Climatic Trends, Cropping Pattern Shifts, and Migration of Rice in India

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The rice area in India has shown a mild shift, both temporally and spatially—from the rain-fed eastern belt to the drier north-west, served by controlled irrigation—despite a declining trend of rainfall observed in both the regions. The shift is part of the broader changes in land use.

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To restrict global warming to below (preferably) 1.5°C relative to the pre-industrial era, 196 parties in Paris (2015) had proposed to put forward their "nationally determined contributions" (NDC). The Intergovernmental Panel on Climate Change (IPCC 2021) report calling for "immediate, rapid, and large-scale" reductions of greenhouse gas (GHG) emissions was a further "wake-up call" (Gulati 2021) consistent with the visualisation of 2030 by the Conference of the Parties (CoP) 26 (UNCCCUK 2021) for both mitigation and adaptation. Despite a lack of unity among the signatories (Arora et al 2018), apprehensions raised by actual climate events created a resolve to curb climate change to protect the human societies from its devastating and irreversible effects.

India's promise to reduce the "GHG intensity" represented an intention of not compromising growth (MoEF&CC 2021). The rephrasing of the commitment from "phase out" to "phase down" of coal, in the protracted negotiations, was attributed to India, among a few, and the target date of 2070 for net-zero emission by India was seen as too distant. With a large agricultural sector and its small farms, India is highly vulnerable to climate change.

India skipped the "Declaration on Forests and Land Use" where 127 countries pledged to "halt and reverse forest loss and land degradation" by 2030. India's 22% forest cover is mostly confined to the hilly, island, and three plain states (Ghosh and Ranganathan 2019). Of the national land, 9% has fallen fallow, which is particularly decried for carbon loss (Wilson et al 1982). India awaits a strong soil cover policy. Forests, industries, and roads also vie for limited land in a highly populated growing economy. Within the inventory of farm lands, food crops occupy a large part; rice and wheat claim 39% of the gross cropped area (GCA), plenty of water, and high doses of nitrogenous fertilisers associated with GHG emissions.

India, China, and Russia, together responsible for about 35% of the atmospheric methane (CH_4), were not among the 105 signatories of the "Global Methane Pledge" to reduce emissions by 30% from the levels of 2020 by 2030 (EC 2021). Unlike carbon dioxide (CO_2), which persists for centuries in the atmosphere, CH_4—a by-product of biomass, agriculture, and livestock—takes a decade to convert to CO_2 or get cycled out but is an extraordinarily powerful heat absorber, causing about 80 times as much warming as the same amount of CO_2; animal products are the largest CH_4 generator. A major staple in Southeast Asian nations, rice is another source of CH_4.

Cultivation of land for agriculture has displaced forests that constitute a critical carbon sink, while modernisation has resulted in higher CH_4 and nitrogenous emissions. Despite industrialisation, India remained largely agrarian explaining why the largest producer of rice and milk and the largest owner of cattle "chose to stay away" from some of the pledges (Aton 2017; Dixit 2021), whereas others joined (Borunda 2021). Regions of the world are varied in climatic and soil conditions to which crops respond in their specific ways and farmers react by evolving cropping patterns. Though devastations of climate change are in focus, the mitigation of cold stress, farmers' adjustment of cropping patterns, and the technological innovations may actually help (Senthil-Nathan 2021).

Agriculture and Monsoon in India

Agriculture occupies 63% of India's commercially used land, employs 50% of its workforce, and nourishes a population of 1.38 billion, due to low import dependence. Green revolution prioritised wheat, in dry north-western India endowed with irrigation facilities, instead of rice—a monsoon crop, compliant with a hot and wet climate and a staple in the low-lying, rainfed states of eastern India. In the course of time, following the GRV, this study finds further dynamics coming as a westward shift of the rice.

Weather is rather uneven within the ambit of any given climate. Thus, making a distinction between the variations of a volatile weather and the changing climate over centuries is not easy. The models for climate change do not always generate convergent results (Ghosh 2011). Making predictions is even more challenging for monsoonal circulations that depend on differential heating in Asia and are influenced by El Niño–Southern Oscillation (ENSO) (Pervez and Henebry 2016). Although the association with anthropogenic global warming are far from clear, the IPCC report cautions that the Indian subcontinent will see a surge of extreme rainfall events, heatwaves, droughts, and coastal calamities like cyclones, depressions, and sea level rise due to the melting snows.

Rice in Indian Agriculture

Three-fourths of the global rice is produced by raising seedlings in a nursery to be transplanted in puddled fields (called puddling) that require extensive irrigation and water management. Some Indian states that are moving towards rice were traditionally specialised in wheat or raised pulses, millets, and oilseeds. Only an impervious soil layer created by repeated puddling operations to restrict water infiltration can suppress weed growth in these coarse and permeable soils that are not ideal for rice. Puddling—known for causing CH_4 emission—consumes voluminous water, estimated to be about 3,000–5,000 litres per kilogram (kg) of rice (Kukal and Aggarwal 2003; Bouman 2009; Geethalakshmi et al 2011). India has become the largest consumer of groundwater, nearly 90% of which is extracted for irrigation purposes (Suhag 2016), which, in turn, draws on power made from fossil fuels, causing CO_2 emission. The rice–wheat rotation of the north-west takes the blame for India becoming water-stressed according to the international norms (Ghoshal 2019). The state, until recently, regulated water by synchronising a legal date for rice planting with monsoon but the delayed rice encroaches into the wheat season compelling quick land clearance by burning the stubble that becomes yet another source of CO_2 and CH_4 emission.

Rice is already in India's discourse for livelihood, fiscal economy, and political conflicts and is associated with soil-health degradation and poor response to fertiliser use but the climate change linkages make the future indeed look "grim" for rice (Sidhu et al 2010; Ghosh 2019). Yet, it has been replacing not only wheat but also other nutritious crops in the diet of the people. In growing regions, infrastructure and institutions keep developing for rice marketing along with public procurements to prevent the price from falling in the face of large production levels. Agriculture accounts for 14% of India's emissions (2016) following electricity, manufacturing, and construction, respectively. Total agricultural emissions, comprising largely of CO_2 (78.6%) and CH_4 (14.4%), nitrous oxides (N_2O) (5.1%), and other gases (1.9%), increased in absolute terms, though its share declined since 1994 (MoEF&CC 2021). Livestock (54.6%), N_2O from soils (19.0%), anaerobic rice cultivation in continuously flooded fields (17.5%), and burning of stubble (2.1%) are major sources of GHG emissions from farming (Gulati 2021).

Objective, Data, and Method

Conducted against the backdrop of evolving climatic conditions, this analysis takes a spatio-dynamic perspective specifically over the northern farm belt in the Indo-Gangetic plains (IGP) to look at India's monsoonal cropping pattern changes with a special focus on rice acreage changes in the recent times. A weaker carbon sink than forests (Agboola 1981; Al Kaisi et al 2005) but essential for food security, rice farms raise concerns for both mitigation and adaptation.

The empirical component in this paper works on a database spanning the last three decades (1990–91 to 2020–21) also contrasted with the post-green revolution (1980) status. Major Indian states are considered in the analysis, among which Bihar, Madhya Pradesh (MP), and Andhra Pradesh (AP) underwent bifurcations within the study period. For pre-2000 years, data for undivided MP and Bihar are reported for the older (O) states that included Chhattisgarh and Jharkhand, respectively while over the entire period, includes Telangana which was separated from the undivided, more recently in 2014. To work out the contributions of climate, water management, and economic incentives to changes in rice acreage between the terminal years 2000–01 and 2019–20, a model for the acreage of rice is estimated for eight states located in the west and east of the IGP. Both terminal years happen to be the years of normal monsoon.

Owing to weather-tolerant seeds and climatic complexities, kharif crops hardly have a rigid growing season. This paper includes rains from local disturbances, the returning monsoon, and post-monsoon cyclones to specify a broader window of monsoon season covering May to November. The spatial unit of climatic homogeneity is the meteorological subdivision (MET) that can encompass a single state, overlap across states, and can be multiple subdivisions within a single state displaying climatic diversity. Rainfall (RFL) data is taken at a monthly interval for 33 relevant METs. Due to the spillover of weather events, especially in the presence of interstate rivers and channels, surrounding METs become hydrologically linked as water-providing units.

A list of reservoirs located in the broader study region is prepared; the sum of their volumes (TRV) in billion cubic metres (BCM) for a reference month-end measures the total water in a set of reservoirs accumulated from the past and cross-state rainfall depending on river flows and interventions on them. The average depth (AGD) of groundwater (in metres), averaged across constituent districts, is a measure of groundwater in the METs of the study state. Both AGD and TRV represent water available to supplement local seasonal rainfall but the utilisation would depend on the facilities of water delivery measured by the area under different sources of irrigation (IRG), namely canals, wells, tanks, and others as reported in public data. Appendix Table A1 (p 43) gives the names, abbreviations used, locations of the METs, states, and the dams with reservoirs. It also reports average measures of two sources of irrigation water TRV and AGD of May end at the start of the kharif season. Official data from the Government of India (GOI) are used for crops (DES website), irrigation, and reservoirs (Central Water Commission [CWC], DES), weather (Indian Meteorological Department [IMD]), labour (DES), and fertiliser (OEA), and public food operations (Ministry of Consumer Affairs). Only kharif food crops—also disaggregated into millets (jowar and bajra), pulses (moong, urad, and arhar), and oilseeds (groundnut and soybean)—are considered in the cropping pattern; cash crops and horticultural crops compete with them for land in the kharif season.

Table 1 reports the average rainfall (mm) of the specified monsoon months

Table 1: Monsoon Rainfall (May–November) Tendencies in Meteorological Subdivisions, 1991–2021

MET Codes		Regions		Total (mm)	May	June	July	August	September	October	November
11	1	Coastal Karnataka	Rainfall share (%)	3,576.3	4.3	25.3	29.4	21.1	12.1	6.2	1.7
			CV (%)	12.3	93.4	29.9	31.1	32.0	107.0	54.4	103.2
			Trend	-3.5	0.5	-15.1*	-14.0*	6.7	16.2*	1.2	1.0
2	2	Konkan and Goa	Rainfall share (%)	3,019.9	1.3	23.1	35.3	22.4	13.3	4.1	0.6
			CV (%)	20.2	157.2	28.1	27.6	38.0	52.1	64.5	171.2
			Trend	41.0*	0.2	6.1	12.4*	8.9*	10.7*	2.1	0.8
	3	Arunachal Pradesh	Rainfall share (%)	2,515.0	12.6	20.9	26.9	17.4	15.3	5.8	1.1
			CV (%)	34.9	53.6	42.1	51.3	55.4	37.8	51.7	83.3
			Trend	-58.0*	-6.4*	-12.7*	-20.5*	-10.3*	-6.3*	-2.2	0.3
4	4	Sub-Himalayan	Rainfall share (%)	2,509.1	11.2	20.3	25.4	19.9	16.7	6.1	0.6
		W Bengal and	CV (%)	15.2	30.4*	24.8	25.5	29.9	32.2	60.6	120.1
		Sikkim	Trend	-14.0*	-3.2	-1.6	-4.2	-2.6	-2.0	-0.9	-0.4
5		Assam and	Rainfall share (%)	1,894.2	15.8	22.4	21.5	18.4	14.4	6.7	0.9
		Meghalaya	CV (%)	15.2	27.4	28.9	23.8	33.1	33.0	45.6	82.3
			Trend	3.4	-1.1	-1.1	3.6	-1.1	3.3*	0.1	-0.3
6	6	Nagaland,	Rainfall share (%)	1,615.8	16.8	19.8	19.6	17.8	15.4	8.9	1.7
		Manipur, Mizoram,	CV (%)	19.1	44.1	31.2	33.0	27.2	30.4	44.1	125.8
		Tripura	Trend	-10.0*	-6.3*	-1.7	-0.5	-0.3	-0.7	-0.4	-0.7
7		Gangetic	Rainfall share (%)	1,491.5	8.6	16.7	24.0	21.5	18.4	9.1	1.6
		West Bengal	CV (%)	17.6	48.7	35.3	31.8	25.1	35.8	75.8	160.7
			Trend	-9.7*	0.0	-1.9	-2.4	-2.5	-1.5	-0.3	-1.1
	8	Odisha	Rainfall share (%)	1,398.8	5.9	14.8	24.3	25.3	18.1	9.5	2.1
			CV (%)	14.8	77.9	33.6	30.6	29.8	31.2	73.7	118.3
			Trend	-2.3	1.3	-1.5	1.8	-2.8	-0.4	0.7	-0.5
	9	Uttarakhand	Rainfall share (%)	1,385.0	5.5	13.7	31.4	31.0	15.6	2.4	0.4
			CV (%)	24.8	72.0	60.9	30.6	27.4	64.3	141.2	169.1
			Trend	-8.1	0.0	-1.0	0.7	-5.4*	-3.1	0.4	-0.1
	10	Chhattisgarh	Rainfall share (%)	1,210.7	1.9	16.1	29.7	29.2	17.5	4.7	0.9
			CV (%)	13.9	82.5	42.2	22.8	23.4	37.4	75.6	171.8
			Trend	0.4	0.2	-0.7	-1.5	-0.4	2.7	0.5	-0.4
	11	Jharkhand	Rainfall share (%)	1,163.7	5.1	16.4	26.3	25.8	18.9	6.7	0.9
			CV (%)	17.6	66.3	46.3	31.2	29.9	36.9	89.3	217.8
			Trend	-8.8*	0.6	-3.5*	0.3	-3.3*	-2.6	0.3	-0.5
	12	Bihar	Rainfall share (%)	1,101.5	6.6	16.4	28.0	24.9	18.6	5.2	0.4
			CV (%)	20.0	70.0	48.5	31.1	29.2	44.0	94.9	251.2
			Trend	-1.4	1.3	-1.5	1.8	-2.8*	-0.4	0.7	-0.5
	13	East Madhya Pradesh	Rainfall share (%)	1,062.7	1.2	12.9	31.2	31.8	19.1	3.0	0.8
			CV (%)	19.5	138.4	60.9	36.1	30.2	58.4	95.8	223.4
			Trend	-2.3	0.4	1.3	-1.4	-2.2	-0.2	0.1	-0.3
	14	Vidarbha	Rainfall share (%)	992.0	1.2	16.4	31.3	27.2	17.2	5.3	1.3
			CV (%)	17.5	111.9	43.7	32.2	28.6	41.3	66.2	170.6
			Trend	1.8	-0.2	0.8	1.3	-1.1	2.4	-0.1	-0.4
	15	Coastal	Rainfall share (%)	954.0	5.6	11.4	15.7	17.2	18.3	20.4	11.6
		Andhra Pradesh	CV (%)	19.9	106.0	57.7	29.8	30.0	42.0	49.9	77.0
			Trend	-2.4	0.0	0.2	1.3	1.1	0.2	-3.9*	-1.3
	16	West Madhya Pradesh	Rainfall share (%)	910.3	0.9	12.3	33.6	31.5	18.0	2.9	0.8
			CV (%)	21.5	135.5	54.0	28.3	35.7	58.7	98.2	202.2
			Trend	6.8*	0.0	1.2	1.6	3.0	1.2	-0.1	-0.1
	17	Gujarat Region,	Rainfall share (%)	905.4	0.5	13.5	37.3	28.3	17.6	2.4	0.4
		D and N Haveli	CV (%)	32.4	254.7	86.9	40.2	63.9	72.1	122.8	235.4
			Trend	6.1	0.1	-1.6	-0.7	5.1	3.1	0.0	0.2
	18	South Interior	Rainfall share (%)	904.4	10.5	13.9	18.4	17.4	15.7	17.8	6.4
		Karnataka	CV (%)	23.9	38.8	45.4	45.5	45.1	37.9	44.6	89.1
			Trend	9.9*	1.2	1.3	3.5*	3.9*	1.7	-1.8	0.3
	19	Telangana	Rainfall share (%)	879.4	3.3	14.7	24.3	26.0	18.6	11.1	2.0
			CV (%)	21.1	63.2	38.6	38.9	30.4	47.2	73.5	104.0
			Trend	6.0	0.0	1.5	1.6	0.7	3.5*	-1.0	-0.4

(Continued)

Table 1: Monsoon Rainfall (May–November) Tendencies in Meteorological Sub-divisions, 1991–2021
(Concluded)

MET Codes	Regions		Total (mm)	May	June	July	August	September	October	November
20	Himachal Pradesh	Rainfall share (%)	865.5	6.5	12.7	28.8	30.9	16.9	2.4	1.7
		CV (%)	24.8	39.0	46.0	36.0	37.0	52.9	141.3	150.2
		Trend	-12.4*	-0.6	-1.1	-3.9*	-3.4*	-3.2*	-0.2	0.1
21	East Uttar Pradesh	Rainfall share (%)	860.4	2.8	13.6	29.6	29.0	20.8	3.7	0.4
		CV (%)	18.0	91.1	63.7	28.9	27.6	44.7	106.6	190.8
		Trend	-4.2	0.6	-0.5	2.5*	-3.7*	-2.8*	-0.1	-0.2*
22	Madhya Maharashtra	Rainfall share (%)	837.7	2.7	19.5	25.3	20.8	18.2	11.3	2.1
		CV (%)	24.5	81.1	37.9	38.2	47.2	40.3	74.0	140.9
		Trend	10.5*	-0.4	-0.2	4.9	4.6	3.1	-1.7	0.2
23	Tamil Nadu and Puducherry	Rainfall share (%)	796.1	8.5	6.4	7.5*	11.4*	13.5*	24.0	28.7
		CV (%)	18.0	64.6	60.1	42.1	36.6	37.1	33.4	46.3
		Trend	-0.8	0.3	-0.4	1.1*	1.2*	0.8	-1.2	-2.6
2 24	Marathwada	Rainfall share (%)	772.5	2.0	17.2	24.5	22.7	21.9	9.8	2.0
		CV (%)	25.5	111.7	52.4	61.7	45.0	50.9	73.5	125.1
		Trend	0.7	-0.5	-0.8	0.0	0.1	2.4	-0.1	-0.3
25	Rayalseema	Rainfall share (%)	734.0	7.2	11.7	13.8	17.2	18.7	19.5	11.8
		CV (%)	25.2	58.3	68.8	51.8	47.4	46.4	53.8	82.4
		Trend	-2.6	0.1	-0.5	-0.1	-1.6	1.2	-2.7*	0.9
26	North Interior Karnataka	Rainfall share (%)	714.6	6.9	16.4	18.9	19.3	19.0	16.3	3.2
		CV (%)	20.0	57.9	35.7	39.3	30.3	40.3	54.1	118.6
		Trend	-1.8	0.4	-0.8	-0.9	-0.4	1.7	-1.9	-0.1
27	West Uttar Pradesh	Rainfall share (%)	708.3	2.7	11.1	33.3	31.4	18.1	2.8	0.5
		CV (%)	24.3	84.2	70.9	37.5	41.5	63.1	137.6	160.8
		Trend	-8.5*	0.2	-0.7	-0.2	-5.3*	-2.4	0.0	-0.1
28	Jammu and Kashmir	Rainfall share (%)	651.1	10.8	12.7	26.1	27.3	13.4	4.7	4.9
		CV (%)	23.5	38.3	48.7	37.3	48.6	79.6	96.3	105.3
		Trend	-0.4	-0.7	0.1	-0.5	-0.5	0.5	0.2	0.5
29	East Rajasthan	Rainfall share (%)	645.4	1.8	10.9	34.8	34.5	15.4	2.2	0.5
		CV (%)	22.9	115.8	53.3	30.4	44.3	51.9	136.7	193.9
		Trend	4.4	0.2	0.1	0.2	2.7	1.3	-0.3	0.1
30	Saurashtra And Kutch	Rainfall share (%)	597.0	1.0	14.3	36.9	24.6	19.3	3.3	0.6
		CV (%)	37.6	283.4	70.4	51.0	91.9	95.1	153.5	315.5
		Trend	9.4*	0.0	-0.5	-1.1	5.8*	5.3*	-0.2	0.2
31	Punjab	Rainfall share (%)	534.6	3.6	14.0	32.6	29.0	17.8	2.2	0.8
		CV (%)	30.3	79.5	60.6	52.8	52.9	64.4	170.6	197.5
		Trend	- 11.3*	-0.2	-1.1	-4.4*	-3.8*	-1.6	-0.3	-0.0
32	Haryana Chandigarh and Delhi	Rainfall share (%)	532.3	4.9	13.6	30.6	30.1	17.8	2.3	0.6
		CV (%)	36.6	84.5	59.8	61.4	59.5	69.8	197.7	164.5
		Trend	-13.0*	-0.2	-1.9*	-3.2	-6.2*	-1.3	-0.5	-0.1
33	West Rajasthan	Rainfall share (%)	311.9	4.1	13.4	33.7	29.7	15.6	3.0	0.5
		CV (%)	29.9	92.8	79.8	54.4	58.4	84.3	212.1	302.9
		Trend	1.1	0.2	-0.4	-0.3	1.2	0.7	-0.4	0.1

Total rainfall is sum of average monthly rainfall of May to November reported by IMD. Ratios of monthly rainfall to the total and the coefficients of variation (CV) of monthly rainfall are computed by the authors. Estimated coefficients of linear time trend regressions are reported as trend. * Denotes significant trend at 10%.
Source: Computed from IMD data, IMD (website). MET codes given by the authors.

over 1990–91 to 2020–21 in the hydrologically connected METs along with their coefficient of variation (CV) to see the variability. A MET is deemed to be dry (D) if the RFL<600, low (L) if 600–800, moderate (M) if 800–1,500, high (H) if 1,500–3,000 and very high (VH) if average RFL>3,000. The same rainfall, regardless of the average, is considered highly variable if the CV>30%, moderately variable if CV is 20%–30% and reasonably stable if CV<20%. To examine climatic changes over time, a simple linear time (*t*) trend is fit over the study period for each rainfall variable and the coefficient of time (*t*) with its statistical significance is reported as the trend.

$$RFL_t = a + b_t \qquad \ldots (1)$$

where *t* is year, t = 1,2,……30

The crop area is determined by varied forces related to economics,[1] weather, water management, and technical progress. Wholesale prices of inputs fertiliser including NPK (DAP, urea), sulphur, pesticide, insecticide, and labour (wage rate) during the sowing months, deflated by the wholesale price index of all commodities (WPIA), are taken as the possible economic determinants representing access to inputs.

RFL in the sowing and pre-sowing months in all relevant METs indicate water and soil moisture availability. Irrigation service is measured by total pre-season reserves (TRV) in relevant water-supplying reservoirs associated with dams on proximate rivers, AGD in the METs within the state and IGN of the state by different sources. A stochastic trend (TN) in the form of dynamics in acreage follows the argument on partial adjustment presented by Nerlove (1958). The past area (Appendix A4, p 45) is a variable that acts as a constraint to acreage adjustment in the short run due to the rigidities of habit, expertise, and specificities of marketing infrastructure and institution but cases of over-adjustment in the short term cannot be ruled out. The model, therefore, factors in both past and current information from public policy in shaping price expectations, past practices for constraining adjustments, and lateral, topographical, and vertical percolations and diversions by intervention to drive the dynamics of water. Equation (2) takes a simple linear form but allows for quadratic terms and interaction among variables.

$$A = a_0 + a_1 Z_1 + a_2 Z_2 + a_3 Z_3 + a_4 Z_4 + a_5 Z_5 + a_6 Z_6 + a_7 Z_7 \ldots (2)$$

where, $Z_1 = EN$, $Z_2 = RFL$, $Z_3 = TRV$, $Z_4 = AGD$, $Z_5 = IGN$, $Z_6 = TN = A_{(t-1)}$ and $Z_7 = Input\ Price$.

TRV and AGD represent past rainfall going back by an year or even more. Since IGN is not expected to show the amount of variation in the short run and, in any case, it serves to utilise water, its interactions with RFL, TRV, and AGD are important. Excess rainfall in the growing season can deter planting (squared RFL) but its impact can be crucial (flooding) if it is untimely or accompanies excesses in reservoir storage or high groundwater levels. Negative mutual interactions of TRV, IGN, AGD, and RFL can also reflect poor water management at administrative and farm levels or farmers' choice of an alternative water-using crop. Flexibility of coefficients allows water to be a necessity, a support, and a discouragement only as the data reflects. Only the squared RFL term is expected to have a negative effect and consistent with farmers' rationality, the crop (input) price coefficient is expected to be positive (negative) while the coefficient of lagged area is required to be less than one in absolute value for model stability. Variable AGD is expected to generate a negative coefficient for a desired crop as its greater magnitude indicates deeper (scarcity of) groundwater but high AGD will have favourable interaction with well irrigation.

The model is estimated for West Bengal, Odisha, Bihar, Jharkhand, Chhattisgarh in the east and Punjab, Haryana, and Gujarat in the west. Single equation regression model over the subsample period from 2000–01 to 2019–20 is fitted, based on contemporary and availability of finalised data. The latest year, 2020–21, is kept for validation. All chosen variables, besides lagged area in selected specifications, show statistically significant coefficients, mostly at 5% significance level (Appendix Tables A2a and A2b, p 44).

Regardless of the coefficient signs, the contribution of a variable to any increase in crop area will also depend on the changes in values of the explanatory variable and the dependent variable between two terminal years 2019–20 (year 1) and 2000–01 (year 0). Following equation (2), the contribution of variable Z_i to acreage change (ΔY) is given by

$$\Delta Y_i = (a_i \,.\, \Delta Z_i) \qquad \dots (3)$$

where Z_i may be constituted of multiple variables under i (such as different sets of specified reservoirs) and the net effect of the change in Z_i (that is, $\Delta Z_i = Z_{i1} - Z_{i0}$), on the change in model–estimated area (that is, $\Delta Y_i = Y_1 - Y_0$) is reported in Table 3. In the case of an interaction variable ($Z_i \,.\, Z_j$), with a coefficient of a_{ij}, ΔY_i is calculated at the value of the interactive variable in year *0*.

$$\Delta Y_i = [(a_i + a_{ij}\, Z_{j0}) \,.\, \Delta Z_i] \qquad \dots (4)$$

Further, the decomposition leads to a residual effect (ΔZ_{ij}) between the changes in either variable

$$\Delta Y_{ij} = [a_{ij} \text{ X } (\Delta Z_i \,.\, \Delta Z_j)] \qquad \dots (5)$$

The contribution of each factor *EN, TRV, AGD, IGN,* and *TN* is worked out as the aggregate effect of the changes in each component taking account of the interactions. For cases where the area declined, signs of coefficient are reverse-adjusted to signify the direction of contribution towards the change in dependent variable. Together with a residual interaction effect of all changes, the contributions of variable changes add up to 100% (or −100% in cases of area decline).

Climates of India

Climate model predictions and theoretical expectations point at intensified water cycle and uncertain as well as uneven onset of monsoon. Melting of snow on mountains is expected to speed up river flows and hydrology, profoundly modulating river basins (Gossain et al 2006; Surinaidu et al 2020) with spatial water effects. Moreover, the inconsistency of climate change effects makes the outlook dynamic, repeatedly altering the regional water allocation. Aided by advances in climate science and detailed regional assessment across the climate system, the IPCC observes unprecedented changes compatible with climate change.

Table 1 shows a big RFL range across Indian METs, from 312 mm to 3,600 mm. Only two of the 33 METs, located contiguously in the western coast, have recorded very high RFL. Among the rainfall categories specified, four METs are in the high category, the largest number of METs (16) are in medium and, seven fall in large. Four METs, even including high-production METs like 31 and 32, are in the dry range. Once considered a desert, 33 records the lowest average rainfall. Monsoon rainfall in the entire period has been variable, the CV being not less than 10% anywhere, but among the most variable are 17, 30, 31, 32, and 33 all in the dry or moderate category of the west, while the majority of eastern states in high and moderate categories have reasonably stable rainfall.

The monthly distribution mostly reveals either June–July or July–August as modal rainfall months except that the peak is recorded later in 15, 23, 25, and 26, all METs in southern India washed by the North East monsoon. Over the 30 years, 20 out of the 33 METs showed negative coefficients, while traditionally rain-deprived west–central states like Gujarat, Rajasthan, Maharashtra, and the western part of MP have received increasing monsoon rainfall. Though not always statistically significant 7, 8, 11, and 12 as well as mountainous 3, 4, and 6 in the east and North East show no increase in monsoon rainfall; only 5 and 10 are water sources of the east that have not shown losses. Apart from the 18, rainfall in the south has not been significantly altered.

Rainfall dwindled significantly in nine METs, including the whole of West Bengal, four eastern METs and the northern rice–wheat belt (27, 31, and 32). None of the water-supplying METs in western Himalayas (9, 20, and 28) showed a positive trend; a positive significant trend is noted in five western METs (2, 16, 18, 22, and 30). Secular movements are more visible and notably significant in July and August.

Preparing Agriculture for the Future

Despite gaps, simulations have helped in defining areas of new research for adaptation. For example, within the horizon of 2050, though climate change can help wheat in the northern plains, by projecting productivity losses in "critical temperature areas," the model highlighted the urgency to develop heat-tolerant wheat germplasm, use water resources efficiently and institute insurance programmes for managing climate change. Market movements that influence farmers' conscious decisions add to bio-physical forces. Sensitive to gluts or deficiencies created by climate change in different parts of the world, prices shape farmer's preferences for crops. The governments, not likely to stay as mute spectators, may further modify markets with their reactive policies.

Did Rice Gain in India's Cropping Pattern?

India grows rice and many other food and cash crops in the kharif season, together making up 63% of the gross cropped area (GCA), but over time, the rabi season's share of food production is increasing; more manageable irrigation from stored water is one reason. Together, the five food crops reported in Table 2 cover nearly half of the kharif acreage, the remaining being cash crops, small millets, minor pulses and oilseed, perennials, and horticulture. Rice gained share from 61% to 63% among them, more so in diversified states, AP and Tamil Nadu in the south and in Haryana, Gujarat, Punjab, and Uttar Pradesh in the north-west. In most eastern states, its share dwindled, though it was stable at 100% in Jharkhand and at 95% in Odisha. Rice also lost share in the drier south-western states of Maharashtra and Karnataka as well as MP, which stretches at the centre. The share of maize increased in three states in the east and south, two in the south-west, but

Table 2: Cropping Pattern among Five Major Monsoon Crops in States

States	Period	Rice	Maize	Millets	Pulses	Oilseeds	Five Crops Share in GCA (%)
		Share to Total Area under Five Crops (%)					
Andhra Pradesh*	2000–01	46	7	7	15	25	48.2
	2019–20	57	11	3	14	16	35.4
Assam	2000–01	99	1	0	0	0	57.1
	2019–20	98	2	0	0	0	48.2
Bihar	2000–01	91	7	0	2	0	48.7
	2019–20	92	7	0	1	0	41.4
Chhattisgarh	2000–01	92	2	0	4	1	76.7
	2019–20	91	3	0	3	2	71.7
Gujarat	2000–01	13	9	26	13	39	41.7
	2019–20	23	8	12	11	47	32.5
Haryana	2000–01	59	1	40	1	0	29.5
	2019–20	73	0	26	0	0	29.9
Jharkhand	2000–01	100	0	0	0	0	72.1
	2019–20	100	0	0	0	0	74.4
Karnataka	2000–01	24	13	18	25	20	38.0
	2019–20	17	24	7	38	14	38.9
Madhya Pradesh	2000–01	19	9	9	9	53	49.5
	2019–20	16	11	3	17	52	46.8
Maharashtra	2000–01	16	3	40	25	16	43.4
	2019–20	15	8	11	20	45	50.0
Odissa	2000–01	95	1	0	3	1	56.7
	2019–20	95	2	0	3	0	85.0
Punjab	2000–01	93	6	0	1	0	35.4
	2019–20	95	4	0	1	0	39.0
Rajasthan	2000–01	2	12	67	8	11	41.1
	2019–20	2	8	46	26	17	42.3
Tamil Nadu	2000–01	62	3	14	6	16	48.2
	2019–20	69	7	12	4	8	44.5
Uttar Pradesh	2000–01	66	10	14	8	1	35.3
	2019–20	68	8	13	10	1	31.4
West Bengal	2000–01	99	0	0	1	0	44.9
	2019–20	98	0	0	2	0	43.1
State total	2000–01	61	5	15	8	11	47.9
	2019–20	63	6	8	9	13	47.2

* Includes present-day Telangana.
Source: Computed from DES (website).

Figure 1: Kharif Rice Area Changes among Regions

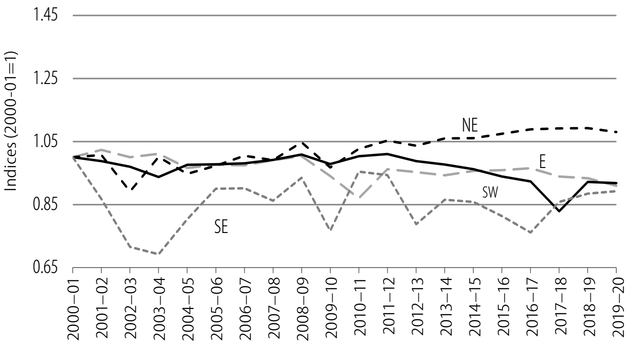
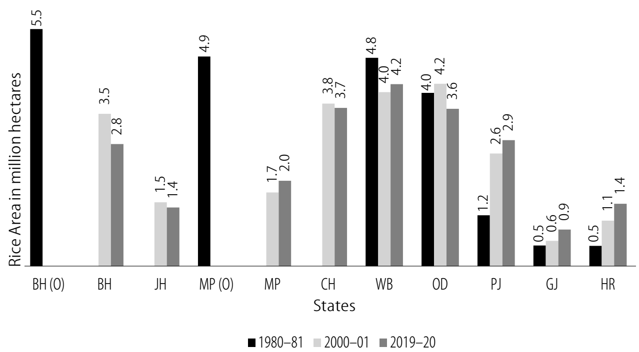


Figure 2: Rice (Kharif) Area in Million Hectares in Select States



State names specified in Appendix Table A1. (O) is undivided pre-2000 state.

Gujarat, Rajasthan, Punjab, Uttar Pradesh, and Haryana moved away. Millets were neither raised in the eastern states nor in Punjab in 2000 and by 2019, they lost share in whichever states they were grown, their average dipping from 15% to 8%.

Both pulses and oilseeds are scarce importable commodities in India. The largest grower state Karnataka saw a positive movement of kharif pulses and so did MP, Rajasthan, Uttar Pradesh, and the minor producing state West Bengal reflected in the 1% average gain in share even while seven states, including AP, Gujarat, and Maharashtra along with smaller producers moved away. Despite their promotion by policy, Punjab and Haryana showed no affinity to pulses. With strong preference shown by major growers Rajasthan, Gujarat, and Maharashtra, oilseeds gained share but some notable growers especially in the south moved away.

Aggregating across regions and using indices for comparison of movements, Figure 1 affirms absolute diminution of rice acreage in the wet eastern region (E) (Assam, Bihar, Odissa, Jharkhand, West Bengal, and Chhattisgarh), losses in dry south-west region (SW) (Karnataka and Maharashtra) and south-east (SE) region (AP and Tamil Nadu), and gains in the north-western (NW) states (Punjab, Haryana, Gujarat, Rajasthan, and Uttar Pradesh) and MP, which is plotted separately. South-eastern states spanning over the plateau and a rain-shadow belt have shown a reversal of tendency in the subsample period. Figure 2 shows the dominance of rice in eastern states and in undivided MP in 1980 but after the bifurcation in 2000, it was Chhattisgarh in its east that was found to be the rice bastion in MP and over time, the acreage in the two parts of aggregate MP moved contrarily, Chhattisgarh following the pattern of its eastern partners.

Factors behind Rice Acreage Changes

Not surprisingly, Appendix Table A2 highlights a broad-based effect of water on the acreage decision. The differential importance of monthly rainfall possibly indicates the duration, multiplicity, and flexibility of state crop calendars and the significance of pre-sowing rainfall in the west. The detrimental effect of late monsoon state-level rainfall in Chhattisgarh and Jharkhand is seen on the area. The effect of early monsoon rains in Punjab and West Bengal could be a sign of land diversion to crops like cotton and jute. The eastern states are sensitive to the monsoon rain of the larger region, covering also the eastern parts of MP and Uttar Pradesh. Rain in the western states, including Rajasthan, guide the planting in Punjab and Haryana while Gujarat responds to the rainfall in Maharashtra, MP, and Karnataka. Eastern states can access water from the north-eastern hill METs and the western states from northern Himalayan METs like 20 and 28, while 9, the source of Ganga, can serve both the west and the east. Rainfall in MP influence planting in Chhattisgarh, Jharkhand, and Gujarat due to river linkages.

In the east, where both early and late kharif rice are commonly grown, deterrent or damaging effect of both, post- (October–February) and pre-monsoon (March–May) rainfall is perceptible. The negative interaction of hill rainfall with irrigation, seen in Haryana and Punjab and not in Gujarat, speaks of water use efficiency. Reservoir volume mostly promotes rice acreage but some negative effects, notably in Haryana, draw concern. Water in the reservoirs of Odisha, MP, Maharashtra, and Himachal Pradesh proved important. Receding groundwater constrained the rice planting in West Bengal, Bihar, and Haryana but positive interactions of its depth with well-irrigation helped raising rice in both Punjab and Haryana. On the economic front, minimum support price (MSP) is an incentive in all the states and being the only one in Haryana. Substitute crops are mostly coarse cereals and pulses but jute is identified in West Bengal and cotton, sugar cane, groundnut, and horticultural crops figure as alternatives to rice in the western states. Past area is not a significant determinant in Gujarat and West Bengal and the negative and significant coefficient in Bihar suggests flexibility to over-adjust towards the reducing rice area.

Contribution of Economics, Weather, and Irrigation

Results indicate that direct changes in rainfall contributed to rice area expansion in the west whereas the role of rainfall changes in contracting rice area is observed in Jharkhand and Bihar in the east (Table 3). The consequence of rainfall on groundwater changes was felt in four states; its responsibility was strong for the expansion of rice area in Punjab and contraction in Bihar and West Bengal and it restrained acreage gain in Haryana. Rice in newly emerging states of Gujarat and, especially, Jharkhand benefited from river management policy, but by and large, the indirect rainfall effect via reservoir storage discouraged acreage expansion. Economics was an important contributor, though it acted against the expansion in Punjab and contraction in Chhattisgarh and Bihar. With the greater role of MSP in Punjab, the negative role can indicate the rising cost of inputs, fertiliser, and labour. Past acreage seems to be a powerful force that drove acreage upwards in Haryana and Punjab and downwards in Chhattisgarh and Odisha. West Bengal, Gujarat and Bihar show flexible acreage adjustment. Changes in water variables (RFL, IGN, AGW, and TRV) have mutually interactive effects except only in West Bengal. They account for 20% of the total effect in Gujarat, but among others, their contribution is largely negative and falls short of 7%.

Table 3: Model Results and Agroeconomic Properties of Select Eight States

States	Net Contribution to Changes in Rice Kharif Area Between 2000–01 and 2019–20								Input Use 2016–18 Rice		Farm Size 2015–16
	Increase Acreage %	Trend (%)	Economic (%)	Rainfall (%)	Ground water (%)	Reservoir (%)	Irrigation (%)	Interactions (%)	Irrigation % Area	Fertiliser kg/Hectare	Hectare
Western state contribution to area increase											
Haryana	40.2	57.9	43.2	12.3	-10.5	-14.7	11.9	-0.1	100.0	220	2.22
Gujarat	30.9	-2.1	37.3	19.3	–	24.3	0.9	20.3	61.5	200	1.88
Punjab	17.0	45.9	-23.5	14.3	77.8	-14.9	7.7	-7.0	99.7	180	3.62
Eastern state contribution to area decrease											
Chhattisgarh	-3.3	-72.9	18.9	7.6	–	-48.1	-1.2	-4.4	37.0	140	1.24
West Bengal	-8.1	-1.8	-33.0	47.3	-51.6	-60.9	–	–	51.1	170	0.76
Jharkhand	-11.8	8.3	-2.7	-140.4	–	40.3	–	-5.4	4.6	330	1.1
Odisha	-13.7	-60.5	-27.1	15.1	–	-19.9	-9.7	2.1	31.5	130	0.95
Bihar	-16.1	41.3	7.4	-21.2	-105.3	-24.3	-0.5	2.6	72.1	130	0.39

Sources: Author computation of net contribution from model (Table A2). Input data is from the cost of cultivation data as the average of 2016–17, 2017–18, and 2018–19. Data for farm size (2015–16)—DES (website).

Concerns and Need for Thought

Migration of rice, observed, is described by rain-fed cultivation giving way to irrigated rice (Table 3) but fertiliser consumption is not distinct between the gaining and losing states,[2] possibly a result of micro-management of soil nutrition. The kinesis of rice farming raises many questions demanding public responses. First, given that deep-water paddy located in eastern states are discredited for large emissions (Bhatia et al 2013), could the movements be seen as an adaptive solution? If the high-rainfall low-lying regions are seen as the natural habitat for rice, evacuation from rice can hardly help but only leave behind unutilised wetlands. Water-saturated oxygen-poor wetlands known for breeding methanogenic microbes, constitute the largest natural source of atmospheric CH_4 in the world. In such a case, a sound wetland policy, with CH_4 capture for fuel, may be explored for eastern India.

If rice shifts from eastern states especially coastal districts due to rainfall changes and saline water intrusion (Bhattacharya et al 2008; Prusty and Farooq 2020; Jamwal 2019), can north-west India, known for its dry climate, be seen as ideal for trying out special management techniques such as the system of rice intensification (SRI), direct seeding, low tillage, mid-season wetting, and their modified forms, all of which are unsuitable for naturally flooded areas (Gulati 2021; Ghosh et al 2017). Punjab and Haryana are reportedly moving towards direct seeding using technology like tensiometer, stubble remover, weeder, water standardisation, laser-leveller, new seed varieties, soil tests, need-based use of water and chemicals, and satellite surveillance (Chaba 2021). A "zero-budget natural farming" (ZBNF), currently referred to as "Bhartiya Prakritik Krishi Padhati" (BPKP) is promoted by the central government. The achievement on this front demands assessment.

Table 4: Rice Production Scenario in India (Kg per Capita)

	Production	Consumption	Procurement	Stocks	Exports	Population (Billion)
1992–93	86.59	78.66	15.38	14.61	0.83	0.93
2000–01	80.43	74.89	20.14	21.95	1.45	1.06 (1.14)
2011–12	84.22	68.25	28.03	26.67	5.74	1.25 (1.18)
2019–20	86.58	–	38.06	23.59	6.95	1.37 (1.09)

Consumption data is not available for 2019–20 (Jha 2019).
Figure in parenthesis is the ratio to the previous year.
Source: Computed from production data of DES (website), Consumption data of NSSO (various rounds).

The third question is about the usefulness of large rice production. While production has grown fast relative to the population, consumption has increased slower since 2001 (Table 4) holding a sign of a dietary shift from rice and a slowing down of the population growth. Procurements and stocks have grown manifold creating huge pressure on the public budget, but it is critical to know whether political pressures are responsible and how far stocks will help tide over food insecurity during consecutive droughts and other calamities. Rice has been an advantage with potentials, and though, in the international market, the stocks can be utilised for biofuel (Hussain and Mohapatra 2021) and edible oil can be supported by the processing technology, the merit of producing high volumes needs a critical assessment. Finally, it will be important to ask if the growth or diminution of rice farming has implications for livelihood, distress migration, land use, and the decline of potentially suitable crops.

Conclusions

The analysis shows signs of climatic changes at the regional levels and of cropping patterns moving away from the millets. The ineffectiveness of the policy for promoting pulses or oilseeds is notable in certain states. Indian agriculture is moving towards rice cultivation but also accompanying a migration of rice away from low-lying wetlands of the east to the irrigated fields of the west, which calls for a fresh thinking on land-use policy. Analysis suggests that past practice and rainfall have been the causative factors for its move in Punjab and Haryana, economics and rainfall in Haryana and Gujarat, and reservoirs and interaction of all changes for Gujarat. Reservoirs and economics did not support rice in most eastern states.

"This text has so many lines on mitigation, but there is nothing on finance" was India's complaint on funding. India has already been pursuing suggestions of CoP26 for the conservation and development of warning systems and resilient infrastructure against the climatic disasters. Adaptation on a real-time basis would require closer surveillance of weather and crop outlook, not only at the local and national front but also with a global purview to gain economic perspectives. Observing water tendencies and understanding the agronomic, behavioural, and public–political responses will be important.

NOTES

1 Economics (EN) is specified by incentive to be fetched later while marketing, the expectation of which is formed based on both wholesale price of the past harvest season and the pre-announced MSP per quintal. The expected price (₹/quintal) is expressed relative to the average expectation about prices of alternative crops that could have been grown on the same land. So long as the price of the reference crop is expected to increase more, relative to the possible substitute crops there will be a preference for the crop. Alternatively, the incentive is specified by the relative revenue in ₹/hectare to account for an incentive coming from yield dynamics, if any, where the expected revenue is the product of past yield and the expected price. The substitute crops are identified as those grown in the same season in the study state.

2 Manure use is recorded at over 1 tonne per hectare in eight states, being particularly high in Gujarat and Maharashtra.

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Appendix Tables and Notes

Table A1: Water Stored from Rainfall in Past and Entire Catchment in End May (Average of 2000–19)

States	Metrological Region (MET) Codes	Reservoir and Dam Names	Total Reservoir Volume	Depth of Groundwater
Unit			BCM	Metres
Bihar (BH)	12	–	–	5.31
Chhattisgarh (CH)	10	Tandula (td), Dudhawa (dw), Mahanadi (mh), Minimata Bango (mm)	1.62	5.40
Gujarat (GJ)	17	Sukhi (sk), Watrak (wt), Hatmati (ht), Karjan (kj), Sardar Sarovar (ss), Panam (pn), Daman Ganga (dg), Kadana (kd), Sabarmati (sb), Ukai (uk)	3.10	20.64
	30	Machchhu 2 (mc), Machchhu 1 (mh), UND 1 (ud), Bramhamani (Bh), Bhadar (bd), Shetrunji (st),		12.46
Haryana (HR)	32	–	–	13.06
Himachal Pradesh (HP)	20	Kol (kl), Pong (pg), Govind Sagar (gs)	2.71	8.43
Jammu and Kashmir (JK)	28	–	–	
Jharkhand (JH)	11	Tenughat (th), Maithon (mn), Panchet (pt), Konar (kn), Tilaiya (ty)	0.53	7.69
Madhya Pradesh (MP)	16	Gandhi Sagar (gs), Kolar (kl), Omkareshwar (os), Tawa (tw), Indira Sagar (is)	4.35	12.40
	13	Sanjay Sarovar (ss), Barna (bn), Bargi (bg), BanSagar (bs)		26.44
Odisha (OD)	8	Hariharjhor (hh), Upper Indravati (ui), Sapua (sp), Hirakund (hk), Salandi (sd), Balimela (bl), Rengali (rg), Upper Kolab (uk), Machkund (Jalaput) (mk)	2.30	5.67
Punjab (PJ)	31	Thein (tn)	0.98	12.67
Rajasthan (RJ)	29	Jhakam (jk), Bilaspur (bs), Ranapratap Sagar (rp)	0.68	17.87
	33	–		32.12
Uttar Pradesh (UP)	21	Rihand (rd)	0.98	6.64
	27	Sardashagar (sd), Matatila (ml)		7.96
Uttarakhand (UTK)	9	Their (tr), Ram Ganga (rg)	0.57	16.71
West Bengal (WB)	7	Kangsabati (ks), Mayurakshi (mk)	0.23	4.93
	4	–		6.20
Maharashtra (MH)	2	Surya (sy), Tillari (tr)	2.96	5.99
	22	Jayakwadi (jy), Koyana (ky), Bhima (bm), Mula (ma), Girna gd), Khadakvasla (kk), Upper Vaitarna (uv), Upper Tapi (ut), Mulshi (ms), Kanher (kr), Bhatsa (bt), Dhom (dm), Dudhganga (dg), Manikdoh (mh), Bhanarara (br), Urmodi (ud), Bhatghar (bh), Nira Deoghar (nd), Thokarwadi (tk)		9.02
	24	Isapur (ir), Yeldari (yr)		10.18
	14	Pench (ph), Upper Wardha (uw)		9.21

Abbreviations are in parentheses, in capital letters for state and MET names, small letters for dams.

Table A2a: Model Estimates (Sample 2000–01—2019–20) of Kharif Rice Area

		Jharkhand		Chhattisgarh		West Bengal*		Odisha	
Category	Sr No	Variable	Coeff (t–stat)	Variable	Coeff (t–stat)	Variable	Coeff (t–stat)	Variable	Coeff (t–stat)
TRV State (Dams)	1	CH (td, dw), JH (mn, pt), OD (sp) Interaction: None	1,217.0 (9.74)	JH (mn, ty), WB (ks), TL (lm, ns) Interaction: None	42.72 (3.25)	OD (mk, ui), WB (ks) Interaction: None	1,512.5 (12.31)	TL (ns), OD (uk, ui) Interaction: RF 9(GW)	−0.47 (−4.89)
	2	JH (kn, mn) Interaction: RF 8 (OD, JH), 5 (SW), 4 (JH), 6 (BH), 7 (EU)	−0.87 (−6.92)	CH(mh), OD (bl, uk), MP (bg, os) Interaction: IG Canal	−0.06 (−10.70)	OD (hk), WB (mk), CH (dw) Interaction: None	−515.9 (−15.5)	JH (mn), WB (mk) Interaction: RF 7 (SW), 5 (EH, OD)	0.65 (6.1)
AGD MET	1					SW, GW	−198.1 (−5.5)		
RF Month (METs)	1	3 (UTK), 6 (OD, EM, GW, JH), 9 (CH), 7 (EM), 8 (GW)	0.54 (13.9)	9 (VD, CH), 8 (EM), 5 (EM, GW, WM), 7 (GW), 6 (JH)	0.22 (14.69)	7 (GW), 8 (EU, GW), 9 (BH, OD)	0.37 (7.07)	5 (BH,OD), 4 (JH), 6 (BH), 8 (BH), 9 (OD, JH) Interaction: IG All sources	0.000 (12.41)
	2	10 (EU, GW, JH), 9 (WU)	−2.02 (−10.2)	6 (SW), 9 (SW, TL),10 (SW), 5 (TL), 8 (GW, BH), 12 (WM), 7 (TL)	0.11 (8.42)	11 (GW, AM)	2.34 (5.88)	10 (CH, BH, GW, SW, TL, CA, JH, OD), 11 (OD), 12 (SW) Interaction: None	0.09 (10.03)
	3	4 (WU, EM)	−14.31 (−6.45)	11 (GW, OD), 8 (OD), 12 (BH, CH)	−0.10 (−4.46)	5 (JH), 7 (AM), 4 (BH, SW, GW, AM, EH), 12 (EH), 2 (1) (SW)	−0.17 (−4.21)	3 (BH) Interaction: None	−1.8 (−2.98)
Input Price	1								
Crop Price	1	MSP, WP	2,282.1	MSP, WP	4.40	MSP, WP	529.77	MSP, WP	1,601.9
Substitute Price (crops)		WP (arhar, moong, urad)	(10.3)	WPIA	(2.46)	WP (jute), MSP, WP (moong, arhar)	(4.83)	MP, WP (moong, jute), MSP (arhar, urad)	(4.75)
Trend	1	Lagged area	0.32 (5.41)	Lagged area	0.56 (11.19)	Lagged area	−0.03 (−0.67)	Lagged area	0.55 (15.39)
Constant	1	C	−1,195 (−8.3)	C	1,157 (5.8)	C	4,988 (16.8)	C	1,181 (11.0)

Table A2b: Model Estimates (Sample 2000–01—2019–20) of Kharif Rice Area

		Haryana		Punjab		Bihar*		Gujarat	
Category	Sr No	Variable	Coeff (t–stat)	Variable	Coeff (t–stat)	Variable	Coeff (t–stat)	Variable Variable	Coeff t–stat)
TRV state (Dams)	1	PJ (tn), HP (gs, kl) Interaction: RFL 7 (HP), 8 (HP), 5 (WU), 3 (HP, JK, ER, WM, HC, PJ), 9 (PJ)	−0.03 (−6.69)	MP (ss), PJ (tn), HP (gs, kl), RJ (jk) Interaction: RFL 8 (PJ)	−0.22 (−8.18)	JH (th, pt, kn), UP (ml), CH (td), UT (tr) Interaction: None	−439.71 (−7.12)	HP (gs, kl) Interaction: RFL 6 (MM)	−0.17 (−8.77)
	2			UT (rg), UP (md), RJ (bs)] Interaction: IGN Canal	0.03 (4.40)	MP (tw), UT (rg, sd) Interaction: IGN (Well, Others)	0.08 (3.54)	MP (bn), GJ (st, mc, pn, sb), MH (kk), RJ (jk) Interaction: IGN Canal, Well	0.05 (9.47)
AGD METs	1	HC Interaction: None	−7.29 (−2.23)			BH	−490.68 (−10.55)		
	2	HC Interaction: RFL 4 (HC, PJ), 3 (WR)	0.00 (7.76)	PJ Interaction: IGN Well	0.01 (5.88)				
RFL Month (METs)	1	7 (HC), 8 (PJ, HP), 6 (PJ), 9 (JK) Interaction: None	0.42 (13.60)	3 (HC, PJ, HP), 5 (WR, PJ, HC), 6 (WR), 7 (PJ, EU) Interaction: IGN Well	−0.21 (−6.61)	5 (SW), 7 (SW), 10 (AM) Interaction: None	−0.37 (−5.26)	3 (PJ), 4 (CK, HP, MT, GR, SK, WM, ER, WR, WU), 5 (WR, ER, GR), 6 (PJ, WM), 7 (GR, WM, EM, PJ), 8 (GR, SK, HP)	0.17 (16.02)
	2	9 (UT, HC) Interaction: IGN All sources	2.31 (3.06)	1–3 (JK), 8 (JK), 4 (WR, JK, PJ, WU, EU), 6 (PJ), 7 (WR), 8 (EU) Interaction: IGN– Canal	0.00 (7.38)	6 (CH, JH), 8 (EU), 9 (BH), 3 (SW)] Interaction: IGN Canal	0.00 (3.43)		
	3	[8 (JK,UT),5 (HP),4 (HP),6 (ER)] Interaction: IGN – Canal	−0.00 (−8.86)						
Input price	1			Labour, fertiliser	−27.74 (−2.37)			Labour, fertiliser	26.84 (2.50)
Crop price	1	MSP	2803	MSP, WP	144.36	MSP, WP	1, 022.16	WSP, MSP	430.51
substitute price (crops)		MSP (Cotton)	(11.4)	MSP, WP (cotton), WP (maize, tomato, cauliflower)	(2.74)	MSP (gram, moong), MSP, WP (maize)	(4.77)	MSP, WP (sugar cane), WP (cotton, groundnut, maize, cabbage, cauliflower)	(5.73)
Trend	1	Lagged area	0.64 (13.85)	Lagged area	0.39 (3.87)	Lagged area	−0.52 (−4.16)	Area (t–1)	−0.02 (−0.23)
Constant	1	C	−501 (−7.8)	C	1, 121 (4.6)	C	7, 292 (13.2)	C	6.8 (0.14)

METS, Price and interaction variables in capital, irrigation sources, inputs, substitute crops, dam names in small letters. Input prices are deflated by WP of all commodities. Months are given by 1, 2, 3. 12 for January, February, March. December. MSP=minimum support price, WP= wholesale price, IGN irrigation, TRV=reservoir volume, AGD=groundwater level depth, RFL=rainfall. * Price variable is revenue, substitute is deflator price, all t-statistics are significant at 10%, all adjusted R2 above 95%, errors are stationary, VIF<5.

A3: Notes on the FASAL (Hybrid) Model

The estimated equation for calculating the contributions of water, past practices, and economics to acreage changes draws on a broad framework built up for the project forecasting agricultural output using space, agro-meteorology and land-based observations (FASAL) which has been tried and developed since 2006 for making early forecasts, funded by the Ministry of Agriculture and Farmers' Welfare, Government of India.

For any crop, the estimated equations for use area equation:

$$A_t = a_0 + a_1 A_{t-1} + a_2 P_t + \left(\sum a_{3j} * R^j_{tMm}\right) + \sum a_{4j} IG^j_{ts} + \sum a_{5j} RV^j_{t0} + \sum a_{6j} GD^j_{tM0} + \sum a_{7z} Z_{tz} \quad \text{... (1)}$$

A_t = area in hectares under study crop, $P_t = P_{t1}$ or P_{t2} where $P_{t1} = (EP^C_{tm})/(EP^S_{tm})$, $P_{t2} = (EP^C_{tm} * Y^C_{t-1})/(EP^S_{tm} * Y^S_{t-1})$

where EP_t (expected price) is the corresponding wholesale price (*WP*) of the crop in previous year or latest MSP or the average of both, R_{tMm} is the rainfall averaged over different alternate sets of *M* and *m*, IRG_{ts} is command area under any irrigation source, TRV_{to} = reservoir volume for benchmark month (m=0), AGD_{tMo}= ground water level for benchmark months (m=0) of MET–regions of the study state, interactions of rainfall (R_{tMm}) with irrigation ($R_{tMm}*IG_{ts}$), and of irrigation and rainfall with reservoir ($TRV^j_{to}*IRG_{ts}$ and $R_{tMm}*TRV^j_{to}$) and ground water levels ($R_{tMm}*AGD^j_{tMo}*IG_{ts}$ and $R_{tMm}*AGD^j_{tMo}$) are also allowed as variables, Z_{tz} = any other relevant z^{th} variable.

Subscripts: *t* is year (2000–01 onwards), M = met region (1, 2…36), m = months (April–March), s = source of irrigation (canal, well and tank, and others). o = benchmark month. Superscripts: c = study crops, s = substitute or competing crop (1, 2, ...n), j = serial number of each water variable set.

Multicollinearity of data is checked using variance inflation factor (VIF), stationarity of error (using augmented Dickey–Fuller [ADF] test, model fit through (Adjusted R^2), and validation (one period forward forecasts) are tested. To overcome the small size of sample, avoid multicollinearity, ensure degrees of freedom, and check robustness; the variables are compositely specified as averages of a number of basic variables (Table A2). Validity of performance is intensely checked by repeated estimation with omitted in-sample observations.

A4: Notes on Acreage Change

$$A_t = A_{t-1} + \gamma (A^*_t - A_{t-1}) \quad \text{... (2a)}$$

where A^* is the desired ideal acreage determined by exogenous variables and γ is the adjustment factor.

Rearranging equation (2a)

$$A_t = \gamma A^*_t + (1-\gamma) A_{t-1} \quad \text{... (2b)}$$

$$|1-\gamma| < 1$$

Adjustment to desired acreage is faster (flexible) if γ is higher, implying also $(1-\gamma)$ is lower.