies, such as switching crop type, could be shown to be non-beneficial or even mal-adaptive (Barnett and O'Neill, 2010). It is important to note that the outcome variable of interest may vary based on the question under consideration. For example, yield and profits may be used as an impact variable when interested in agricultural output, crop nutritional value and stability in yield may be of interest when considering food security, and environmental impacts may be considered for questions related to sustainability. Regardless of the question in consideration, it is important to examine the relevant outcome of decision-making in order to identify whether coping strategies are adaptive and if there are any coping strategies that are more adaptive than others. It is important to note that a strategy that may be adaptive considering one set of outcomes may not be the most adaptive or may even be mal-adaptive considering another set of outcomes. For example, studies have shown that heavy groundwater use may be an adaptive way to currently improve yields in the face of weather variability, but this use may be unsustainable meaning that the strategy is mal-adaptive considering environmental impacts and longer-term food security (Dubash, 2002; Barnett and O'Neill, 2010). Examining outcomes of decision-making will allow us to more accurately identify which individuals are best able to adapt to weather variability and change.

2.3. Differential decision-making across sub-groups

While all farmers in a given community experience the same weather patterns, not all farmers respond to and cope with weather variability in the same way. For example, if monsoon rains are delayed, some farmers may cope by switching crop type while others may shift planting date. One main reason for this variability in decision-making may be that farmers face different resource constraints that affect their ability to adopt different adaptation strategies. For example, farmers who have consistent access to irrigation may make different decisions about how best to cope with fluctuations in weather compared to rain-fed farmers. Yet many studies on adaptation use single models that consider all individuals within the population of interest simultaneously, which may mask nuances in how and why adaptation strategies may vary across different sub-groups (i.e., irrigated vs rain-fed farmers). By conducting subsetted analyses that examine each sub-group independently, we can both identify if there are certain adaptation strategies that are better suited for a particular sub-group, and/or how the factors associated with decision-making vary across these individuals. Considering adaptation policies, understanding the cause and consequences of this heterogeneity in decision-making is key to designing policies that are appropriately targeted to diverse individuals within a given community.

It is necessary to define which sub-groups are important to consider, and we suggest that this may be done by using a combination of (1) theories derived from previous literature and qualitative experience from the field and (2) analyses of whether these theoretically important variables are statistically significant drivers of decision-making. First, theory from the literature, experience from the field, and knowledge from local experts can suggest which resources constrain decision-making within a given system. For example, farmers may state that the soil type of their farm constrains the cropping decisions that he or she can make, as it may be easier for farmers to adopt certain coping strategies, such as switching crop type, in certain soils (e.g., loamy soils) that can support a wide range of crops compared to other soil types (e.g., clay-like, easily flooded soils); in this case, crop switching may be a profitable and viable strategy for those farmers with loamy soils, but may not be a good choice for those with clay-like soils that are only well-suited to flood-tolerant crops. Next, while experience from the field may suggest that soil type places significant constraints on decision-making, we can test whether this variable is significantly associated with decision-making by statistically analyzing our data. For example, we can use variable importance metrics (e.g., through model fit metrics as measured by AIC), and if the variable of interest (i.e., soil type) contributes significantly to model fit, then our data suggest that our hypothesis is correct and that this resource likely plays an important role in decision-making. Thus, it may be valuable to subset our data into farmers with different soil types and see how and why decision-making varies across these heterogeneous sub-groups. We illustrate this specific approach and our framework more generally using data collected on household decision-making in Gujarat, India in Sections 3 and 4.

3. Methods

3.1. Village selection

We collected data across fifteen villages in central and northern Gujarat, India, specifically in Kheda, Ahmedabad, Mehsana, Gandhinagar, Sabarkantha, and Patan districts (Fig. 3), which lie in a hot dry semi-arid eco-region (Gajbhiye and Mandal, 2000). We selected five different clusters of villages at random across a rainfall gradient (i.e., 300–1800 mm per year) and an irrigation gradient (i.e., no irrigation, canal irrigation, groundwater irrigation), and each cluster comprised three villages. We selected one cluster in a low-rainfall, rain-fed region (Patan district), one cluster in a high rainfall, canal irrigated region (Kheda district), and three clusters in a medium rainfall, groundwater irrigated (spanning Ahmedabad, Mehsana, Gandhinagar, and Sabarkantha districts) region. We concentrated our survey sampling in groundwater-irrigated regions because we were particularly interested in understanding how differential access to groundwater influenced cropping decisions. This is because water tables are declining rapidly across this region, and examining decision-making across a gradient of access to groundwater may suggest how decision-making may change as access to groundwater becomes increasingly scarce (Rodell et al., 2009; Shah, 2009). It is important to note that these clusters of villages vary in their soil type, main crop types planted during the monsoon season, and the type and amount of irrigation to which farmers have access (Table 1).

3.2. Survey data collection

3.2.1. Focus groups and key informant interviews

We used a mixed methods approach to collect information on how farmers respond to weather variability. First, we visited each of the fifteen villages and conducted a series of informal interviews with community members and focus groups to assess farmers' perceptions of the monsoon and whether they generally alter their cropping strategies in response to inter-annual monsoon

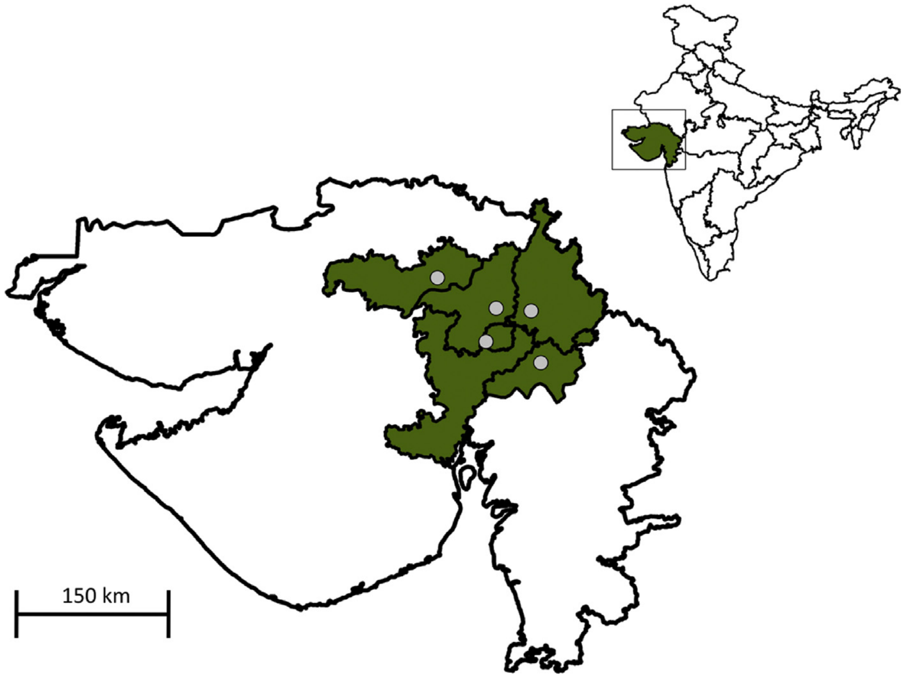

Fig. 3. Map of villages considered in this study. The districts where we conducted our research, Ahmedabad, Kheda, Gandhinagar, Mehsana, and Patan, are highlighted in the map of Gujarat. Each gray circle represents a cluster of three villages where we conducted our focus groups and structured household surveys.

variability. These preliminary visits were conducted during the monsoon seasons of 2010 and 2011. In these interviews, we found that a majority of farmers stated that monsoon onset date was a primary weather signal that they used in their decision-making. Specifically, farmers stated that they switched crop type, delayed the date of sowing, and/or increased the number of irrigations used during delayed monsoon onset years (Table 1). We used the knowledge derived from these focus groups and key informant interviews to construct structured household surveys (described below), which we administered once per year to each farmer in our survey sample during the monsoon seasons of 2011–2013.

3.2.2. Structured household surveys

In each of the fifteen villages, we interviewed approximately 50–60 households, which resulted in a total sample of 779 farmers. To survey households that were a representative sample of each community that we visited, we selected households at random stratified across landholding size and caste – landholding size may be a proxy for the wealth of a household, and caste has been shown to be associated with differences in cropping practices, social capital, and income in a given community (Borooah, 2005; Deshpande, 2000). For each household, we asked all family members present in the household who the main decision-maker was regarding agricultural decisions, including which crops to plant, the timing of planting, and when to sell crops. We then only conducted our survey with this main decision-making farmer; in the rare case where two individuals were mentioned, we conducted the survey with both farmers. It is important to note that we did not survey any agricultural laborers who did not own their own land. These farmers typically do not make their own cropping decisions, and instead carry out the decisions of the farmer whose land they are cultivating. We surveyed the main

Table 1
We list the percent of farmers in each region that reported the following in our survey data. Categories do not always add to 100% in each region because some farmers may have listed another option that we do not list here or may not have responded to our question.

		Canal region	Rain-fed region	Groundwater region
Predominant monsoon season crop types in 2011	Cotton	3.17%	13.68%	61.70%
	Castor	3.97%	17.99%	66.97%
	Sorghum	3.97%	63.93%	45.61%
	Rice	91.37%	0%	0%
General adaptation strategies	Switch crop type	13.68%	17.46%	40.64%
	Main crop change	Rice to grass	Cotton to castor or sorghum	Cotton to castor
	Shift planting date	16.67%	21.37%	36.84%
	Increase irrigation	86.51%	0%	88.30%
Irrigation access	Rain-fed	3.17%	100%	10.52%
	Shallow well	67.46%	0%	0.29%
	Canal	75.40%	0%	9.65%
	Bore owner	0%	0%	11.53%
	Bore shareholder	0%	0%	27.41%
	Bore water buyer	0%	0%	48.29%
Soil type	Sandy	27.78%	36.75%	61.40%
	Loamy	16.24%	7.93%	28.85%
	Clay	63.49%	47.01%	9.94%

decision-making farmer three times in each monsoon season of 2011–2013. This allowed us to assess cropping decisions, the yield of each crop, and the profit earned for each crop for the 2011–2013 agricultural seasons. For the purposes of this study, we focus on survey results for the monsoon season of 2011, when the monsoon was delayed by three weeks. Each structured interview was approximately thirty minutes in length and was conducted orally in Gujarati, the local language, by local field assistants. In these surveys, we collected data on farmers' cropping decisions, yield, and profit for each crop, as well as various biophysical, economic, social, and cognitive factors that were identified to be important determinants of cropping decisions from the literature, focus groups, and time spent in the field (Section 2.1; Table 2).

3.3. Alteration strategies to a delayed monsoon onset and hypotheses

Through our initial focus groups and informal interviews, we identified how farmers generally respond to a delayed monsoon onset. We found that the main types of crops planted and possible strategies to cope with a delayed monsoon onset varied across our three regions. Some farmers stated that during late monsoon onset years they switch crop type. Others stated that they continue to plant the same crop but delay the date of sowing and/or increase the amount of irrigation used during times of no to low rainfall (Table 1). We describe possible alteration strategies for each region below, which are supported by data from our structured household surveys (Tables 1 and 3). We then use this information to inform

Table 2
We list each of the variables considered in our analyses, a description, how it was coded, its hypothesized relationship with adaptation, and associated literature used to form hypotheses.

Type	Variable	Description	Hypothesis	Associated literature	Coded
Dependent variable – cropping decisions in 2011	Crop type	Whether or not a farmer planted a given crop in the monsoon 2011 season (i.e. cotton, castor, rice, grass)	NA	NA	Binary (1 = plant crop, 0 = do not plant crop)
	Sowing date	The week in which farmers sowed their crop for the monsoon 2011 season. We aggregated data to week given possible inaccuracies in remembering exact planting dates.	NA	NA	Ordinal (1 = May 15 to 12 = August 15)
	Irrigation used	The number of times farmers applied irrigation to their crop throughout the monsoon growing season in 2011	NA	NA	Ordinal (0 = no irrigation to 7 = at least 7 or more)
Dependent variable – outcome	Yield	Self-reported yields of each crop reported in local units of *mand* (20 kg) per *bhiga* (1.75 ha) for the 2011 growing season	NA	NA	Continuous (*mand* per *bhiga*)
	Profit	The profit (rupees) earned per *bhiga* (1.75 ha) for a given crop for the 2011 growing season, accounting for total costs (e.g. irrigation, seeds, labor, fertilizers, pesticides)	NA	NA	Continuous (profit in rupees per bhiga)
Social factors	Caste	The caste of a given farmer	+	(Borooah, 2005; Fishman et al., 2013)	Categorical
	Sources of information	Where farmers receive agricultural advice	+	(Matuschke and Qaim, 2009; Vasilaky, 2013)	Categorical (no information, government sources, social networks)
Economic factors	Assets	The assets of a given farmer calculated as the first PCA transform of all durable goods (e.g. bikes, cook stove, television, etc.)	+	(Filmer and Pritchett, 2001; Shiferaw et al., 2008)	Continuous
	Land owned	Number of bhigas (1.75 ha plots) that a farmer owns	+	(Erenstein and Laxmi, 2008; Morduch, 2002)	Continuous
	Main income source	The main income source for a household	+	(Reardon et al., 1992; Kelly and Adger, 2000)	Categorical (labor, farm/livestock, job)
Biophysical factors	Access to borewell irrigation	Whether the farmers use any borewells to irrigate their crops	–	(Fishman, 2012; Hassan and Nhemachena, 2008)	Categorical (owner, shareholder, water buyer, no access)
	Access to canal irrigation	Whether farmers use canal irrigation to water their crops	–	(Fishman, 2012; Hassan and Nhemachena, 2008)	Binary (1 = access, 0 = No access)
	Access to shallow well irrigation	Whether farmers use shallow wells to irrigate their fields	–	(Fishman, 2012; Hassan and Nhemachena, 2008)	Binary (1 = access, 0 = no access)
	Soil type	The predominant soil type of the farmers' plots	+	(Kurukulasuriya and Mendelsohn, 2008)	Ordinal (1 = sandy, 2 = loamy, 3 = clay)
Perceptional factors	Total rainfall amount	Whether farmers believe the total amount of rainfall in the last five years has changed compared to the previous fifteen years	–	(Grothmann and Patt, 2005; Mertz et al., 2009)	Ordinal (1 = increase, 0 = same, −1 = decrease)
	Timing of monsoon onset	Whether farmers believe the monsoon onset date has changed over the last five years compared to the previous fifteen years	–	(Grothmann and Patt, 2005; Mertz et al., 2009)	Ordinal (0 = Same, 1 = Changed)
	Risk-taking behavior	Risk-taking experiment – the more money the farmer bet on whether the coin landed on heads or tails, the more risk-taking the farmer was thought to be	+	(Feder, 1980; Marra et al., 2003)	Ordinal (1 = low risk preference to 4 = high risk preferences)
Control	Village	Village name	NA	NA	Categorical

Table 3
We present summary data on sowing date, harvest date, number of irrigations, percent of farmers who plant the crop with no irrigation, yield, cost, selling price, and profit. Data are presented as means collected from our household dataset.

Crop type	Sowing week	Harvest month	Number of irrigations applied	% Farmers plant with no irrigation	Yield (*mand* per *bhiga*)	Cost (rupees per *bhiga*)	Selling price (rupees per *mand*)	Profit (rupees per *bhiga*)
Cotton	June 3rd week	November	4.78	9.38%	28.04	7374	837	23,920
Castor	August 1st week	February	4.31	15.48%	28.66	5688	704	19,349
Sorghum	July 3rd week	October	4.86	0.00%	NA	2607	332	NA
Rice	July 3rd week	November	5.07	0.71%	42.66	6063	211	6,469

hypotheses regarding farmers' cropping decisions for 2011, when the monsoon onset was delayed by three weeks, and we ran statistical analyses to test these hypotheses, which are described in the next section (Section 3.4).

3.3.1. Groundwater region

In this region, most farmers state that they prefer to plant cotton, the main cash crop in the region because it is the most profitable and has a short growing season, which allows farmers to sow a subsequent winter crop (Table 3). However, during delayed monsoon onset years, some farmers may switch from cotton to castor, a cash crop that requires less irrigation and has a later sowing date window (August) compared to cotton (June; Table 3). It is important to note that since the cultivation cost of castor is lower than cotton (Table 3), due to fewer required inputs like irrigation and pesticides, there are no economic constraints to switching to castor. Yet because castor is typically harvested in February, it precludes the opportunity for farmers to plant a subsequent winter crop (Table 3). Thus, during late monsoon onset years, farmers may alternatively continue to plant cotton but delay the date of sowing to limit its exposure to the dry period before monsoon onset and/or increase the amount of irrigation used during this period with no rainfall. However, sowing cotton early and increasing the amount of irrigation used is likely only an option for those who have secure access to groundwater, particularly those who own their own bore-well or are part of a shareholder cooperative. Farmers who do not own their own well have less secure access to irrigation, given that they are able to purchase irrigation at an hourly rate if bore-well owners are willing to sell excess irrigation (see supplementary information for more details).

We hypothesize that farmers who are poor and have less access to irrigation are likely to switch to planting castor because the costs of planting and irrigating cotton before monsoon onset, during the ideal sowing window for cotton (June), are too high. On the other hand, we hypothesize that rich farmers who have secure access to irrigation will continue to plant cotton and increase the amount of irrigation used during the dry period prior to monsoon onset. Finally, we predict that farmers who have secure access to irrigation but are risk averse will continue to plant cotton but delay the date of sowing to reduce the amount of time that cotton is exposed to the dry period before monsoon onset.

3.3.2. Canal region

Farmers prefer to plant rice in this region, given that the majority of soils are clay-like and become easily flooded during periods of high rainfall, which results in crop failure for most other crop types (Table 1). Despite this, during late monsoon onset years, some farmers switch from planting rice to planting sorghum, which can be planted later in the growing season and also requires less irrigation than rice (Table 3). Given that the input costs of sorghum are lower than rice, due to reduced irrigation and labor, there are no economic constraints to switching to sorghum (Table 3). Alternatively, farmers may continue to plant rice but either delay its date of sowing to match the onset of the monsoon, or increase the amount of irrigation used during the dry period before monsoon onset. Yet, because most farmers rely on canal irrigation and this form of irrigation is sensitive to the timing of monsoon onset (the government only releases canal water once the source reservoir has stored enough monsoon rains), planting rice and using irrigation before the start of the monsoon is only an option for those who have access to additional shallow well groundwater irrigation (see supplementary information for more details).

We hypothesize that those farmers who have sandier soils will be more likely to switch from rice to sorghum because these soils have less risk of flooding during periods of high rainfall, which would result in crop failure for sorghum. Considering planting date, we hypothesize that poorer farmers who rely more on canal irrigation will be more likely to delay their date of sowing because they will not be able to afford shallow well irrigation that is necessary to irrigate rice before the start of the monsoon. Finally, we predict that richer farmers who have shallow well irrigation will be more likely to continue planting rice but will increase the amount of irrigation used.

3.3.3. Rain-fed region

In this region, soils are predominantly clay-like and become easily flooded during periods of high rainfall (Table 1). Unlike in the canal region, however, farmers cannot plant rice because they do not have access to irrigation to supplement the flooding of rice during periods of no to low rainfall. Therefore, farmers prefer to plant cotton, castor, or sorghum. Farmers state that the main alteration strategy to a delayed monsoon onset is switching away from cotton, which requires early sowing (i.e., June), to castor or sorghum, which can be sown later in the growing season (i.e., July and August; Table 3). Similar to the other study areas, there are no economic constraints to switching to castor or sorghum given that both crops have reduced input costs compared to cotton (Table 3). Alternatively, some farmers continue to plant cotton during late monsoon onset years but push back the date of sowing to match the onset of the monsoon (Table 1; see supplementary information for more details).

In this region, we hypothesize that farmers who are less risk-taking and have more clay-like soils that become easily flooded will be more likely to switch from planting cotton to sowing castor or sorghum, as these crops have a later sowing window and also are more resilient to flooding than cotton. We hypothesize that farmers who are less risk taking will be more likely to delay the sowing date of cotton to ensure that adequate soil moisture is stored for the germination of cotton after the onset of the monsoon.

3.4. Statistical analyses

Following our framework, we analyzed which biophysical, economic, social, and cognitive factors were associated with cropping decisions during the monsoon season of 2011, when the monsoon onset was delayed by three weeks. We also analyzed outcomes of the cropping decisions in terms of yield and profit to identify whether switching crop type, shifting planting date, or increasing irrigation, were indeed adaptive strategies. It is important to note that we were unable to assess profits of sorghum given that this crop is typically not sold to the market and instead is used as personal livestock feed. We measured crop switching by asking farmers what crop they would have planted had the monsoon rains arrived on time, and compared that to the crop type they actually planted during the year of our study. To examine delayed planting date and increased irrigation use, we asked farmers the date of sowing of their crop and the number of irrigations they used during the year of our study; thus, discussions of late planting date and increased irrigation are in comparison to other farmers in our survey sample during the year of our study and not in comparison to what they would have done had the monsoon arrived on time. We believe that this analysis still gives us an understanding of coping mechanisms because farmers generally stated that they prefer to sow crops as early as possible and use as much irrigation as possible, and our analysis examines why farmers deviate from these ideals (i.e., by planting later or by irrigating less) compared to farmers with similar access to resources.

Since crop choice and alteration strategies varied across each of our three regions (Table 1; Section 3.3), we conducted our statistical analyses separately for each region. For all analyses, we dropped covariates that had a correlation >0.5 to avoid parameter tradeoffs. Based on this criterion, we dropped caste from our analysis, since it was significantly correlated with assets. We also dropped the main livelihood of each farmer from our analysis because it was strongly correlated (>0.2) with both assets and livestock ownership (with laborers having lower assets, and those having a salaried profession typically with higher assets), and we noticed parameter trade-offs when different combinations of these variables were included. Furthermore, village was considered as a random effect in all models to control for possible differences in decision-making caused by unobserved variables that vary at the village level. We then conducted stepwise variable selection using Akaike Information Criterion with a correction for small sample size (AIC_c) to select the best model (Hurvich and Tsai, 1989). To facilitate the interpretation of effect magnitudes among covariates, all continuous predictors were standardized by subtracting their mean and dividing by twice their standard deviation (Gelman and Hill, 2007).

We next identified if we should conduct any follow-up sub-group analyses for subsets of the population that may face different resource constraints. Based on experience from focus groups, time spent in the field, and published accounts, we hypothesized that soil type and access to irrigation are the largest resource constraints that differentially influence cropping decisions in this region. Which crops farmers can plant, when, and the amount of irrigation used are all heavily influenced by the type and amount of irrigation that farmers in this region have access to (as described in Section 3.3). Soil type may also be an important constraint given that some soils allow only one crop type to be planted (e.g., clay-like soils) whereas other soil types provide high yields for a range of crop types (e.g., loamy to sandy soils). To identify whether irrigation access and soil type played a significant role in decision-making, we dropped each variable one at a time from the best logistic regression model for each of our analyses and compared the AICc from the resulting model with the AICc from the best model (Burnham and Anderson, 2002). If the difference in AICc scores was greater than ten, we considered this variable to contribute significantly to model fit (Burnham and Anderson, 2002). We found that irrigation contributed significantly to the model fit of two out of the three models in which it was found, whereas soil type did not contribute significantly in the five models in which it was found (Table S1). Based on these results, we considered irrigation in additional sub-group analyses but not soil type. We used R Project Software (R Statistical Computing 2012, Version 2.14.1) and the lme4 package for all analyses.

4. Results

4.1. Groundwater region

4.1.1. Factors associated with decision-making

Rich farmers who have more secure access to groundwater irrigation were more likely to continue to plant cotton, sow cotton earlier, and irrigate cotton more compared to other farmers in our survey sample during 2011 (Table 4). Considering those who did not own their own well, farmers were more likely to switch to castor if they owned more land and if they perceived that the monsoon onset date had changed (Table 4). These results confirm our hypotheses that richer farmers who have more secure access to irrigation are likely to continue to plant cotton and irrigate it during periods of no rainfall prior to monsoon onset, whereas poorer farmers who do not own their own well are more likely to switch to castor. Interestingly, weather perceptions were also significantly associated with crop switching.

4.1.2. Outcomes of decision-making

We found that increasing irrigation had a positive impact on cotton yields, suggesting that this is a beneficial alteration strategy (Table 7). For planting date, we found that sowing week is present in the final statistical model that predicts cotton yield with a negative sign, suggesting that an earlier sowing date may have a positive relationship with yield; this relationship however is not significant (Table 7). Finally, considering crop switching, we find that the profits of cotton and castor for the monsoon season are not statistically different, after accounting for the higher input costs required to plant cotton. This result holds true when we consider all farmers, only those who own wells, only those who do not own wells, and only those who use few irrigations for their crops (<3). However, farmers are unable to sow a winter crop after planting castor since it is a long-duration crop, and therefore it is more profitable for those farmers who have access to irrigation and are able to sow a winter crop to plant cotton during the monsoon season; cotton leads to significantly greater profits considering both the monsoon and winter seasons together (Table 7).

4.2. Canal region

4.2.1. Factors associated with decision-making

We were unable to run statistical models predicting which factors were associated with crop switching because only two farmers in our sample switched crop type during the monsoon 2011 season. This is likely because the predominant soil type in this region, clay-like soils that become easily flooded, makes it difficult for farmers to switch to other crops that may fail during periods of heavy rainfall and subsequent flooding. Our results, however, suggest that rich farmers were more likely to irrigate rice more, while poor farmers were more likely to sow rice later, corroborating our hypotheses (Table 5). We also found that climate perceptions played a strong role in decision-making, particularly for those farmers who did not have access to shallow wells, which allow farmers to sow rice prior to monsoon onset (Table 5). In addition, risk aversion played a significant role in decision-making, with more risk-averse farmers irrigating rice more (Table 5).

4.2.2. Outcomes of decision-making

Considering the impact of alteration strategies on yield, increasing irrigation led to higher yields (Table 8). Sowing date, on the other hand, did not appear to be significant in any of our models, though there is evidence that a later sowing date led to

Table 4
Factors associated with cropping decisions in 2011 in the groundwater region for all farmers, farmers who owned their own well, and for farmers who did not own their own well. The parameter estimate and standard error (in parentheses) are recorded for each variable in our model, and those variables that dropped out during model selection are marked with a dash. Significance values are starred (+ denotes $p < 0.10$, * denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$).

	Crop switching						Delay planting			Increase irrigation		
	Plant cotton 2011			Switch to castor 2011			Cotton planting date 2011			Number of irrigations for cotton in 2011		
	All farmers	No well	Own well	All farmers	No well	Own well	All farmers	No well	Own well	All farmers	No well	Own well
Asset index	0.296+ (0.166)	0.502* (0.210)	–	−0.151 (0.131)	−0.541 (0.472)	−0.710* (0.299)	−0.053 (0.038)	−0.054 (0.048)	–	0.127** (0.038)	–	0.066 (0.050)
Own land	−0.036 (0.028)	−0.136* (0.060)	–	0.062** (0.022)	1.075* (0.493)	0.052 (0.032)	−0.013* (0.006)	–	0.017** (0.006)	–	–	–
Total rain change	0.323 (0.232)	0.789* (0.331)	–	–	–	–	0.076 (0.050)	–	0.111* (0.053)	–	−0.239+ (0.131)	–
Onset change	0.439 (0.346)	0.80+ (0.452)	0.048 (0.720)	0.660+ (0.365)	1.284* (0.571)	–	–	–	–	0.026 (0.084)	0.032 (0.159)	–
Bore well												
Owner	3.953*** (1.051)	NA	–	–	NA	−0.671 (0.625)	−0.255+ (0.147)	NA	−0.199* (0.097)	–	NA	–
Shareholder	2.822** (0.893)	NA	NA	–	NA	NA	−0.068 (0.131)	NA	NA	–	NA	NA
Water buyer	1.713* (0.808)	1.825* (0.822)	NA	–	1.744 (3.057)	NA	0.181 (0.124)	–	NA	–	–	NA
Farm info												
Social	–	–	–	–	–	–	–	–	–	–	–	–
Government	–	–	–	–	–	–	–	–	–	–	–	–
Soil type	–	−0.611* (0.308)	0.287 (0.450)	–	–	–	−0.062 (0.049)	−0.155+ (0.080)	–	0.124* (0.053)	–	0.096 (0.055)
Risk	–	−0.171 (0.185)	0.366 (0.350)	–	0.555 (0.386)	–	–	–	0.041 (0.039)	–	–	–
Village RE	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	Y

higher yields for those who had access to shallow wells given that sow date appeared in the final statistical model (Table 8).

4.3. Rain-fed region

4.3.1. Factors associated with decision-making

In this region, we find that farmers who have sandier soils and are more risk-taking were more likely to continue to plant cotton in the 2011 growing season despite the delayed monsoon onset (Table 6). Risk-averse farmers, on the other hand, were more likely to switch to castor, confirming our hypothesis that risk aversion plays a strong role in crop switching. Considering planting date, farmers who were poorer and thought that monsoon rainfall had changed were more likely to plant cotton later (Table 6).

4.3.2. Outcomes of decision-making

In the year of our study, a large proportion of crops failed due to heavy monsoon rainfall toward the end of the growing season that flooded fields, particularly of those farmers who had clay-like soils. Thus, we were unable to assess the impact of sowing date and crop switching on yield and profit in this region. Those farmers who planted castor, however, had a lower rate of crop failure (65%) compared to those who planted cotton (95%), suggesting that switching to castor may be a beneficial strategy to cope with the flooding of agricultural fields that have clay-like soils.

5. Discussion and conclusion

Farmers may alter their cropping strategies in response to weather variability and change, however, not all farmers may respond in the same way. To understand the causes and consequences of differential decision-making, we developed a framework to examine farmer decision-making in response to weather variability and change. We then applied this framework to identify how farmers in Gujarat, India altered their cropping strategies in response to a delayed monsoon onset. We found that farmers responded to a delayed monsoon onset in a variety of ways, and that, based on self-reported yield and profit data, these strategies were adaptive in the year of our study. Some farmers switched crop type, while others continued to plant the same crop they plant in normal onset years, but delayed the date of sowing or increased the amount of irrigation used to cope with the extended dry period prior to monsoon onset. Overall, our results highlight that even though all farmers experience the same weather stimuli, there is great diversity in the ways farmers cope with weather variability and the factors that drive decisions to adapt.

Across our three study regions, we find that assets, access to irrigation, weather perceptions, and risk aversion were the strongest factors associated with decision-making in the year of our study. The most preferred alteration strategy across these regions was planting the same crop type typically planted in normal monsoon years (i.e., cotton or rice) but increasing the amount of irrigation used during the dry period prior to monsoon onset (Table 1). This strategy was particularly adopted by richer farmers who had more secure access to irrigation (Tables 4 and 5). Interestingly, when we considered less irrigation secure farmers in our sub-group analyses, we found that cognitive variables began to play a more significant role in the cropping decisions farmers made (Tables 4–6). Specifically, farmers who believed that the monsoon onset date had changed over the past 15 years were more likely to adopt crop switching in the groundwater region (Table 4), and delay sowing in the canal region (Table 5). In the rain-fed region, individuals' perceptions of risk were strongly associated with crop choice; those farmers who were more risk averse were more likely to practice crop switching (Table 6). These results highlight the importance of considering sub-group analyses within a given

Table 5
Factors associated with cropping decisions in the canal region in 2011 for all farmers, farmers who do not have access to shallow wells, and farmers who have access to shallow wells. The parameter estimate and standard error (in parentheses) are recorded for each variable in our model, and those variables that dropped out during model selection are marked with a dash. Significance values are starred (+ denotes $p < 0.10$, * denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$). We could not assess crop switching because too few farmers ($n = 2$) switched from planting rice to planting sorghum.

	Delay planting Rice planting date 2011			Increase irrigation Number of irrigations for rice in 2011		
	All farmers	No shallow well	Shallow well	All farmers	No shallow well	Shallow well
Asset index	−0.636** (0.229)	-	−0.802** (0.286)	0.059+ (0.032)	0.125+ (0.069)	0.060+ (0.035)
Total rain change	0.692+ (0.371)	–	–	–	–	–
Onset change	–	0.905+ (0.493)	–	–	–	0.200** (0.070)
Canal irrigation	0.974 (0.667)	1.982* (0.807)	−0.354 (0.716)	–	–	−0.182+ (0.103)
Shallow well irrigation	–	–	1.231 (0.743)	–	–	–
Farm info						
Social	–	–	–	–	−0.526* (0.196)	–
Government	–	–	–	–	0.663 (0.411)	–
Soil type	–	−0.341 (0.765)	–	−0.068+ (0.039)	–	–
Risk	–	–	–	−0.061+ (0.033)	–	−0.101** (0.035)
Village RE	Y	Y	Y	Y	Y	Y

community to understand the varying factors driving heterogeneous decision-making. Without separately analyzing individuals with more versus less secure irrigation access, we would have largely masked the important influence of cognitive variables on decision-making.

Considering the outcomes of these coping strategies, the relative adaptive benefit as measured by yield and profit varied across the farmers in our study sample. Our results suggest that planting the same crop type as one would during normal monsoon onset years but increasing the amount of irrigation used was the most adaptive strategy, and allowed farmers to maintain high yields and profits despite a delayed monsoon onset (Tables 7 and 8). It is important to note, however, that this option was not available to all farmers, particularly poorer farmers who had little to no access to irrigation. While these farmers typically had lower yields than those who used more irrigation, we found that delaying sowing date had no effect on yields and switching crop type may have been a beneficial strategy in the year of our study (Tables 7 and 8). In the groundwater region, castor had lower input costs and required fewer irrigations than cotton, yet still provided similar profits after controlling for irrigation, suggesting that switching to castor was a beneficial strategy for poorer farmers who had less access to irrigation (Table 7). In the rain-fed region, our results suggest that those farmers who switched to castor had less crop failure during the year of our study, possibly because castor was more resilient than cotton to flooding. Broadly, these results suggest that both the richer farmers who had more access to irrigation and the poorer farmers who had less access to irrigation made the most adaptive decisions considering the constrained set of choices that they had access to.

Table 6
Factors associated with cropping decisions in the rain-fed region in 2011. The parameter estimate and standard error (in parentheses) are recorded for each variable in our model, and those variables that dropped out during model selection are marked with a dash. Significance values are starred (+ denotes $p < 0.10$, * denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$).

	Crop switching		Delay planting
	Plant cotton 2011	Switch to castor 2011	Cotton planting date 2011
Asset index	0.415 (0.382)	−0.427 (0.315)	−3.535+ (1.586)
Own land	–	–	2.345 (1.644)
Total rain change	–	0.839 (0.708)	6.156+ (2.463)
Onset change	–	−1.593* (0.692)	−6.596* (2.585)
Farm info			
Social	−0.889 (1.417)	–	–
Government	3.582** (1.186)	–	–
Soil type	−1.031* (0.449)	–	−2.404 (1.982)
Risk	0.738* (0.297)	−0.872* (0.413)	–
Village RE	Y	Y	Y

It is important to consider the implications of these results for how effectively farmers may cope with future weather variability and change. Across our study regions, for those farmers who were able to (i.e., the richer and more irrigation secure farmers), increasing irrigation was the preferred alteration strategy to a delayed monsoon onset, and this strategy was also associated with the highest yields and profits across our study sample. This suggests that from a policy perspective, one way to enhance farmers' adaptive capacity is to provide increased access to irrigation or improve access to credit, which may allow farmers to invest the capital necessary to increase irrigation access and grow high-yielding cash crops even during late monsoon onset years. However, this strategy may be mal-adaptive in the long-term given that water tables are rapidly declining across this region of Gujarat (current water tables are 200–300 m below ground and farmers state that they are declining at a rate of 2–3 m per year) and increasing groundwater use may not be a sustainable strategy moving forward (Dubash, 2002; Shah, 2009). For less irrigation secure farmers, our results suggest that weather perceptions played a strong role in farmers' decisions to adapt to a delayed monsoon onset. This suggests that one possible way to enhance adaptive capacity in this region would be to increase awareness of current and future weather projections and their predicted impacts on yields, which may influence individuals' perceptions of weather variability and ultimately which coping strategies farmers decide to employ. In fact, previous studies in the Indo-Gangetic Plains of India suggest that providing farmers with short-term and seasonal monsoon weather forecasts allows farmers to adjust their cropping decisions accordingly, resulting in higher profits than those who did not receive weather forecasts (Cooper et al., 2013; Balaji and Craufurd, 2014).

While these results offer important insights into the ability of farmers to autonomously adapt to weather variability in this region, there are several areas that should be explored further with future research. First, our study does not attempt to make agronomic recommendations about which crop type should be planted, ideal sowing dates, or the amount of irrigation that should be used during late monsoon onset years. Our yield data are self-reported, and there are likely inaccuracies and biases in these measures. We simply report these data to highlight that farmers do shift their cropping behavior based on weather parameters, and

Table 7
Factors associated with the yield and profit of crops in the groundwater region. The impact of irrigation is captured with the variables "number of irrigations" and "bore well." The impact of sowing date is captured by the variable "sow week." Finally, the impact of planting cotton versus castor to identify differences in profit is captured by the variable "plant cotton." The parameter estimate and standard error (in parentheses) are recorded for each variable in our model, and those variables that dropped out during model selection are marked with a dash. Significance values are starred (+ denotes $p<0.10$, * denotes $p<0.05$, ** denotes $p<0.01$, and *** denotes $p<0.001$).

	Yield (impact of sowing date and increasing irrigation)			Profit (impact of crop switching)				
	Cotton yield (*mand* per *bhiga*)			Cotton vs castor (profit, INR per *bhiga*)				
	All farmers	No well	Own well	All farmers monsoon profit	All farmers monsoon & winter profit	No well monsoon profit	Own well monsoon profit	Low irrigation (<3) monsoon profit
Number of Irrigations	0.976* (0.481)	–	–	–	0.040+ (0.020)	0.058+ (0.029)	–	0.294** (0.091)
Bore well								
Owner	6.399+ (3.456)	NA	–	0.439** (0.145)	–	NA	0.146 (0.108)	–
Shareholder	5.025 (3.184)	NA	NA	0.300* (0.127)	–	NA	NA	–
Water buyer	3.441 (3.106)	–	NA	0.234+ (0.127)	–	–	NA	–
Number of fertilizer applications	–	–	–	–	–	–	−0.032 (0.054)	–
Number of pesticide applications	–	–	–	–	–	–	–	–
Soil type	0.862 (1.198)	3.479+ (1.855)	–	–	0.035 (0.047)	–	–	–
Sow week	−0.296 (0.370)	–	−0.745 (0.546)	–	–	–	–	–
Asset index	2.486** (0.912)	2.525* (1.136)	2.150+ (1.281)	0.157*** (0.036)	0.163*** (0.037)	0.156** (0.051)	0.160** (0.060)	0.298** (0.090)
Plant cotton	NA	NA	NA	–	0.144* (0.067)	–	–	–
Village RE	Y	Y	Y	Y	Y	Y	Y	Y

our coarse-resolution yield data suggest that these alteration strategies were adaptive during the year of our study. Second, our study focuses on short-term adaptation strategies during the monsoon season for one year. It would be interesting for future research to examine decision-making over multiple years to assess whether these results are generalizable, and also consider possible longer-term adaptation strategies that farmers in this region may employ, such as diversifying income sources, switching to livestock, or migrating out of agriculture (Fishman et al., 2013).

Considering our framework, our results highlight the importance of considering multiple biophysical, economic, social, and cognitive factors that may influence decision-making. Doing so allowed us to assess the relative importance of these various factors and, interestingly, we found that economic (e.g., assets), biophysical (e.g., irrigation access), and cognitive (e.g., weather perceptions, risk aversion) factors were the most important factors associated with decisions to adapt. Furthermore, by analyzing outcomes, such as yield and profit, of the coping strategies farmers employed, we were better able to assess which coping strategies were the most beneficial and which farmers made the most adaptive decisions during the year of our study. Finally, using our framework, we conducted additional sub-group analyses for those farmers who had more or less secure access to irrigation, given that irrigation was found to be an important resource constraining coping decisions in this region. By doing this, we were better able to assess the differential importance of various factors for decision-making (e.g., assets were more important for irrigated farmers, while perceptions were more important for less irrigation secure farmers) as well as the relative benefit of different coping strategies considering yield and profit for each sub-group. What was the most adaptive strategy for one group (e.g., crop switching for irrigation insecure farmers) was not the most adaptive strategy for another (e.g., increasing irrigation for those with secure access to irrigation). Thus, the framework we developed in this study allowed us to assess both the drivers and outcomes of differential decision-making, which can help contribute to a more mechanistic and predictive understanding of how, why, and how effectively different individuals may adapt to future changes in weather.

Table 8
Factors associated with the yield and profit of crops in the canal region. The impact of irrigation is captured with the variables "Number of Irrigations", "Shallow Well Irrigation", and "Canal Irrigation." The impact of sowing date is captured by the variable "Sow Week." The parameter estimate and standard error (in parentheses) are recorded for each variable in our model, and those variables that dropped out during model selection are marked with a dash. Significance values are starred (+ denotes $p<0.10$, * denotes $p<0.05$, ** denotes $p<0.01$, and *** denotes $p<0.001$). We could not assess crop switching because sorghum, the main crop farmers switch to, was not sold to the market for profit.

	Yield (impact of sowing date and increasing irrigation)		
	Rice yield (*mand* per *bhiga*)		
	All farmers	No shallow well	Shallow well
Number of irrigations	1.285+ (0.756)	2.454* (1.926)	–
Shallow well irrigation	–	NA	NA
Canal irrigation	9.308** (3.649)	–	7.049+ (4.179)
Number of fertilizer applications	–	8.256** (2.811)	−2.991 (2.417)
Number of pesticide applications	–	–	–
Soil type	2.609 (1.664)	–	3.502+ (1.950)
Sow week	–	–	0.407 (0.581)
Asset index	–	−1.761 (1.621)	3.204* (1.463)
Village RE	Y	Y	Y

Acknowledgements

We thank the Columbia Water Center (CWC) for providing logistical support and guidance, as well as our field assistants, including Tarun Patel, Jaydip Prajapati, and Kanu Prajapati, who helped us collect these data. We would especially like to thank Amit Goberbhai Patel who served as our project manager. We would also like to thank those who helped enter data, including Alexandra Varga, Prabhat Barnwal, Hardik Patel, Kajal Patel, and Angelica Menchaca Rodriguez. We also thank and acknowledge our various funding sources, including the National Science Foundation (Grant #s 11-44155 and 1311594), NASA Land Cover Land Use Change (LCLUC) (Grant #NNX11AH98G), National Geographic Young Explorers Grant, the CWC, and the Columbia AC4. Finally, we would like to thank the DeFries, Naeem, and Uriarte lab groups for invaluable feedback on this work. This work was conducted with IRB approval from Columbia University (Protocol #AAAF3697).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.12.008.

References

Adger, N.W., 2003. Social capital, collective action, and adaptation to climate change. Econ. Geogr. 79, 387–404.

Balaji V., Craufurd P., Using information and communication technologies to disseminate and exchange agriculture-related climate information in the Indo-Gangetic Plains, *CCAFS Working Paper No 78*, 2014, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); Copenhagen, Denmark.

Barnett, J., O'Neill, S., 2010. Maladaptation. Global Environ. Change 20, 211–213.

Below, T.B., Mutabazi, K.D., Kirschke, D., Franke, C., Sieber, S., Siebert, R., Tscherning, K., 2012. Can farmers' adaptation to climate change be explained by socio-economic household-level variables? Global Environ. Change 22, 223–235.

Borooah, V.K., 2005. Caste, inequality, and poverty in India. Rev. Dev. Econ. 9, 399–414.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference, 2nd ed. Springer, New York.

Burton, I., Huq, S., Lim, B., Pilifosova, O., Schipper, E.L., 2002. From impacts assessment to adaptation priorities: the shaping of adaptation policy. Clim. Policy 2, 145–159.

Cooper P.J.M., Capiello S., Vermeulen S.J., Campbell B.M., Zougmore R., Kinyangi J., Large-scale implementation of adaptation and mitigation actions in agriculture, *CCAFS Working Paper No. 50*, 2013, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); Copenhagen, Denmark.

Deressa, T.T., Hassan, R.M., Ringler, C., Alemu, T., Yesuf, M., 2009. Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. Global Environ. Change 19, 248–255.

Deshpande, A., 2000. Does caste still define disparity? A look at inequality in Kerala, India. Am. Econ. Rev. 90, 322–325.

Dubash, N.K., 2002. Tubewell Capitalism: Groundwater Development and Agrarian Change in Gujarat. Oxford University Press.

Erenstein, O., Laxmi, V., 2008. Zero tillage impacts in India's rice–wheat systems: a review. Soil Till. Res. 100, 1–14.

Eriksen, S.H., Kelly, P.M., 2006. Developing credible vulnerability indicators for climate adaptation policy assessment. Mitig. Adapt. Strat. Glob. Change 12, 495–524.

Fazey, I., Fazey, J.A., Fischer, J., Sherren, K., Warren, J., Noss, R.F., Dovers, S.R., 2007. Adaptive capacity and learning to learn as leverage for social–ecological resilience. Front. Ecol. Environ. 5, 375–380.

Feder, G., 1980.In: Risk Aversion and the Adoption of New Technology under Uncertainty, Oxford Economic Papers 32. pp. 263–283.

Feder, G., Umali, D.L., 1993. The adoption of agricultural innovations: a review. Technol. Forecast. Soc. 43, 215–239.

Filmer, D., Pritchett, L.H., 2001. Estimating wealth effects without expenditure data – or tears: an application to educational enrollments in states of India. Demography 38, 115–132.

Fishman R., Jain M., Kishore A., Patterns of migration, water scarcity and caste in rural northern Gujarat, *International Growth Centre Working Paper*, 2013, 1–26.

Fishman R.M., Climate change, rainfall variability, and adaptation through irrigation: evidence from Indian agriculture, *Job Market Paper*, 2012.

Gajbhiye, K.S., Mandal, C., 2000. Agro-Ecological Zones, their Soil Resource and Cropping Systems.

Gelman, A., Hill, J., 2007. Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press.

Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Global Environ. Change 15, 199–213.

Hassan, R., Nhemachena, C., 2008. Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis. Afr. J. Agric. Res. Econ. 2, 83–104.

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D., Lindgren, E., Surjan, A., 2014. Climate change 2014: impacts, adaptation, and vulnerability. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1327–1370.

Hurvich, C., Tsai, C., 1989. Regression and time-series model selection in small samples. Biometrika 76, 297–307.

Jain, M., Lim, Y., Arce-Nazario, J.A., Uriarte, M., 2014. Perceptional and socio-demographic factors associated with household drinking water management strategies in rural Puerto Rico. PLOS ONE 9, e88059.

Kelly, P.M., Adger, W.N., 2000. Theory and practicing in assessing vulnerability to climate change and facilitating adaptation. Clim. Change 47, 325–352.

Kumar, K.K., Rupa Kumar, K., Ashrit, R.G., Deshpande, N.R., Hansen, J.W., 2004. Climate impacts on Indian agriculture. Int. J. Climatol. 24, 1375–1393.

Kumar, K.S., Parikh, J., 2001. Indian agriculture and climate sensitivity. Global Environ. Change 11, 147–154.

Kurukulasuriya, P., Mendelsohn, R., 2008. Crop switching as a strategy for adapting to climate change. AfJARE 2, 105–126.

Laube, W., Schraven, B., Awo, M., 2011. Smallholder adaptation to climate change: dynamics and limits in Northern Ghana. Clim. Change 111, 753–774.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319, 607–610.

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

Mall, R.K., Singh, R., Gupta, A., Srinivasan, G., Rathore, L.S., 2006. Impact of climate change on Indian agriculture: a review. Clim. Change 78, 445–478.

Marra, M., Pannell, D.J., Ghadim, A.A., 2003. The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: where are we on the learning curve? Agric. Syst. 75, 215–234.

Matuschke, I., Mishra, R.R., Qaim, M., 2007.In: Adoption and Impact of Hybrid Wheat in India. Working Paper 35, pp. 1422–1435.

Matuschke, I., Qaim, M., 2009. The impact of social networks on hybrid seed adoption in India. Agric. Econ. 40, 493–505.

Mendelsohn, R., Nordhaus, W., Shaw, D., 1996. Climate impacts on aggregate farm value: accounting for adaptation. Agric. Forest Meteorol. 80, 55–66.

Mendelsohn R., Seo N., Changing farm types and irrigation as an adaptation to climate change in Latin American agriculture, *World Bank Policy Research Working Paper*, 2007, 1–41.

Mertz, O., Mbow, C., Reenberg, A., Diouf, A., 2009. Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. Environ. Manage. 43, 804–816.

Ministry of Agriculture, 2010. Crop Calendar of Major Crops. Government of India.

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

Morduch J., Consumption smoothing across space: testing theories of risk-sharing in the ICRISAT study region of South India, *World Institute for Development Economics Working Paper*, 2002, 55.

Morton, J.F., 2007. The impact of climate change on smallholder and subsistence agriculture. Proc. Natl. Acad. Sci. U. S. A. 104, 19680–19685.

Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., Iván Ortiz-Monasterio, J., Reynolds, M., 2008. Climate change: can wheat beat the heat? Agric. Ecosyst. Environ. 126, 46–58.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533.

Reardon, T., Delgado, C., Matlon, P., 1992. Determinants and effects of income diversification amongst farm households in Burkina Faso. J. Dev. Stud. 28, 264–296.

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002.

Schlenker, W., Roberts, M., 2006. Nonlinear effects of weather on crop yields: implications for climate change. Rev. Agric. Econ. 28, 391–398.

Shah, T., 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environ. Res. Lett. 4, 035005.

Sheikh, A.D., Rehman, T., Yates, C.M., 2003. Logit models for identifying the factors that influence the uptake of new "no-tillage" technologies by farmers in the rice–wheat and the cotton–wheat farming systems of Pakistan's Punjab. Agric. Syst. 75, 79–95.

Shiferaw, B.A., Kebede, T.A., You, L., 2008. Technology adoption under seed access constraints and the economic impacts of improved pigeonpea varieties in Tanzania. Agric. Econ. 39, 309–323.

Smit, B., McNabb, D., Smithers, J., 1996. Agricultural adaptation to climatic variation. Clim. Change 33, 7–29.

Thomas, D.S.G., Twyman, C., Osbahr, H., Hewitson, B., 2007. Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. Clim. Change 83, 301–322.

Tompkins, E.L., Adger, W.N., 2004. Does adaptive management of natural resources enhance resilience to climate change? Ecol. Soc. 9, 10.

Vasilaky, K., 2013. Female social networks and farmer training: can randomized information exchange improve outcomes? Am. J. Agric. Econ. 95, 376–383.

Vermeulen S., WynterA., Working with farmers for agricultural innovation and climate adaptation, *CCAFS Working Paper No. 77*, 2014, CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS); Copenhagen, Denmark.

Vincent, K., 2007. Uncertainty in adaptive capacity and the importance of scale. Global Environ. Change 17, 12–24.

Wood, S.A., Jina, A.S., Jain, M., Kristjanson, P., DeFries, R.S., 2014. Smallholder farmer cropping decisions related to climate variability across multiple regions. Global Environ. Change 25, 163–172.