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“Climate Cost of Cultivation”: A New Crop Index Method to Quantify Farmers’ Cost of Climate Change Exemplified in Rural India[†]

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We model the impact of agricultural droughts with a new multi-parameter index (using both climatic and non-climatic parameters) and propose a new risk transfer solution for crop insurance, called Climate Cost of Cultivation (CCC). We used 1979/80 to 2012/13 data relevant for wheat in Bihar, India to test the variation in the CCC values. The variance (risk to farmer) increased significantly in the second half of the period (two-tailed F-test, $p=0.00045$). We examine the efficiency of CCC by comparing it to typical index insurance (TII), and both indices to wheat yield data (2000/01 to 2012/13). The correlation of CCC index payouts with actual yield losses is improved by a factor of ~3.9 over TII results (76.0 per cent, compared with 19.6 per cent). The pure risk premium of the CCC index is lower by around 90 per cent than the premium of the TII. We also elaborate a method to quantify the premium’s climate change cost component. *The Geneva Papers* (2016) **41**, 280–306. doi:10.1057/gpp.2016.6

Keywords: India; Bihar; agricultural insurance; index-based insurance; basis risk; climate change

Article submitted 21 June 2015; accepted 27 January 2016

The online version of this article is available Open Access

Introduction

Years of experience with index-based crop insurance¹ show that uptake has remained very low relative to the target population² or arable land,³ mainly credit-linked,⁴ and with only minimal voluntary uptake by farmers.⁵ India has the largest agriculture insurance scheme in the world today in terms of the number of policyholders.⁶ The Government of India (GoI) has been promoting index-based crop insurance schemes for years.⁷ However, voluntary

[†] This paper was granted the 2016 Shin Research Excellence Award—a partnership between The Geneva Association and the International Insurance Society—for its academic quality and relevance by decision of a panel of judges comprising both business and academic insurance specialists. The article went through the journal’s normal peer review process.

¹ Dercon (2005); Miranda and Farrin (2012).

² Da Costa (2013); Gehrke (2014); Zant (2008); McIntosh *et al.* (2013).

³ Glauber (2004).

⁴ Binswanger-Mkhize (2012); Raghuvanshi (2008).

⁵ Goodwin (1993); Roberts and Dick (1991).

⁶ Clarke *et al.* (2012); Mahul and Stutley (2010); Giné *et al.* (2010); Herweijer *et al.* (2009).

⁷ Raju and Chand (2008).

uptake of crop insurance by farmers in India is very low.⁸ Such low uptake suggests that the hopes of both managing risks better and enhancing farmers' livelihoods via crop insurance are, for the time being, frustrated.

Several explanations for this low uptake have been offered. One major reason is high basis risk,⁹ namely the risk that payouts do not match farmers' actual incurred losses. Alternatively, this issue can be expressed by the very low correlation between actual losses and payouts.¹⁰

Another reason is that, typically, index-insurance models do not cover all relevant production costs/risks.¹¹ This may be linked to the practice (in India and elsewhere) to limit index insurance to the amount loaned for inputs, but not to include all production costs in the insurance, and require borrowers to buy it as collateral.^{7,12}

Most index insurance models are structured around a single weather parameter, for example, rainfall or temperature,¹³ while disregarding other subordinate yet relevant parameters which also impact crop yield.¹⁴ We note that impact assessment studies, hydrological studies and vulnerability mappings have been using both climatic and non-climatic parameters¹⁵ but agricultural index insurance design has so far ignored non-climatic parameters. Including additional weather and non-climatic parameters in the index insurance design can reflect better the agricultural risk profile of farmers.¹⁶

Moreover, climate change is increasing climate variability and farming risk, which is already observable in many geographies.¹⁷ It is increasingly recognised that the "polluter pays" principle¹⁸ should apply; as smallholder farmers are not the polluters, they should not be required to pay for the climate change-related costs. In reality, farmers do pay the incremental risk due to climate change probably because nobody has developed a method to quantify the climate change-related cost of cultivation. We show in this article one way of calculating this, making it possible to remove that share of the cost from the premium of index insurance, thereby applying of the "polluter pays" principle.

There is general agreement that higher uptake of index insurance is desirable. The review of the literature suggests that certain issues related to index insurance have been identified and solved (e.g. dealing with certain production risks); others have been identified but not yet resolved (e.g. reducing basis risk significantly). The challenge is to put the various pieces together. The purpose of this article is to address this gap. We submit that achieving this

⁸ Nair (2010); Giné *et al.* (2010); Mahul *et al.* (2012); Cole *et al.* (2013).

⁹ Dercion *et al.* (2014); Jensen *et al.* (2014); Miranda and Farrin (2012); Binswanger-Mkhize (2012); Clarke *et al.* (2012); Woodard and Garcia (2008); Osgood *et al.* (2007); Barnett (2004).

¹⁰ Clarke *et al.* (2012).

¹¹ Smith and Watts (2009); Wright and Hewitt (1994); Gardner and Kramer (1986).

¹² Raju and Chand (2008); Vyas and Singh (2006); Glauber (2004); Ifft (2001).

¹³ Daron and Stainforth (2014); Kellner and Musshoff (2011); Berg and Schmitz (2008); Barnett and Mahul (2007); Martin *et al.* (2001).

¹⁴ Carter *et al.* (2014).

¹⁵ Ruiz *et al.* (2010); Knijff *et al.* (2010); Berg *et al.* (2009); Faramarzi *et al.* (2009); Bondeau *et al.* (2007); Ritchie (1985).

¹⁶ Turvey (2001); Gómez and Blanco (2012); Turvey and Mclaurin (2012); Osgood *et al.* (2007); Khalil *et al.* (2007).

¹⁷ Kurukulasuriya and Rosenthal (2013); Morton (2007); Fischer *et al.* (2005); Parry *et al.* (1999); Rosenzweig and Parry (1994).

¹⁸ Stevens (1994).

objective would require revisiting the design of index insurance to make it context-relevant. Specifically, a better understanding of location-specific crop production risks¹⁹ requires higher resolution of climate data and the inclusion of certain non-climatic parameters. We propose a new model that describes production risks better, namely through an improved modelling of the financial impact of drought. By combining climatic and non-climatic parameters, our model addresses the question of the correlation between losses and payouts differently, and contains a formula to calculate the added cost of climate change. We call this the “Climate Cost of Cultivation” (CCC) method.

Readers might be familiar with crop models (that simulate the crop yield based on crop type, weather, soil, pest and disease, and nutrient supply parameters and conditions, as well as farming practices).²⁰ Unlike crop models, the CCC method estimates the risks to farmers based on the interaction between adverse climatic and non-climatic conditions (the influence of which is recognised in agronomic and soil-water balance models²¹). Consider a simple example: farmers can decide to irrigate (where irrigation facilities are available) when rainfall is insufficient, rather than suffer crop yield loss; the trade-off is better yield with an increased input cost (irrigation) vs yield loss. Hence, our definition of cost of cultivation combines both *increase in irrigation costs*, if rainfall patterns are unfavourable, and *yield losses*, if losses cannot be mitigated easily, for example, in the case of high temperatures. The CCC method aims to quantify the financial implications for farmers of certain climatic conditions by considering the *combined effect of increased input costs and yield loss with the severity of these factors*, which depends notably on non-climatic parameters.

We demonstrate the improved modelling of the impact of agricultural droughts (hereafter “droughts”) with the CCC method by reference to winter wheat in Bihar, India. In Bihar, the rainfall in the winter season is usually very low (on average around 30 mm), providing roughly 10 per cent of the winter wheat water requirement. Therefore, winter wheat is irrigated. Most smallholder farmers in Bihar usually irrigate well below the water required for optimal wheat yield to save the cost and effort involved. The cost comprises the rental charges of tube-well pumps and the diesel fuel to operate the pumps, as most farmers use groundwater for irrigation. Average (or higher) seasonal rainfall can save one to two irrigations in Bihar. Higher soil moisture at the time of sowing, because of above-average precipitation during the preceding monsoon months, can also make a difference.

Typical index insurance (TII) for winter wheat in India, used here as the reference to which we compare the CCC method (“CCC index”), covers yield losses due to high temperature (mean and maximum temperature for different time periods respectively) or excess rainfall, but does not compensate for insufficient rainfall. The CCC method, in addition to losses due to high temperature and excess/untimely rainfall (following a slightly different method), also covers the risk of above-average irrigation costs. In the CCC method we determine the initial seasonal soil moisture as a function of the aggregated pre-season (monsoon) rainfall, to capture the risk of lower soil moisture in the winter (post-rainy) season due to low rainfall during the preceding monsoon. Additionally, daily rainfall during the

¹⁹ Giné *et al.* (2010); Gómez and Blanco (2012); Patankar (2011); Carriquiry and Osgood (2012).

²⁰ Aggarwal *et al.* (2006); Krishnan *et al.* (2007); Stockle *et al.* (1994); Mo *et al.* (2005); Steduto *et al.* (2009).

²¹ Smith M. (1992); Neitsch *et al.* (2011); Galle *et al.* (2001); Ritchie (1998); Soltani and Sinclair (2012); Brisson *et al.* (1992).

winter season is incorporated into the daily soil moisture modelling. Incorporating aggregated pre-season and daily seasonal rainfall and non-climatic parameters improves the accuracy of the modelling of droughts and their financial impacts (increased irrigation costs). Stated simply, the CCC method models the random shock of below-average soil moisture for the season (due to unseasonal/insufficient rainfall, high temperatures etc.). This random risk is ignored by TII.

The article is organised as follows: in the next two sections we provide details on the study area, data sources and methods used. The results are presented in the fourth section, discussion in the fifth and conclusions are presented as the last section.

Study area

The study was conducted in Bihar, the third most populous Indian state (>100 million persons) and the 12th largest in terms of area (94,200 km²) located in the eastern part of India.²² The river Ganges divides Bihar into North Bihar (53,300 km²) and South Bihar (40,900 km²) and contributes significantly to its bio-physical and socio-economic settings.²³ Bihar is prone to waterlogging, floods and droughts.²⁴

Nearly 81 per cent of the Bihari population is employed in agricultural production. Wheat, paddy, maize and pulses are the principal crops.

Data and methods

In this study, CCC is tested with wheat, a major post-rainy season (*Rabi*) crop that is largely irrigated. The *rabi* lasts from November to March. The growth duration of wheat lasts 120 days.

Data used

The relevant parameters we used are described in Table 1.

Methods

The CCC estimation combines the effect of four climatic situations, three with negative implications on crop ((i) water deficit leading to additional irrigation cost; (ii) excess water leading to drainage cost; and (iii) high temperatures leading to yield loss) and one situation with a positive impact on crop yield (increasing concentration of atmospheric CO₂). The CCC method does not consider other cultivation costs/risks that we assume to be, by and large, independent of climate. Although waterlogging situations are captured in the CCC method, floods are not, as they are often triggered by heavy rainfall upstream or breaches of river embankments outside the study area. A schematic representation of the method is shown in Figure 1.

²² GoI (2015).

²³ Government of Bihar (2015).

²⁴ GoI (2008).

Table 1 Data requirement for Climate Cost of Cultivation modelling

Category	Parameter	Data type	Range	Source
Climatic	Precipitation	Gridded data (0.25°×0.25°), daily	1979/80– 2012/13	Indian Meteorological Department
	Maximum temperature	Gridded data (1°×1°), daily	1979/80– 2012/13	Indian Meteorological Department
	Minimum temperature	Gridded data (1°×1°), daily	1979/80– 2012/13	Indian Meteorological Department
	Relative humidity	Satellite gridded data (approx. 1.9°×1.9°), daily	1979/80– 2012/13	NCEP Reanalysis II
	Wind speed	Satellite gridded data (approx. 1.9°×1.9°), daily	1979/80– 2012/13	NCEP Reanalysis II
	Solar radiation	Satellite gridded data (approx. 1.9°×1.9°), daily	1979/80– 2012/13	NCEP Reanalysis II
	CO ₂ concentration	CO ₂ concentration data at the Mauna Loa Observatory, annual	1979/80– 2012/13	NOAA-ESRL, ftp://ftp.cmdl. noaa.gov/cc/coc2/trends/ co2_anmeaa_mlo.txt
Non- climatic	Soil type	Raster image	2013	National Bureau of Soil Survey and Land Use Planning, India
	Groundwater depth	Groundwater tables, post-monsoon	2005– 2013	Central Groundwater Board, India
Data for result validation	Cost of cultivation data	Crop yield and irrigation costs, seasonal	2000/01– 2012/13	Directorate of Economics and Statistics, Dept. of Agriculture and Cooperation, Ministry of Agriculture, Govt. of India

Method to calculate costs due to additional irrigation

The calculations for water deficiency necessitating irrigation cost are informed by the difference between the daily soil moisture available at root zone and the daily crop water requirement. The crop water requirement is interpreted as the potential crop evapotranspiration ET_C . ET_C is calculated using the reference evapotranspiration ET_0 and the crop coefficient K_C ²⁵:

$$ET_C = ET_0 \cdot K_C, \quad (1)$$

where ET_0 is the reference evapotranspiration calculated using the FAO Penman-Monteith method and K_C is the crop coefficient factor; see Table 2.

The crop water requirements are satisfied in the study area by rainfall and groundwater. The soil moisture in the root zone is modelled on a daily basis using the water balance equation.^{26,27} This model for soil moisture resembles FAO's CROPWAT model,²⁵ with a few notable differences: customisation of crop factor, modelling runoff using the Soil Conservation Service (SCS) curve number method, setting initial soil moisture conditions

²⁵ Allen *et al.* (1998).

²⁶ Neitsch *et al.* (2005).

²⁷ Smith *et al.* (1996).

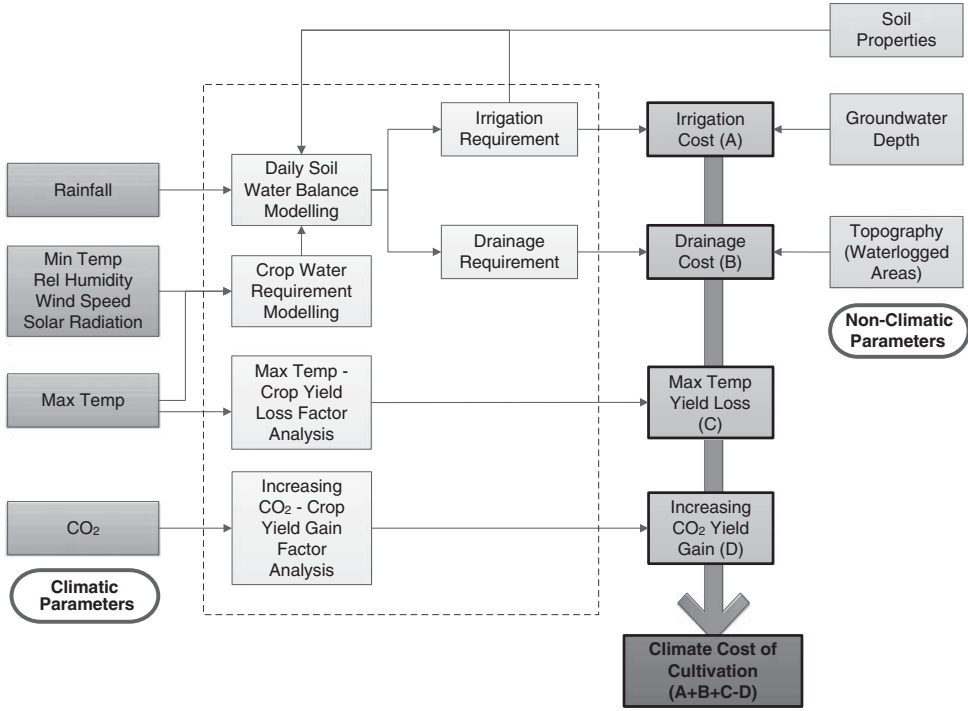


Figure 1. Schematic depiction of Climate Cost of Cultivation (CCC) method.

depending on rainfall before crop season, introduction of controlled irrigation in the last few days prior to harvest. The model has been calculated with Microsoft Excel 2010 and allows for daily modelling over decades.

$$RD_0 = r_0 \cdot AWC \cdot ID = r_0 \cdot (\theta_{FC} - \theta_{WP}) \cdot ID, \quad (2)$$

$$RD_i = RD_{i-1} + (r_i - r_{i-1}) \cdot AWC \cdot ID + ET_{c,i} - (P_i - RO_i) - I_{i-1} + DP_i \quad (3)$$

for $i=1, 2, 3, \dots$, where

RD_i	root zone depletion at the end of day i (before any irrigation) [mm]
AWC	available water capacity [m^3/m^3]
θ_{FC}	water content at field capacity [m^3/m^3]
θ_{WP}	water content at wilting point [m^3/m^3]
ID	initial depletion at day 0 [per cent]
r_i	rooting depth on day i [mm]
$ET_{c,i}$	crop evapotranspiration on day i [mm]
P_i	precipitation over day i [mm]
I_i	net irrigation on day i (water from irrigation that infiltrates the soil) [mm]
RO_i	water loss by runoff from the soil surface on day i [mm]

DP_i water loss out of root zone by deep percolation on day i [mm].

Standard values for the available water capacity (AWC) for each soil type were considered.^{28,29} We set the initial depletion ID at the onset of a crop season as crop, season and year specific (see Table 2). In years with ample rainfall in the off-season preceding the crop season, the initial soil moisture would be higher, and farmers would spend less on irrigation than in years with lower rainfall.

The runoff is calculated using the SCS runoff curve number method.^{30,31,32} Following a method developed by Choi *et al.*³³ the curve numbers are interpolated based on the daily soil moisture computed:

$$RO_i = \begin{cases} \frac{(P_i - 0.2 \cdot S_{i-1})^2}{P_i + 0.8 \cdot S_{i-1}} & \text{for } P_i \geq 0.2 \cdot S_{i-1} \\ 0 & \text{for } P_i < 0.2 \cdot S_{i-1} \end{cases} \quad (6)$$

with the potential retention parameter S_i given as

$$S_i = \frac{25400}{CN_i^{adj}} - 254 \quad (7)$$

Table 2 Crop-specific model parameters

<i>Crop growth stage</i>	<i>Days</i>	<i>K_C value</i>	<i>Rooting depth</i>	<i>Critical soil depletion (%)</i>	<i>Initial soil depletion</i>
Initial (Start: 15 th November)	15	0.35	Linearly interpolated from 300 mm to 1,500 mm	55	25%+3% * rainfall in preceding off-season/100 mm (Off-season=end of previous <i>Rabi</i> season until beginning of next <i>Rabi</i> season)
Development	25	Linearly interpolated from 0.35 to 1.15		55	
Mid-season	50	1.15	1,500 mm	55	
Late season	30	Linearly interpolated from 1.15 to 0.39 within the first 20% of the time, that is, 6 days, and then kept constant	1,500 mm	90	

²⁸ Saxton *et al.* (1986).

²⁹ Pedosphere.ca (2013).

³⁰ Boughton (1989).

³¹ Bosznay (1989).

³² Mockus (1964).

³³ Choi *et al.* (2002).

and interpolated SCS runoff curve number

$$CN_i^{\text{adj}} = \begin{cases} 2 \cdot \left(1 - \frac{RD_i}{AWC}\right) \cdot (CN^{\text{II}} - CN^{\text{I}}) + CN^{\text{I}} & \text{for } \frac{RD_i}{AWC} > \frac{1}{2}, \\ 2 \cdot \frac{RD_i}{AWC} \cdot (CN^{\text{II}} - CN^{\text{III}}) + CN^{\text{III}} & \text{for } \frac{RD_i}{AWC} \leq \frac{1}{2}, \end{cases} \quad (8)$$

where CN^{I} , CN^{II} , CN^{III} are the curve numbers for three antecedent moisture conditions, namely dry, average condition of moisture and upper limit of moisture. Depending on cover type (here we chose “small grain”), treatment (here “straight row”), hydrological condition (here “good”) and hydrologic soil group (soil type dependent) the CN^{II} value is set.³⁴ The curve numbers CN^{I} , CN^{III} are derived from CN^{II} ³⁵:

$$CN^{\text{I}} = CN^{\text{II}} - \frac{20 \cdot (100 - CN^{\text{II}})}{100 - CN^{\text{II}} + e^{[2.533 - 0.0636 \cdot (100 - CN^{\text{II}})]}}, \quad (9)$$

$$CN^{\text{III}} = CN^{\text{II}} \cdot e^{0.00673 \cdot (100 - CN^{\text{II}})}. \quad (10)$$

In this model any additional water from precipitation after runoff in excess of the amount of water necessary to reduce the root depletion RD_i to zero, that is, to reach maximum soil moisture, will be percolating below root zone:

$$DP_i = -\min(0, RD_{i-1} + (r_i - r_{i-1}) \cdot AWC \cdot ID + ET_{c,i} - (P_i - RO_i)). \quad (11)$$

We assume that farmers will irrigate the crop rather than incur crop yield loss, but do so as late as they can. The field will be irrigated if the depletion rate (i.e. root zone depletion divided by the maximum soil moisture available to the plant, $RD_i/(r_i \cdot AWC \cdot ID)$), reaches or exceeds the critical soil depletion threshold (see Table 2). Though usually the net irrigation amount is the previous day’s root zone depletion, during the late stage of the crop cycle, the net irrigation amount is the previous day’s root zone depletion times the remaining days until harvest, divided by the length of the late stage in days. This additional rule obviates intensive irrigations just a few days before harvest, which we assume that no farmer would do.

For $1 \leq i \leq 90$ we thus set

$$I_i = \begin{cases} RD_i & \text{for } \frac{RD_i}{r_i \cdot AWC \cdot ID} \geq 0.55 \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

and for $91 \leq i \leq 120$ we set

$$I_i = \begin{cases} \frac{120-i}{30} \cdot RD_i & \text{for } \frac{RD_i}{r_i \cdot AWC \cdot ID} \geq 0.90 \\ 0 & \text{otherwise.} \end{cases} \quad (13)$$

Furthermore, we assume that farmers in Bihar apply flood irrigation with field efficiency of 70 per cent, that is, only 70 per cent of the gross irrigation will percolate to the root zone of the plant.²⁵ The gross irrigation amounts were aggregated, I^{total} , for the entire period of 120

³⁴ USDA (1986).

³⁵ USDA (1972).

days for wheat for every year from 1979/80 to 2012/13.

$$I^{total} = \frac{100}{70} \cdot \sum_{i=1}^{120} I_i. \quad (14)$$

In Bihar, irrigation is sourced from groundwater that is pumped up with diesel-operated tube-wells (most commonly the 5 horsepower (HP) diesel pumps of 80 per cent efficiency). The irrigation costs depend on two variables: the groundwater depth (assumed to be *time constant but spatially variable*) and gross irrigation quantum (which *varies in space and time*).

The cost of irrigation is obtained by multiplying the diesel consumption (1.2 liters per hour for 5 HP (= 5*746 W) pump) by the time the pump needs to draw the gross groundwater amount required, adding a total dynamic head of 15 m to surface level (i.e. 15 m is the equivalent height the water has to be pumped to reflect friction loss and the height reached by the pipe after the pump; the exact value of the total dynamic pump head is specific to each location, and a change in this parameter can lead to changes in the costs). We use a constant diesel price for the entire period under consideration (1979/80 to 2012/13) to reduce confounders, as our study focuses on climate-related variations of cultivation costs only. The assumed diesel price is PPP\$3.09 per liter (INR51.69 per liter³⁶ and at an INR–PPP\$ exchange rate of 16.72 in 2013^{37,38}). The cost of irrigation in PPP\$ per hectare is then:

$$\begin{aligned} & \text{Irrigation cost} \left[\frac{\text{PPP \$}}{\text{ha}} \right] \\ &= \frac{I^{total} \cdot 1\text{ha} \cdot \rho_{\text{water}} \cdot g \cdot (d_{GW} + 15\text{m})}{80\% \cdot 5 \cdot 746\text{W}} \cdot 1.2 \frac{\text{liter}}{\text{ha} \cdot \text{hour}} \cdot 3.09 \frac{\text{PPP \$}}{\text{liter}}, \end{aligned} \quad (15)$$

where ρ_{water} is the density of water, $\rho_{\text{water}}=1000 \text{ kg/m}^3$, g is the standard gravity, $g=9.81 \text{ m/s}^2$, and d_{GW} is the groundwater depth.

Method to calculate costs due to excess water

When soil moisture exceeds the field capacity, additional rainfall can lead to waterlogging on the soil surface. We assume that farmers drain waterlogged precipitation rather than accept yield loss. The drainage costs depend on rainfall induced runoff. The daily runoff was aggregated over the cultivation period of the crop to compute the surplus water amount. The amount of diesel required to drain the surplus water is calculated assuming a total dynamic head of 10 m. The drainage cost was generated by multiplying diesel amount with the price of diesel:

$$\begin{aligned} & \text{drainage cost} \left[\frac{\text{PPP \$}}{\text{ha}} \right] \\ &= \frac{\left(\sum_{i=1}^{120} RO_i \right) \cdot 1\text{ha} \cdot \rho_{\text{water}} \cdot g \cdot 10\text{m}}{80\% \cdot 5 \cdot 746\text{W}} \cdot 1.2 \frac{\text{liter}}{\text{ha} \cdot \text{hour}} \cdot 3.09 \frac{\text{PPP \$}}{\text{liter}}. \end{aligned} \quad (16)$$

³⁶ MyPetrolPrice (2015).

³⁷ Year 2013 is taken as the base year as the validation data are available only from 2000/01 to 2012/13.

³⁸ World Bank (2015).

Method to calculate high temperature losses

The relationship between high temperature and yield loss is complex and only partially understood.^{39–41} Open field investigations,^{42,43} laboratory experiments^{44,45} and computer simulations^{43,46–51} have been conducted to assess the impact of temperature on crop yield. Based on studies conducted for wheat,^{41,52–55} we assume a yield loss of 8 per cent respectively per 1°C above-seasonal-average maximum temperature in the reference period (1979/80 to 2012/13) plus 1°C. For the calculation, we used crop yield data for Bihar for the year 2012/13 as a reference. For every season with yield loss, we multiplied the percentage of loss by the proxy for the market price of wheat, set at the Bihar government minimum support prices for 2012/13, which was 0.81 PPP\$/kg.⁵⁶

Method to calculate CO₂ fertilisation

Long-term experiments have revealed that an increase in atmospheric CO₂ has a positive impact on yield for some crops.^{57–60} We assume 0.028 per cent increase in wheat yields with a 1 ppm increase of CO₂ in the atmosphere.⁶¹ In the time period considered here, the CO₂ concentration has increased from 336.78 ppm in 1979 to 393.82 ppm in 2012. The annual change in yield due to CO₂-effect was calculated with reference to 2012 leading to lower yields in the past, *ceteris paribus*.

Calculation of the CCC values and the CCC index

The CCC values in each location are calculated as the sum of costs due to deficient rainfall (irrigation costs), excessive rainfall (drainage costs) and maximum temperature (yield losses) minus the positive impacts of atmospheric CO₂ (fertilisation leading to higher yields).

³⁹ Washington *et al.* (2012).

⁴⁰ Moorthy (2012).

⁴¹ Khan *et al.* (2009).

⁴² Samra and Singh (2004).

⁴³ Pathak *et al.* (2003).

⁴⁴ Lobell *et al.* (2012).

⁴⁵ Dhillon and Ortiz-Monasterio (1993).

⁴³ Pathak *et al.* (2003).

⁴⁶ Kumar *et al.* (2011).

⁴⁷ Kalra *et al.* (2008).

⁴⁸ Mall *et al.* (2006).

⁴⁹ Chaudhari *et al.* (2009).

⁵⁰ Aggarwal *et al.* (1994).

⁵¹ Aggarwal and Sinha (1993).

⁵² Hundal and Kaur (2007).

⁵³ Pandey *et al.* (2009).

⁵⁴ Tripathy *et al.* (2009).

⁵⁵ Hundal and Kaur (1996).

⁵⁶ GoI (2013).

⁵⁷ Kurukulasuriya and Rosenthal (2013).

⁵⁸ Gornall *et al.* (2010).

⁵⁹ Lobell and Burke (2010).

⁶⁰ Long *et al.* (2005).

⁶¹ McGrath and Lobell (2013).

Based on the calculated CCC values, for each location the CCC index payout has been defined as

- 0, if the CCC value was below the average of all years,
- the positive deviation, if the CCC value was above the average.

The average CCC values were calculated location-specific for the years 2000/01 to 2012/13 (with the exception of 2009/10, for which official cost of cultivation records were unavailable) for the purpose of this comparison. The CCC index payout is thus defined as the positive deviation of the CCC values in each location from the temporal average. Although the CCC values reflect location-specific heterogeneities (soil type, groundwater depth, micro-climate), which cannot be insured, the CCC index in each location measures the positive deviation of the CCC values from the temporal average, which can be insured. The heterogeneities can then be reflected in the pricing and design of the CCC index.

All maps shown in this article were generated using ArcGIS software version 9.3.

Comparing the CCC index to a typical index insurance

To assess the effectiveness of the CCC index in reducing the risk to farmers, we compared the CCC and TII payouts with cost of cultivation data available for wheat at plot level.⁶² We have taken all points which are sampled each year by the Government of Bihar for the purpose of collecting cost of cultivation data at farm level.⁶³

The cost of cultivation data set contains all costs, such as inputs, irrigation and labour, plot size and crop yield. Irrigation costs constitute the major climate-related costs. Therefore, we determined the net income subject only to the yield income and irrigation costs with fixed prices at 2012/13 levels (0.81 PPP\$/kg for wheat produce, 2.39 PPP\$ per hour of irrigation) to remove the inflation in costs and to allow for comparison with the CCC values. Other costs (e.g. human labour, seeds, pesticides, fertiliser) were ignored, because they are either independent of climatic conditions or negligible.

The yield data were de-trended to remove the effect of technological advancements and to calibrate the data at 2012/13 levels following the approach of Deng *et al.*⁶⁴ and Ye *et al.*⁶⁵ The plot level trends were calculated by first determining the slopes of the linear trends of the average yield on Bihar level through ordinary least squares (OLS) regressions. For each plot in each sample period the linear trend was calculated through OLS regression under the constraint that the slope of the trend at plot level was set as the Bihar level one.

The net income was calculated as the difference between de-trended yield income and irrigation costs. Only plots with at least two years of net income data were considered. The expected yield was set at the mean value and plots were considered to have zero loss in years where the actual yield was equal to or larger than the expected yield, while in the other years, the loss was equal to the shortfall.

⁶² Collected from sampled plots in sampled villages by the Directorate of Economics and Statistics (DES), Dept. of Agriculture and Cooperation, Ministry of Agriculture, Govt. of India.

⁶³ Every three years, the DES samples new villages, but within a sampling period, the villages and plots remain the same. Each year, the cost of cultivation data cover around 40–50 villages across the state of Bihar. In each village, data on plots of approximately 3–8 farmers are captured.

⁶⁴ Deng *et al.* (2007).

⁶⁵ Ye *et al.* (2015).

Decomposition of pure risk premium into “normal” and “climate change increment”

The CCC captures the most important climate-related input parameters and quantifies the risk to farming holistically. Therefore, statistically significant different CCC values (in mean, variance or both) in two (non-overlapping) extended time periods indicate climatic changes from one period to the other. In this case the pure risk premium of the CCC index can be decomposed into a “normal” pure risk component, PR^{normal} , and a “climate change increment” pure risk, PR^{CC} , in the following way for the time periods given by $t_1 < t_2 \leq t_3 < t_4$:

$$PR(t_3, t_4) = PR^{normal}(t_1, t_2) + PR^{CC}(t_1, t_2, t_3, t_4), \quad (17)$$

$$PR^{normal}(t_1, t_2) := PR(t_1, t_2), \quad (18)$$

$$PR^{CC}(t_1, t_2, t_3, t_4) := PR(t_3, t_4) - PR(t_1, t_2), \quad (19)$$

where $PR(t_a, t_b)$ is the pure risk premium based on (historic) CCC values in the time period $t_a < t_b$. The time period from t_1 to t_2 would indicate the base/reference period before climate-change.

Results

We compute the CCC by considering its four climatic components (deficient rainfall, excessive rainfall, maximum temperature and atmospheric CO₂) from 1979/80 to 2012/13 (for which data were available). Moreover, for each year from 2000/01 to 2012/13 (where wheat data were available), we calculated the average loss and the correlation between average loss and average CCC index payout for all plots representing the sample for Bihar state. The risks of farming without insurance are reflected by standard deviations of the average losses, and the risks of farming with insurance are reflected by the differences of average losses after considering average CCC index payouts.

The benchmark for comparison of the performance of the CCC index is a typical weather index insurance product (TII) which was sold for winter (*Rabi*) wheat season 2013 in Bihar; we compare the correlation between losses and payout, and risk reduction properties.

Climatic and non-climatic parameters affecting farm losses

For all 12 *Rabi* wheat seasons where crop data were available, we calculated plot-level farm net income losses. The results are shown in Table 3: We regress the farm net income loss against climatic (seasonal rainfall, pre-season rainfall and average maximum temperature) and non-climatic parameters (groundwater depth and soil type that inform available water capacity and infiltration rate).

The regression illustrates that the influence of seasonal rainfall, pre-season rainfall, seasonal maximum temperature and the infiltration rate of the soil is statistically significant, while the R^2 value is still very low (0.006967). As expected, farmers incur lower losses when seasonal and pre-season rainfall are adequate and atmospheric CO₂ increases, and more losses when average maximum temperatures are high. One would expect that losses increase as irrigation water is fetched from greater depth, but the regression did not confirm significant losses due to groundwater depth increases.

Table 3 Regression of farm net income loss against climatic and non-climatic parameters (2000/01 to 2012/13)

<i>Dependent variable:</i>	<i>Plot level net farm income loss</i>		R^2	<i>0.0091</i>
<i>Independent variables</i>	<i>Coefficients</i>	<i>Standard error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	393.15	119.97	3.28	0.001052
Seasonal rainfall (mm)	-0.10	0.03	-3.27	0.001087
Pre-season rainfall (mm)	-0.02	0.00	-4.58	0.000005
Seasonal max temp. (°C)	8.40	2.33	3.61	0.000311
Groundwater depth (m)	-1.53	1.72	-0.89	0.373857
AWC (m ³ /m ³)	0.08	0.07	1.15	0.250319
Infiltration (mm)	-6.99	1.91	-3.65	0.000259
CO ₂ (ppm)	-0.93	0.25	-3.68	0.000236

CCC calculation: Temporal and spatial variation

We use data for 34 years (from 1979/80 to 2012/13) and 45 locations where the Government of Bihar collected crop yield and irrigation data. The CCC in each of the 1,530 points (34×45) is the sum of costs due to deficient rainfall, excessive rainfall and maximum temperature minus the positive impacts of atmospheric CO₂. The total CCC and each of its components and the CCC index payouts are shown in Table 4. The CCC index payouts are determined for each location as the positive deviation from the temporal average of the CCC values and thus the index insures against one or several of the following weather-related adverse events on crops: high maximum temperatures, higher than average irrigation costs due to insufficient rainfall (during the season and before the season) and/or due to higher evapotranspiration (e.g. because of higher temperature), and excess rainfall costs.

Table 4 informs firstly the relative contribution of the various components of the CCC towards its results. The irrigation costs comprise 91.8 per cent of the total costs for *rabi* wheat in Bihar, which is understandable, as rainfall is minimal during that season and wheat requires well-defined quantities of water. The second highest contribution to CCC comes from excessive heat (contribution of only 1.8 per cent to the overall CCC), but its standard deviation is comparatively high (17.9 PPP\$/ha vs 35.0 PPP\$/ha for total CCC); this parameter leads to losses in 7 of the 34 years analysed, with a significant impact in 2005 (96.2 PPP\$/ha) and in 2008 (48.1 PPP\$/ha). The impact of excess rainfall is negligible. And, the CO₂ fertilisation effect increased from -31.3 to 0 PPP\$/ha in the study area, as CO₂ concentration increased by 57.04 ppm from 1979 to 2012. The large contribution of irrigation costs to the CCC does not imply that the CCC index payouts are dominated by the variations in irrigation costs. Consider that the correlation of CCC index payouts with irrigation costs is 70.2 per cent, while it is 89.2 per cent with high temperature losses.

The CCC would display an increasing and statistically significant trend over the period, which, however, disappears due to the effect of increasing CO₂. This is shown in Figure 2.

Figure 2 also illustrates the temporal variations. We divided the period of 34 years into two equal phases (1979/80 to 1995/96 and 1996/97 to 2012/13). Although the mean CCC value for all 45 locations was essentially similar in the two phases (265.3 vs 269.8 PPP\$/ha),

Table 4 CCC values and their components from 1979/80 to 2012/13

Costs in PPP\$/ha (average across all 45 locations)

Year	CCC total	Irrigation	Excess water	High temp.	CO ₂	CCC payout	Year	CCC total	Irrigation	Excess water	High temp.	CO ₂	CCC payout
1979	283.7	251.2	1.2	0.0	-31.3	25.6	1996	286.7	269.5	0.1	0.0	-17.1	23.8
1980	240.8	209.8	0.8	0.0	-30.2	5.9	1997	198.9	181.9	0.5	0.0	-16.5	0.6
1981	273.5	243.3	0.7	0.0	-29.5	17.0	1998	282.4	263.5	0.0	4.0	-14.9	21.7
1982	290.0	261.2	0.1	0.0	-28.7	26.6	1999	263.6	249.6	0.1	0.0	-14.0	13.1
1983	248.0	218.0	2.2	0.0	-27.9	9.2	2000	298.3	285.0	0.0	0.0	-13.3	34.3
1984	265.7	238.6	0.1	0.1	-27.0	13.2	2001	237.2	224.6	0.1	0.0	-12.4	5.4
1985	254.4	228.2	0.1	0.0	-26.2	8.8	2002	243.5	231.0	1.2	0.0	-11.3	6.4
1986	252.4	223.0	0.7	3.2	-25.5	7.4	2003	225.7	215.7	0.1	0.0	-9.9	0.6
1987	257.3	225.6	0.7	6.5	-24.5	10.6	2004	260.3	251.2	0.1	0.0	-9.0	13.5
1988	281.4	257.6	0.6	0.0	-23.2	21.6	2005	407.0	303.1	0.0	96.2	-7.7	144.7
1989	266.8	244.1	0.3	0.0	-22.3	11.6	2006	282.1	274.6	0.9	0.0	-6.5	23.6
1990	282.2	258.0	0.3	2.3	-21.6	22.2	2007	235.5	226.7	3.3	0.0	-5.5	1.8
1991	259.9	238.8	0.2	0.0	-21.0	13.5	2008	313.9	261.2	0.0	48.1	-4.5	51.5
1992	295.6	274.8	0.2	0.0	-20.5	30.9	2009	249.5	246.0	0.0	0.0	-3.5	7.7
1993	238.0	216.6	1.2	0.0	-20.2	1.8	2010	255.8	253.0	0.6	0.0	-2.2	8.3
1994	286.9	267.4	0.2	0.0	-19.2	27.3	2011	236.6	234.3	1.1	0.0	-1.2	3.2
1995	233.7	214.1	1.6	0.0	-18.1	3.7	2012	309.4	308.5	0.9	0.0	0.0	42.1
Mean	265.3	239.4	0.7	0.7	-24.5	15.1	Mean	269.8	251.7	0.5	8.7	-8.8	23.7
STD	19.3	20.1	0.6	1.7	4.1	9.0	STD	47.1	32.0	0.8	25.4	5.5	34.6
Mean (1979 to 2012)								267.6	245.6	0.6	4.7	-16.7	19.4
STD (1979 to 2012)								35.0	26.6	0.7	17.9	9.2	24.9

STD=Standard deviation

the standard deviation (which is a measure for the farmers' risk) increased from 19.3 to 47.1 PPP\$/ha (two-tailed F-test, $p=0.00045$) and this difference is statistically significant and material (Table 4). As we assume that non-climatic parameters remain constant during the study period, this result clearly indicates that climatic parameters (e.g. untimely rainfall, heat waves) have caused that increase in farmers' risk exposure. The increase in risk is also reflected in higher average CCC index payouts: 15.1 PPP\$/ha in phase I compared with 23.7 PPP\$/ha in phase II (+56.7 per cent) (Table 4). This temporal comparison makes it possible to quantify the increase in farmers' climate change-related risks (the longer the studied time period, and inclusion of the pre-climate change scenario period, should provide a more robust analysis of the impact of climate change). In this example, the climate change-related increase was 8.6 PPP\$/ha, that is, 36.2 per cent of the current risk premium of 23.7 PPP\$/ha. This calculation makes it possible, for the first time, to identify the share of costs that should be reduced from premiums payable by farmers if the "polluter pays" principle is applied.

In Table 4 we show the temporal variation in CCC, and in Figure 3 we show the spatial variation, for the entire time-period and the two partial phases. As can be seen, notwithstanding the slight changes in rainfall and temperatures over the 34 years across Bihar, North and South Bihar represent low and high CCC values respectively.

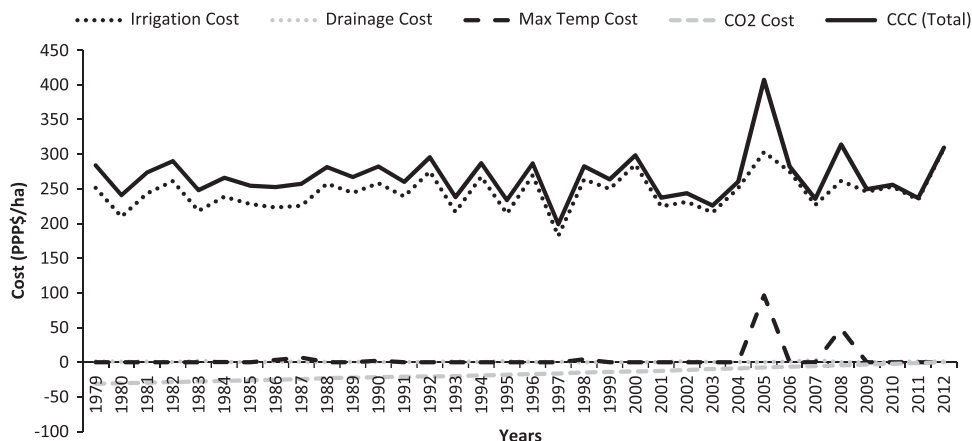


Figure 2. Average Climate Cost of Cultivation of wheat in Bihar from 1979/80 to 2012/13.

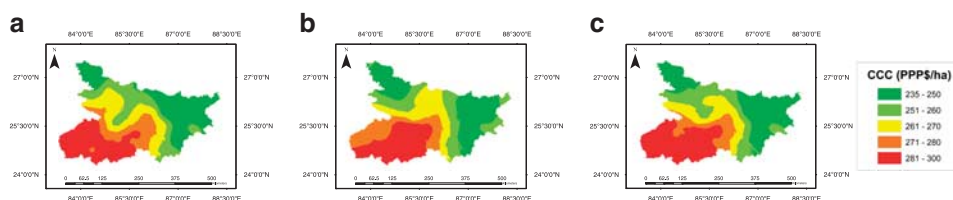


Figure 3. CCC (a) 1979/80–1995/96; (b) 1996/97–2012/13; (c) 1979/80–2012/13.

Higher average CCC values reflect spatial heterogeneity, but do not per se result in higher CCC index payouts.

We examine in detail the specific influence on the spatial CCC profile of climatic (aggregated seasonal and pre-season rainfall and average maximum temperature) and non-climatic parameters (groundwater depth, available water capacity and infiltration rate of soil) (Figure 4). The analysis (compare Figures 3 and 4) indicates that the largest influence on the spatial CCC profile is due to groundwater depth.

When groundwater depth increases uniformly by 1 m, the CCC values increase by 13 PPP \$/ha on average (see the “Methods” section for the calculation model). This result is not negligible, and justifies the argument that irrigation costs (and groundwater depth, as irrigation costs increase linearly as groundwater depth increases) should not be ignored in the design of index insurance of crops that are usually groundwater irrigated.

Performance and sensitivity analysis of the CCC index

The calculation of CCC is based on climatic and non-climatic parameters (most importantly temperature, seasonal and pre-season precipitation, groundwater depth and soil type). The CCC captures three climatic situations with negative implications on crops, namely *water deficit* leading to additional irrigation cost, *excess water* leading to drainage cost and *high temperatures* leading to yield loss. The CCC index indemnifies against

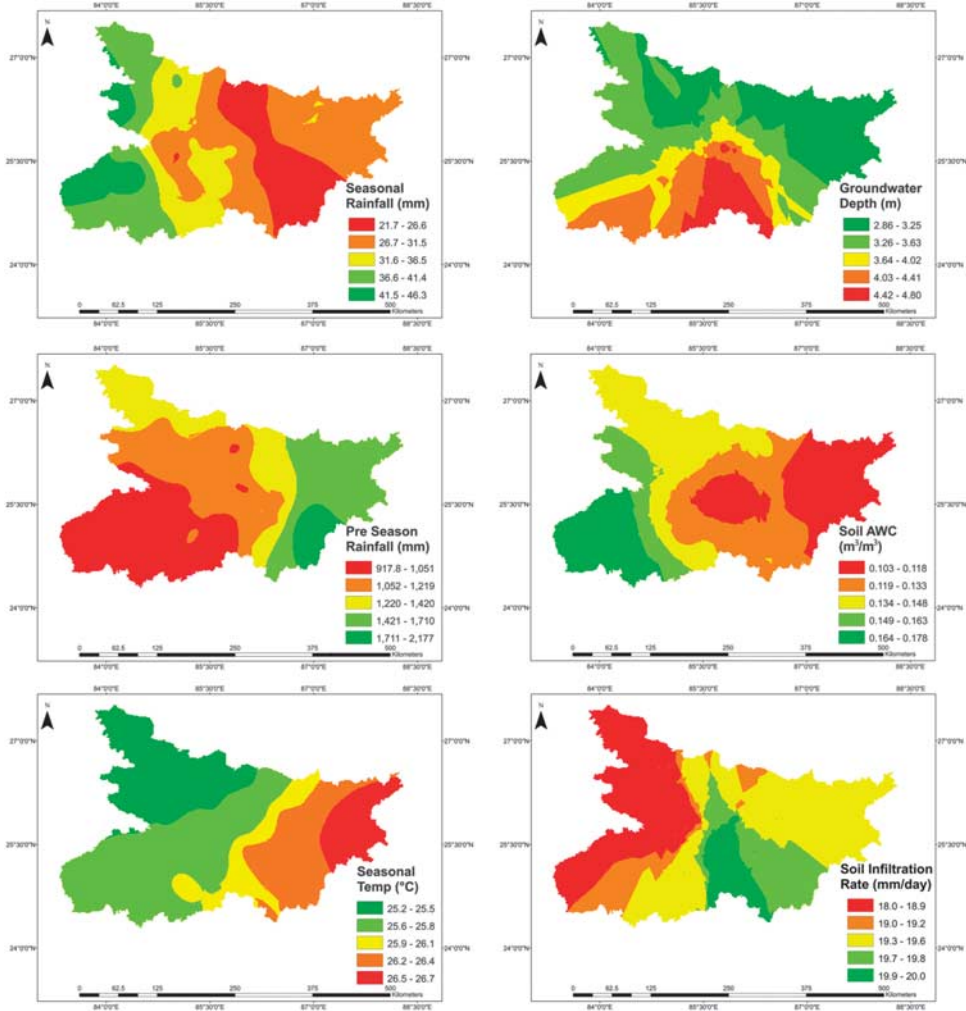


Figure 4. Spatial maps of climatic and non-climatic parameters influencing irrigation costs.

above-average CCC values. In this section we compare the plot-level net income losses (NIL) with the CCC index and TII payouts. We also analyse how much the incorporation of non-climatic parameters improves the performance of the CCC, and the impact of ignoring the climatic conditions leading to additional irrigation costs or high temperature losses. We will also see how much better than the TII the CCC index captures agricultural droughts. We consider the following six CCC options (in addition to the CCC index with no changes) leading to different CCC index payouts:

1. CCC with constant groundwater depth (fixed at the spatial average of 3.75 m), that is, groundwater depth is not considered as a parameter;

2. CCC with constant soil type (namely loam, the most prevalent soil type in the study area), that is, soil type is not considered as a parameter;
3. CCC with constant groundwater depth and soil type, that is, Options 1 and 2 combined;
4. CCC with constant initial soil moisture (fixed at the temporal and spatial average of 59.6 per cent), that is, year-to-year variations in aggregated pre-season rainfall are ignored;
5. CCC with no irrigation cost component, that is, additional irrigation costs due to insufficient precipitation or higher evapotranspiration are ignored;
6. CCC with no high temperature loss component, that is, yield losses due to above-average maximum temperatures are ignored, and the CCC is mainly due to additional irrigation costs. However, high temperature leading to higher evapotranspiration and hence irrigation costs is still considered.

We did not consider the CCC option that ignores costs due to excess rainfall, as these costs are negligible in the non-rainy season studied here (see also Table 4).

The comparison of plot-level NIL, CCC index and TII payouts are shown in Table 5.

The CCC index (no change) performed better than any of the partial CCC options examined, in terms of correlation with NIL and the reduction of risk, estimated by comparing the standard deviation of loss and loss minus payout for the cases of uninsured and insured, respectively (correlation: 76.0 per cent; risk reduction: -34.5 per cent). The largest contribution to the correlation of the CCC index payouts with NIL is the high temperature loss component; CCC Option 5 (ignoring irrigation costs, i.e. mainly considering high temperature losses) unveils a correlation of 66.9 per cent. However, CCC Option 6 (ignoring high temperature losses, i.e. mainly considering above-average irrigation costs) yields non-negligible correlation of 51.0 per cent. Hence, the combination of high temperature losses and above-average irrigation costs is required to achieve a correlation of 76.0 per cent. Compare that with the TII with a correlation of 19.6 per cent with NIL. It is recalled that TII includes high temperature losses and excess rainfall similar to the CCC but not the risk of insufficient rainfall (in other words the impacts of agricultural droughts) and the consequential need for additional irrigation. Including a simple cover that protects against insufficient rainfall to the TII would most likely not improve the performance of the TII much; one might hypothesise that a better calibration of the strikes and notional of the TII high temperature cover could perhaps improve the correlation with losses (maybe comparable to CCC Option 5), which would still fall short of the results we have for the unmodified CCC of 76.0 per cent.

The mean of the CCC index payouts is 22 PPP\$/ha, while the mean payout under TII is 251 PPP\$/ha or about 11.4 times larger than CCC index. Considering that the CCC index reduces the risk by 34.5 per cent, compared with the almost quadrupled risk effect of the TII (+300.8 per cent), the TII payout seems incongruous.

Ignoring pre-season rainfall (CCC Option 4) reduces the correlation by 2.2 percentage points from 76.0 per cent (CCC index, no change) to 73.8 per cent and the risk reduction by even 9.4 percentage points from -34.5 to -25.1 per cent. This indicates that including the aggregated pre-season rainfall in the agricultural drought modelling is justified.

CCC Option 3 (with non-climatic parameters constant) reduced the correlation with NIL by 1.4 percentage points to 74.6 per cent and the risk reduction by 3.0 percentage points to -31.5 per cent, which shows that including non-climatic parameters improves the correlation in a modest way for the winter wheat.

Table 5 Comparison of farm net income losses with CCC index and TII payouts

Year	#Plots	NIL ^a	CCC options							
			CCC (no change)		Option 1		Option 2		Option 3	
			PO ^a	NIL-PO	PO	NIL-PO	PO	NIL-PO	PO	NIL-PO
2000	610	78	19	58	19	59	34	43	34	44
2001	610	93	5	88	5	88	3	90	3	90
2002	714	123	3	120	3	120	4	119	4	119
2003	818	97	1	96	1	96	0	97	0	97
2004	791	57	3	53	3	53	2	55	2	55
2005	858	199	123	76	123	76	131	68	131	68
2006	893	97	27	70	27	70	19	78	19	78
2007	846	41	1	40	1	40	2	39	2	39
2008	714	61	38	24	38	23	37	24	38	23
2010	714	63	6	57	6	57	7	55	7	55
2011	1,079	100	3	97	3	97	2	98	2	98
2012	1,079	103	34	69	37	66	39	64	41	62
Mean		93	22	71	22	70	23	69	24	69
STD ^a		41	35	27	35	27	37	28	37	28
Reduction in STD compared with NIL				-34.5%		-34.3%		-31.7%		-31.5%
Correlation with NIL			76.0%		75.9%		74.7%		74.6%	

Year	#Plots	NIL ^a	CCC options							
			Option 4		Option 5		Option 6		Typical Index Insurance (TII)	
			PO	NIL-PO	PO	NIL-PO	PO	NIL-PO	PO	NIL-PO
2000	610	78	55	23	0	78	30	48	90	-12
2001	610	93	1	92	0	93	9	84	167	-74
2002	714	123	0	123	0	123	6	117	207	-84
2003	818	97	0	97	0	97	2	95	100	-2
2004	791	57	4	53	0	57	6	50	510	-453
2005	858	199	151	48	85	114	39	160	434	-235
2006	893	97	22	75	0	97	36	61	482	-385
2007	846	41	2	39	9	32	2	39	101	-60
2008	714	61	30	31	32	29	11	51	138	-77
2010	714	63	0	63	0	63	11	52	466	-403
2011	1,079	100	0	100	1	100	6	94	161	-61
2012	1,079	103	35	68	0	103	43	60	162	-59
Mean			25	68	11	82	17	76	251	-159
STD ^a			44	31	25	31	15	36	168	165
Reduction in STD compared with NIL				-25.1%		-25.4%		-12.9%		300.8%
Correlation with NIL			73.8%		66.9%		51.0%		19.6%	

^aNIL=Net income losses; PO=Payout; STD=Standard deviation.

1. CCC (GW depth const., 3.75 m). 2. CCC (soil type const., loam). 3. CCC (GW depth & soil type const.).
4. CCC (const. initial soil moisture, 59.6%). 5. CCC (no irrigation cost). 6. CCC (no high max. temp. loss).

Discussion

We set out to prove that the inclusion of certain climatic and non-climatic parameters in the design of index insurance can deliver a better estimate of farmers' risks, lead to a better correlation between losses and payouts, and quantify the added cost to farmers of the impact of climate change. We demonstrated the results by reference to winter wheat in Bihar, India by comparing a new method (which we call "Climate Cost of Cultivation" or CCC) to the TII in use in India, and to alternative options of CCC with fewer parameters.

The CCC index provides a more robust modelling of farmers' risk exposure compared with TII notably because the CCC refines the estimate of agricultural droughts in the non-rainy season by considering the residual impact of precipitation in the preceding (rainy) season on soil moisture and conducting a detailed daily soil moisture modelling (which incorporates daily seasonal rainfall, temperature data and non-climatic parameters). This calibration of the index to soil moisture variations rather than to the observation of a single climatic parameter during the season is novel. It registers a better understanding of farmers' risk of agricultural drought even in regions that are otherwise rich with groundwater, like Bihar. The advantage of such a region is that irrigation is possible and practiced, and, as irrigation compensates for drought conditions, there is every justification to include irrigation costs in the CCC, considering that the purpose of index insurance is to compensate farmers for the adverse impact of unstable or changing patterns of climate on crop yields. Including irrigation costs is another important innovation of the CCC model.

The basic thought underlying the CCC model is that index insurance should include, additional to climatic parameters, other parameters that influence the economic results of farming. The parameters with which we demonstrated the usefulness of the model for a specific crop (wheat), season (*rabi*) and location (Bihar) were chosen in order to model the daily soil moisture at root level, which is the major indicator both for plant growth and for additional irrigation costs (and for which many of the climatic parameters are essentially proxy indicators). Obtaining meaningful results on soil moisture necessitates the inclusion of soil properties (e.g. available water capacity—portion of water that can be absorbed by plant roots—and infiltration rate) and groundwater depth, in areas relying on groundwater irrigation for plant growth. TII does not incorporate non-climatic parameters and does not allow to compensate for additional irrigation costs in the non-rainy season. During low rainfall periods, farmers replenish low soil moisture levels through irrigation to reduce or avoid crop yield reduction. In Bihar, as in other parts of the world where groundwater can be pumped for irrigation, the cost of each water unit pumped is directly linked to the depth from which the water is fetched, and the cost of the energy required (in Bihar this is mainly diesel, to operate tube wells). Therefore, we included in the CCC method both groundwater depth and the estimated cost of diesel, in addition to soil properties.

We show that an increase in groundwater depth increases not only the cost of cultivation, but also farmers' risks. Including the cost of irrigation in the CCC index makes it possible to compensate farmers for that financial loss.

In Bihar, groundwater levels are shallow and do not fluctuate much spatially, which explains the modest contribution of this parameter to the CCC performance and why groundwater depth did not exhibit a statistically significant impact on net income losses (Table 3). Nonetheless, inclusion of groundwater depth and soil type improved the performance of the CCC compared with options which ignored these parameters partially

(Table 5). And, it stands to reason that the impact of groundwater depth on improving the CCC will be bigger in regions where groundwater depth varies spatially more than in Bihar.

Table 5 also reveals that neglecting additional irrigation costs (CCC Option 5) or high temperatures (CCC Option 6) reduces the performance of the CCC more significantly.

We conclude that the first important insight arising from the findings is that both climatic and non-climatic parameters have to be included in index design to model farming risks more accurately.

The second essential insight is that the CCC informs the assessment of the risk to farmers due to climatic changes over time, and by how much. The increase in average CCC index payout, and hence in the pure risk premium, has been material for winter wheat in Bihar (+56.7 per cent during 1996/97 to 2012/13 compared with 1979/80 to 1995/96; see Table 4). However, as already mentioned, the robust analysis of the impact of climate change should be based on longer time periods *and* should comprise a pre-climate change scenario. Respecting this caveat, climate change has already increased the cost of index insurance and this increase might be ongoing, which in turn could lower the likelihood that smallholder farmers in developing countries would buy index insurance. The first counter-measure would be to remove the share of the premium that reflects climate change trends (and the justification why farmers, whose carbon signature is negligible, should not be required to pay the climate change-related surcharge is known and self-explanatory). We have shown how the principle of “polluter-payer” can be applied. Applying this principle would reduce the cost of the premium significantly and enhance the likelihood that farmers would buy index insurance that compensates their risks. Considering that the incremental climate change-related addition to the pure risk premium is specific to each location, crop and season, our CCC method offers an actionable method to contextualise the quantification of this cost component, so that its subtraction from premiums could be applied in practice.

The third important insight is that the CCC index offers a much better correlation between farmers’ net losses and payouts than TII (76.0 vs 19.6 per cent). Applying an index that offers a much-improved correlation between losses and payouts leads to a significant reduction in farmers’ risks, measured as the standard deviation of CCC-adjusted net farm income losses. Not only would that translate into lower premiums, which in the analysed context was lower by 91 per cent compared with TII, but the lower premiums would suffice to sustain the index insurance as a business, since the payouts would be lower in years of little or no loss. The CCC thus points a way to reduce farmers’ basis risk drastically (i.e. the risk of mismatch between incurred losses and index-triggered payouts) as well as the cost of crop insurance.

Lastly, we submit that risk exposure cannot be treated as “one size fits all”, even if this is the prevailing practice now. Within the new CCC method, we incorporated spatial heterogeneities because of varying groundwater depth, soil type and microclimate. We suggest that arable areas that represent systemically higher risk should command a higher premium, just as lower risk areas should command lower premiums. Spatial heterogeneities would feed into the insurance design, to apply justified differential premiums and payouts. For example, farmers could choose an insurance package where groundwater depth and soil type are one of the parameters customised to their conditions.

Although the CCC method seems to be data intensive, all the data are available for all of India and most of the data are freely accessible to a global extent; regional information (like soil type, groundwater depth, rainfall and temperature) is available in most countries

through local authorities. In our study area, we assumed that groundwater depth was constant over the last decades, as data did not suggest otherwise. However, if groundwater levels vary, the CCC method can easily be adjusted to accommodate this calibration of the index. For other regions of investigation, the irrigation cost module in the CCC method would have to be adapted to the different irrigation sources and facilities used: for instance, in regions which are entirely rain-fed, water stress would not lead to additional input costs due to irrigation, but would affect yield losses (which can be incorporated into the CCC). In the analysis of CCC for wheat in Bihar, we identified that crop losses were associated with extended periods of high maximum temperatures. Similarly, for other crops, other parameters might be more relevant, for example, high/low minimum temperature, high wind speeds etc.

The discussion leads to the conclusion that CCC can be applied to other crops, seasons and locations once the necessary calibration is done; and the method explained in this article shows the way how to do this. Some crops might require the elaboration of other permutations of CCC that include other or additional relevant parameters, both climatic and non-climatic parameters.

The CCC method is subject to some limitations. For one, certain weather-related risks are not purely local, for example, floods are sometimes caused by weather conditions upstream (and would not be easily covered through local weather data); pests and diseases may be associated with certain weather conditions but are not necessarily caused by them. Agriculture extension services/advisories could reduce certain risks which cannot easily be covered in an index. Losses against excess rainfall could be better accounted for with the inclusion of a drainage index based on certain non-climatic parameters, including topography (risk to water-logging), land use and soil type. We were unable to use a drainage index in the study of Bihar as the data were unavailable. Elevation modelling at low vertical gaps is one of the missing pieces of data and therefore a better reflection of the consequences of excess rainfall-induced risks is for the time being imperfect.

Conclusions

The CCC method offers a novel way to quantify farmers' economic risks that can be insured.

We have referred to all the main drivers of climate change parameters impacting the productivity of agricultural crops as identified by the World Bank,⁶⁶ namely changes in precipitation, temperature, CO₂ fertilisation (CO₂-induced crop yield gain), climate variability and surface water runoff. We have shown that the nonlinear, multi-parameter CCC index, which incorporates both climatic and non-climatic parameters, reflects the financial risks of farmers more accurately than TII. The CCC index has a higher correlation to farm income losses, better risk reduction properties and much lower pure risk premiums than TII. The CCC index also provides a method to calculate the percentage of the pure risk premium which can be attributed to climate change, thus providing the needed tool to deal with this issue at a policy level, rather than continuing the unfair practice of charging it to farmers. The CCC thus contains several novelties: one that provides better modelling of agricultural droughts (influenced in post-rainy season notably by rain in the previous rainy season) and a

⁶⁶ World Bank (2007).

new design of an index that is easily contextualised to crop-season-location specificities, both climatic and non-climatic ones. Researchers, practitioners and policymakers can apply this CCC method for a wide range of uses, be it the application of policy measures to apply the “polluter pays” principle, or reducing farmers’ basis risk, or making crop index insurance more attractive for farmers.

Acknowledgements

The authors gratefully acknowledge funding support from the Climate Change and Development Division of the Embassy of Switzerland in India, as part of the “Climate Resilience through Risk Transfer (RES-RISK)” project led by the Micro Insurance Academy (MIA), New Delhi, and co-implemented with BASIX. The authors acknowledge Mr. Sonu Agrawal, Founder & Managing Director Weather Risk Management Services Limited, New Delhi for valuable inputs. Special thanks go to MIA for logistical, technical and administrative support. We gratefully acknowledge the critical and constructive comments by the reviewers.

References

- Aggarwal, P.K., Kalra, N., Chander, S. and Pathak, H. (2006) ‘InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description’, *Agricultural systems* 89(1): 1–25.
- Aggarwal, P.K., Kalra, N., Singh, A.K. and Sinha, S.K. (1994) ‘Analyzing the limitations set by climatic factors, genotype, water and nitrogen availability on productivity of wheat I. The model description, parametrization and validation’, *Field Crops Research* 38(2): 73–91.
- Aggarwal, P.K. and Sinha, S.K. (1993) ‘Effect of probable increase in carbon dioxide and temperature on wheat yields in India’, *Journal of Agricultural Meteorology* 48(5): 811–814.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) *Crop evapotranspiration—Guidelines for computing crop water requirements*, FAO Irrigation and Drainage Paper 56’, Vol. 300, Food and Agriculture Organization of the United Nations, Rome, p. 6541.
- Barnett, B. (2004) *Agricultural index insurance products: strengths and limitations*, Paper No 32971, presented at the Agricultural Outlook Forum 2004, United States Department of Agriculture, from www.econpapers.repec.org/paper/agsusaof/32971.htm, accessed 15 June 2015.
- Barnett, B.J. and Mahul, O. (2007) ‘Weather index insurance for agriculture and rural areas in lower-income countries’, *American Journal of Agricultural Economics* 89(5): 1241–1247.
- Berg, A., Quirion, P. and Sultan, B. (2009) ‘Can weather index drought insurance benefit to least developed countries’ farmers? A case study on Burkina Faso’, *Weather, Climate and Society* 1(1): 71–84.
- Berg, E. and Schmitz, B. (2008) ‘Weather-based instruments in the context of whole-farm risk management’, *Agricultural Finance Review* 68(1): 119–133.
- Binswanger-Mkhize, H.P. (2012) ‘Is there too much hype about index-based agricultural insurance?’ *Journal of Development Studies* 48(2): 187–200.
- Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W. and Smith, B. (2007) ‘Modelling the role of agriculture for the 20th century global terrestrial carbon balance’, *Global Change Biology* 13(3): 679–706.
- Bosznay, M. (1989) ‘Generalization of SCS curve number method’, *Journal of Irrigation and Drainage Engineering* 115(1): 139–144.
- Boughton, W. (1989) ‘A review of the USDA SCS curve number method’, *Soil Research* 27(3): 511–523.
- Brisson, N., Seguin, B. and Bertuzzi, P. (1992) ‘Agrometeorological soil water balance for crop simulation models’, *Agricultural and Forest Meteorology* 59(3): 267–287.
- Carriquiry, M.A. and Osgood, D.E. (2012) ‘Index insurance, probabilistic climate forecasts, and production’, *The Journal of Risk and Insurance* 79(1): 287–300.
- Carter, M., de Janvry, A., Sadoulet, E. and Sarris, A. (2014) *Index-based weather insurance for developing countries: A review of evidence and a set of propositions for up-scaling*, background document for the workshop

- “Microfinance products for weather risk management in developing countries: State of the arts and perspectives”, Paris, 25 June 2014.
- Chaudhari, K.N., Oza, M.P. and Ray, S.S. (2009) ‘Impact of climate change on yields of major food crops in India’, *Proceedings of ISPRS Archives* 38(8): 1–6.
- Choi, J.-Y., Engel, B.A. and Chung, H.W. (2002) ‘Daily streamflow modelling and assessment based on the curve-number technique’, *Hydrological Processes* 16(16): 3131–3150.
- Clarke, D.J., Mahul, O., Rao, K.N. and Verma, N. (2012) *Weather based crop insurance in India*, World Bank Policy Research Working Paper 5985, World Bank Group eLibrary, from www.dx.doi.org/10.1596/1813-9450-5985, accessed 15 June 2015.
- Cole, S., Giné, X., Tobacman, J., Townsend, R., Topalova, P. and Vickery, J. (2013) ‘Barriers to household risk management: Evidence from India’, *American Economic Journal. Applied Economics* 5(1): 104.
- Da Costa, D. (2013) ‘The “rule of experts” in making a dynamic micro-insurance industry in India’, *Journal of Peasant Studies* 40(5): 845–865.
- Daron, J.D. and Stainforth, D.A. (2014) ‘Assessing pricing assumptions for weather index insurance in a changing climate’, *Climate Risk Management* 1: 76–91, doi:10.1016/j.crm.2014.01.001.
- Deng, X., Barnett, B.J. and Vedenov, D.V. (2007) ‘Is there a viable market for area-based crop insurance?’ *American Journal of Agricultural Economics* 89(2): 508–519.
- Dercon, S. (2005) ‘Risk, insurance, and poverty: A review’, in S. Dercon (ed) *Insurance Against Poverty*, Oxford/New York: Oxford University Press, pp 9–37.
- Dercon, S., Hill, R.V., Clarke, D., Outes-Leon, I. and Seyoum Taffesse, A. (2014) ‘Offering rainfall insurance to informal insurance groups: Evidence from a field experiment in Ethiopia’, *Journal of Development Economics* 106(C): 132–143.
- Dhillon, S. and Ortiz-Monasterio, I. (1993) *Effects of Date of Sowing on the Yield and Yield Components of Spring Wheat and their Relationship with Solar Radiation and Temperature at Ludhiana, Punjab, India: Long Version*, Mexico, D.F.: Centro internacional de Mejoramiento de Maíz y Trigo (CIMMYT).
- Faramarzi, M., Abbaspour, K.C., Schulin, R. and Yang, H. (2009) ‘Modelling blue and green water resources availability in Iran’, *Hydrological Processes* 23(3): 486–501.
- Fischer, G., Shah, M., N. Tubiello, F. and van Velhuizen, H. (2005) ‘Socio-economic and climate change impacts on agriculture: An integrated assessment, 1990–2080’, *Philosophical Transactions of the Royal Society B: Biological Sciences* 360(1463): 2067–2083.
- Galle, S., Brouwer, J. and Delhoume, J.-P. (2001) ‘Soil water balance’, in D.J. Tongway, C. Valentin and J. Seghier (eds) *Banded Vegetation Patterning in Arid and Semiarid Environments*, New York: Springer, pp 77–104.
- Gardner, B.L. and Kramer, R.A. (1986) ‘Experience with crop insurance programs in the United States’, in P. Hazell, C. Pomareda and A. Valdés (eds) *Crop Insurance for Agriculture Development: Issues and Experiences*, Baltimore, MD: Johns Hopkins University Press, pp 195–222.
- Gehrke, E. (2014) ‘Insurability in agricultural microinsurance’, *The Geneva Papers on Risk and Insurance—Issues and Practice* 39(2): 264–279.
- Giné, X., Menand, L., Townsend, R.M. and Vickery, J.I. (2010) *Microinsurance: a case study of the Indian rainfall index insurance market*, World Bank Policy Research Working Paper Series, Vol.
- Glauber, J.W. (2004) ‘Crop insurance reconsidered’, *American Journal of Agricultural Economics* 86(5): 1179–1195.
- GoI (2008) *Bihar’s Agriculture Development: Opportunities and Challenges—A Report of the Special Task Force on Bihar*, New Delhi, India: Government of India.
- GoI (2013) *Agricultural Statistics at a Glance, 2013*. Directorate of Economic and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India.
- GoI (2015) “Census 2011 of India”, from www.censusindia.gov.in/, accessed 15 June 2014.
- Gómez, C.M.G. and Blanco, C.D.P. (2012) ‘Do drought management plans reduce drought risk? A risk assessment model for a Mediterranean river basin’, *Ecological Economics* 76: 42–48, doi:10.1016/j.ecolecon.2012.01.008.
- Goodwin, B.K. (1993) ‘An empirical analysis of the demand for multiple peril crop insurance’, *American Journal of Agricultural Economics* 75(20): 425–434.
- Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K. and Wiltshire, A. (2010) ‘Implications of climate change for agricultural productivity in the early twenty-first century’, *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1554): 2973–2989.

- Government of Bihar (2015) "Department of Agriculture, Government of India", from www.krishi.bih.nic.in/, accessed 14 June 2015.
- Herweijer, C., Ranger, N. and Ward, R.E. (2009) 'Adaptation to climate change: Threats and opportunities for the insurance industry', *The Geneva Papers on Risk and Insurance—Issues and Practice* 34(3): 360–380.
- Hundal, S.S. and Kaur, P. (1996) 'Climate change and its impact on crop productivity in Punjab, India', in Y.P. Abrol, S. Gadgil and G.B. Pant (eds) *Climate Variability and Agriculture*, New Delhi: Narosa Publishing, pp. 377–393.
- Hundal, S.S. and Kaur, P. (2007) 'Climatic variability and its impact on cereal productivity in Indian Punjab: A simulation study', *Current Science* 92(4): 506–511.
- Ifft, J. (2001) 'Government vs weather the true story of crop insurance in India', *Research Internship Papers* 1–7, from <http://unpan1.un.org/intradoc/groups/public/documents/APCITY/UNPAN023816.pdf>, accessed 15 June 2015.
- Jensen, N.D., Barrett, C.B. and Mude, A. (2014) *Basis risk and the welfare gains from index insurance: Evidence from Northern Kenya*, MPRA Paper 59153, University Library of Munich, Germany, from www.mpra.ub.uni-muenchen.de/59153/.
- Kalra, N., Chakraborty, D., Sharma, A., Rai, H.K., Jolly, M. and Chander, S. *et al.* (2008) 'Effect of increasing temperature on yield of some winter crops in northwest India', *Current Science* 94(1): 82–88.
- Kellner, U. and Musshoff, O. (2011) 'Precipitation or water capacity indices? An analysis of the benefits of alternative underlyings for index insurance', *Agricultural Systems* 104(8): 645–653.
- Khalil, A.F., Kwon, H.-H., Lall, U., Miranda, M.J. and Skees, J. (2007) 'El Niño–Southern Oscillation-based index insurance for floods: Statistical risk analyses and application to Peru', *Water Resources Research* 43(10): W10416.
- Khan, S.A., Kumar, S., Hussain, M.Z. and Kalra, N. (2009) 'Climate change, climate variability and Indian agriculture: Impacts vulnerability and adaptation strategies', in S.N. Singh (ed) *Climate Change and Crops*, Berlin/ Heidelberg: Springer, pp. 19–38.
- Knijff, J. M. V. D., Younis, J. and Roo, A. P. J. D. (2010) 'Lisflood: A GIS-based distributed model for river basin scale water balance and flood simulation', *International Journal of Geographical Information Science* 24(2): 189–212.
- Krishnan, P., Swain, D., Bhaskar, B.C., Nayak, S. and Dash, R. (2007) 'Impact of elevated CO₂ and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies', *Agriculture, Ecosystems & Environment* 122(2): 233–242.
- Kumar, S.N., Aggarwal, P.K., Rani, S., Jain, S., Saxena, R. and Chauhan, N. (2011) 'Impact of climate change on crop productivity in Western Ghats, coastal and northeastern regions of India', *Current Science* 101(3): 332–341.
- Kurukulasuriya, P. and Rosenthal, S. (2013) *Climate change and agriculture: a review of impacts and adaptations*, Climate Change Series—Paper No. 91. Washington, DC: The World Bank (informal publication).
- Lobell, D.B., Sibley, A. and Ortiz-Monasterio, J.I. (2012) 'Extreme heat effects on wheat senescence in India', *Nature Climate Change* 2(3): 186–189.
- Lobell, D. and Burke, M. (2010) 'Global and Regional Assessments', in D. Lobell and M. Burke (eds) *Climate Change and Food Security: Adapting Agriculture to a Warmer World*, Dordrecht, the Netherlands, Springer: pp. 177–192.
- Long, S.P., Ainsworth, E.A., Leakey, A.D.B. and Morgan, P.B. (2005) 'Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields', *Philosophical Transactions of the Royal Society B: Biological Sciences* 360(1463): 2011–2020.
- Mahul, O. and Stutley, C.J. (2010) *Government Support to Agricultural Insurance: Challenges and Options for Developing Countries*, Washington, DC: The World Bank.
- Mahul, O., Verma, N. and Clarke, D. (2012) *Improving farmers' access to agricultural insurance in India*, World Bank Policy Research Working Paper, (5987).
- Mall, R.K., Singh, R., Gupta, A., Srinivasan, G. and Rathore, L.S. (2006) 'Impact of climate change on Indian agriculture: A review', *Climatic Change* 78(2–4): 445–478.
- Martin, S.W., Barnett, B.J. and Coble, K.H. (2001) 'Developing and pricing precipitation insurance', *Journal of Agricultural and Resource Economics* 26(1): 261–274.
- McGrath, J.M. and Lobell, D.B. (2013) 'Regional disparities in the CO₂ fertilization effect and implications for crop yields', *Environmental Research Letters* 8(1): 014054.

- McIntosh, C., Sarris, A. and Papadopoulos, F. (2013) 'Productivity, credit, risk, and the demand for weather index insurance in smallholder agriculture in Ethiopia', *Agricultural Economics* 44(4–5): 399–417.
- Miranda, M.J. and Farrin, K. (2012) 'Index insurance for developing countries', *Applied Economic Perspectives and Policy* 34(3): 391–427.
- Mo, X., Liu, S., Lin, Z., Xu, Y., Xiang, Y. and McVicar, T. (2005) 'Prediction of crop yield, water consumption and water use efficiency with a SVAT-crop growth model using remotely sensed data on the North China Plain', *Ecological Modelling* 183(2): 301–322.
- Mockus, V. (1964) 'Chapter 9: Hydrologic soil-cover complexes', *National Engineering Handbook, Section 4: Hydrology*, Washington, DC: U.S. Department of Agriculture, Soil Conservation Service.
- Moorthy, A. (2012) "Essays on development, ownership structure, and agriculture", PhD dissertation, University of California at Los Angeles.
- Morton, J.F. (2007) 'The impact of climate change on smallholder and subsistence agriculture', *Proceedings of the national academy of sciences* 104(50): 19680–19685.
- MyPetrolPrice (2015) "Patna diesel price", from www.mypetrolprice.com/27/Diesel-price-in-Patna, accessed 1 October 2015.
- Nair, R. (2010) 'Crop insurance in India: Changes and challenges', *Economic and Political Weekly* 45(34): 73–81.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R. (2011) *Soil and Water Assessment Tool: Theoretical Documentation Version 2009*, Texas Water Resources Institute Technical Report No. 406, College Station, TX: Texas A&M University.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. and King, K.W. (2005) *Soil and Water Assessment Tool: Theoretical Documentation Version 2005*, Temple, TX: Agricultural Research Service.
- Osgood, D.E., McLaurin, M., Carriquiry, M., Mishra, A., Fiondella, F., Hansen, J.W., Peterson, N. and Ward, M.N. (2007) *Designing Weather Insurance Contracts for Farmers in Malawi, Tanzania and Kenya: Final Report to the Commodity Risk Management Group, ARD, World Bank*.
- Pandey, V., Patel, H.R. and Karande, B.I. (2009) 'Impact analysis of climate change on different crops in Gujarat, India', *ISPRS Archives* 38(8): W3.
- Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G. and Livermore, M. (1999) 'Climate change and world food security: A new assessment', *Global Environmental Change* 9(Supplement 1): S51–S67.
- Patankar, M. (2011) *Comprehensive risk cover through remote sensing techniques in agriculture insurance for developing countries: A pilot project*, ILO Microinsurance Innovation Facility Research Paper No. 6, International Labour Office, Geneva.
- Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S. and Singh, Y. *et al.* (2003) 'Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains', *Field Crops Research* 80(3): 223–234.
- Pedosphere.ca (2013) "Soil hydraulic properties based on the U.S. texture triangle", from www.pedosphere.ca/resources/texture/worktable_us.cfm, accessed 1 November 2013.
- Raghuvanshi, R.S. (2008) 'Crop insurance—a case for effective implementation of policies by India', *Connecticut Insurance Law Journal*. forthcoming, from <http://ssrn.com/abstract=934491>, accessed 15 June 2015.
- Raju, S. and Chand, R. (2008) *Agricultural insurance in India: Problems and prospects*, National Center for Agriculture Economics and Policy Research, NCAP working paper, (8).
- Ritchie, J. (1998) 'Soil water balance and plant water stress', in G.Y. Tsuji, G. Hoogenboom and P.K. Thornton (eds) *Understanding Options for Agricultural Production*, Springer Netherlands, pp. 41–54.
- Ritchie, J.T. (1985) "A user-orientated model of the soil water balance in wheat", in W. Day and R.K. Atkin (eds) *Wheat Growth and Modelling*, Proceedings of a NATO Advanced Research Workshop on Wheat Growth and Modelling, 9–12 April 1984, Bristol, U.K., NATO ASI Series vol. 86, New York: Springer, pp. 293–305, from <http://link.springer.com/book/10.1007/978-1-4899-3665-3/page/2>, accessed 19 May 2015.
- Roberts, R.A.J. and Dick, W.J.A. (eds) (1991) *Strategies for crop insurance planning*, FAO Agricultural Services Bulletin No. 86, Rome: UN Food and Agriculture Organization.
- Rosenzweig, C. and Parry, M.L. (1994) 'Potential impact of climate change on world food supply', *Nature* 367(6459): 133–138.
- Ruiz, L., Varma, M.R.R., Kumar, M.S.M., Sekhar, M., Maréchal, J.-C., Descloîtres, M., Riotte, J., Kumar, S., Kumar, C. and Braun, J. (2010) 'Water balance modelling in a tropical watershed under deciduous forest (Mule Hole, India): Regolith matrix storage buffers the groundwater recharge process', *Journal of Hydrology* 380(3–4): 460–472.
- Samra, J.S. and Singh, G. (2004) 'Heat wave of March 2004: Impact on agriculture', *Indian Council of Agricultural Research* :32.

- Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.I. (1986) 'Estimating generalized soil-water characteristics from texture', *Soil Science Society of America Journal* 50(4): 1031–1036.
- Smith, M. (1992) *CROPWAT: A Computer Program for Irrigation Planning and Management*. Rome: Food and Agriculture Organization of the United Nations, pp. 126.
- Smith, M., Allen, R. and Pereira, L. (1996) "Revised FAO methodology for crop water requirements", in C.R. Camp, E.J. Sadler and R.E. Yoder (eds) *Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling*, 3–6 November, American Society of Agricultural Engineers, St. Joseph, Michigan, USA, pp. 116–123.
- Smith, V.H. and Watts, M. (2009) *Index Based Agricultural Insurance in Developing Countries: Feasibility, Scalability and Sustainability*, Bozeman, MT: Montana State University.
- Soltani, A. and Sinclair, T.R. (2012) 'Soil water balance', in A. Soltani and T.R. Sinclair (eds) *Modeling physiology of crop development, Growth and Yield*, Wallingford, U.K.: CABI, pp. 170–191.
- Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E. (2009) 'AquaCrop—The FAO crop model to simulate yield response to water: I. concepts and underlying principles', *Agronomy Journal* 101(3): 426–437.
- Stevens, C. (1994) 'Interpreting the polluter pays principle in the trade and environment context', *Cornell International Law Journal* 27(3): 577–590.
- Stockle, C.O., Martin, S.A. and Campbell, G.S. (1994) 'CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yield', *Agricultural Systems* 46(3): 335–359.
- Tripathy, R., Ray, S.S. and Singh, A.K. (2009) 'Analysing the impact of rising temperature and CO₂ on growth and yield of major cereal crops using simulation model', *ISPRS Archives* 38(8): W3.
- Turvey, C.G. (2001) 'Weather derivatives for specific event risks in agriculture', *Review of Agricultural Economics* 23(2): 333–351.
- Turvey, C.G. and Mclaurin, M.K. (2012) 'Applicability of the normalized difference vegetation index (NDVI) in index-based crop insurance design', *Weather, Climate, and Society* 4(4): 271–284.
- USDA, S. (1972) *National Engineering Handbook, Section 4: Hydrology*, Washington, DC: Government Printing Office.
- USDA, S. (1986) *Urban hydrology for small watersheds*, Technical Release No. 55, Washington, DC: United States Department of Agriculture, pp. 2–6.
- Vyas, V. and Singh, S. (2006) 'Crop insurance in India: Scope for improvement', *Economic and Political Weekly* 41(43/44): 4585–4594.
- Washington, R., New, M., Hawcroft, M., Pearce, H., Rahiz, M. and Karmacharya, J. (2012) *Climate change in CCAFS regions: Recent Trends, Current Projections, Crop-Climatic Suitability, and prospects for Improved Climate Model Information*, CCAFS project report, Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
- Woodard, J.D. and Garcia, P. (2008) 'Basis risk and weather hedging effectiveness', *Agricultural Finance Review* 68(1): 99–117.
- World Bank (2007) *World Development Report 2008: Agriculture for Development*, Washington, D.C.: TheWorld Bank.
- World Bank (2015) "PPP conversion factor (GDP) to market exchange rate ratio", from www.data.worldbank.org/indicator/PA.NUS.PPPC.RF, accessed 1 October 2015.
- Wright, B.D. and Hewitt, J.A. (1994) 'All-risk crop insurance: Lessons from theory and experience', in D.L. Hueth and W.H. Furtan. (eds) *Economics of Agricultural Crop Insurance: Theory and Evidence*, Boston, MA/London: Kluwer, pp. 73–112.
- Ye, T., Nie, J., Wang, J., Shi, P. and Wang, Z. (2015) 'Performance of detrending models of crop yield risk assessment: Evaluation on real and hypothetical yield data', *Stochastic Environmental Research and Risk Assessment* 29(1): 109–117.
- Zant, W. (2008) 'Hot stuff: Index insurance for Indian smallholder pepper growers', *World Development* 36(9): 1585–1606.

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