Agricultural Economics Research Review 2020, 33 (2), 147-160
DOI: 10.5958/0974-0279.2020.00028.2

Identifying sustainable rice cultivation zones in India: the implications of the crop water footprint

Prem Chand*, Sulakshana Rao, Rajni Jain, and Suresh Pal

ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi 110 012

*Corresponding author: prem.chand@icar.gov.in

Abstract This paper examines the water footprint of rice in the agroclimatic zones (ACZ) in India and identifies the sustainable rice-growing zones. The major rice-producing ACZs of the irrigated north-western and semi-arid tropics are unsustainable. Rice can be cultivated sustainably in eastern, central, and (the coastal zones of) western India, because the water footprint is lower, and it can be lowered even more because the crop yield is very low. The study suggests that, based on the water availability and footprint, the cropping pattern in the ACZs needs to be realigned.

Keywords Crop water use, blue water, water footprint, water productivity, sustainability

JEL codes Q15, Q20, Q25

In India 54% of the land area experiences extreme water stress (Luo et al. 2018). Agriculture consumes 78% of the available utilizable water (CWC 2014). The irrigation of rice, along with wheat and sugarcane, consumes more than 80% of the water available. Increasing the area under paddy cultivation has serious implications: the water table is declining; the groundwater quality in terms of salinization is declining; and arsenic contamination is spreading (MacDonald et al. 2016; Rodell et al. 2009). The intensive rice–wheat cropping system has led to an alarming fall of the water table in recent years and raised questions over its sustainability. If the paddy–wheat cycle is allowed to continue, the water table will fall below 70 foot in 66% of the area of central Punjab, 100 foot in 34%, and 130 foot in 7% of the area (Humphreys et al. 2010; Sidhu et al. 2010); agricultural output will fall, and potable water will be in short supply and these, in turn, will lead to extensive socio-economic stress. To make crop production sustainable and water use rational, especially in water-scarce areas, India must review its current trend of producing water-intensive crops, such as sugarcane and rice (Dhawan 2017).

Several studies quantify the water footprint of agriculture in India (Hoekstra and Chapagain 2007; Kampman 2007; Jayaram and Mathur 2015). Analysing water use and the water footprint at the level of a more homogeneous unit is beneficial for better crop planning, and this study analyses and quantifies the agricultural water footprint at the level of the agroclimatic zone (ACZ). This study considers the spatial variation in the rice calendar—unlike previous studies, which assume a single representative calendar for rice in all the zones (Chapagain and Hoekstra 2011). To overcome the overestimation of the blue water footprint, our study considers a fairly large rain-fed area of the states of Assam and Odisha.

Coverage and data

The study analyses the water footprint at the ACZ level in 21 major rice-producing states, and it uses the boundaries of the ACZs delineated by the ICAR under the National Agricultural Research Project (NARP) (Ghosh 1991). Under the NARP zones, states are indivisible units, but zones tend to cut across district boundaries. If a district cuts across zones, it is

Table 1 Variables used and data sources

Variable	Data sources	Year
District-wise total area, irrigated area, and production of rice	Directorate of Economics and Statistics, Government of India (https://eands.dacnet.nic.in/)	TE 2014–15
District/regional crop calendars	Rao et al. (2015), Department of Agriculture, Co-operation and Farmers Welfare, Government of India (https://nfsm.gov.in/nfmis/rpt/calenderreport.aspx)	-
District-wise monthly rainfall	India Meteorological Department (http://hydro.imd.gov.in/hydrometweb/(S(nhs5w1rkjjq5tqqjw1nqkjma))/DistrictRaifall.aspx)	Quinquennial ending 2016–17
Reference evapotranspiration (ET0)	Rao et al. (2012)	-
Length of crop growth stages and crop coefficients (K_c)	Mohan and Arumugam (1994); Allen et al. (1998), Tyagi et al. (2002)	-

considered to be in the zone where it occupies the highest area. These zones are delineated based on the homogeneity of soil type, climate, and rainfall pattern. Besides, this study considers the state-specific redefining of the NARP zones based on various studies and reports for some of the states (Figure A1 and Table A2 in the Appendix). The analysis of water footprint in this study is based on secondary data compiled from sources like the Department of Agriculture, Co-operation and Farmers Welfare, India Meteorological Department, and published reports and papers (Table 1).

Concepts and analytical framework

Estimation of crop water requirement

The crop water requirement was estimated using Equations 1 and 2.

$$CWR_{z,s} = 10 * \Sigma^{4}_{CGS=1}\, ET\_opt_{CGS} * T_{CGS} \quad (1)$$

$$ET\_opt_{CGS} = K_{c,CGS} * ET0 \quad (2)$$

where,

$CWR_{z,s}$ is water requirement of paddy in the z^{th} zone in season s (cubic metre per hectare, m^3/ha);

CGS is the crop growth stage (initial, crop development, mid-season, and late season);

ET_opt_{CGS} is the optimum evapotranspiration in the crop growth stages;

T_{CGS} is the total number of days in the referred crop growth stage in season s;

$K_{c,CGS}$ is the crop coefficient in season s; and

ET0 is the ACZ- and season-specific reference evapotranspiration.

Crop water use and water footprint

Crop water use, also known as actual evapotranspiration (AET), consists of two components: crop rainwater use (CWUR) and blue or irrigation water use (CWUI). The CWUR was estimated using Equation 3.

$$CWUR_{z,s} = Min\,(CWR_{z,s}, P_{Eff}) \quad (3)$$

where,

$CWUR_{z,s}$ is rainwater use in the z^{th} zone in season s (m^3/ha);

$CWR_{z,s}$ is the water requirement; and

P_{Eff} is effective rainfall in the zone, defined as the amount of the total precipitation (P_{tot}, mm/day) used by the crop for evapotranspiration and the soil surface together.

The effective rainfall was estimated based on the approach of the Food and Agriculture Organization (FAO 1992). The crop CWUI is the volume of water actually applied through irrigation. The data on crop irrigation water use is not available from secondary sources, and we used Equations 4 and 5 to estimate the blue water.

$$IWR_{z,s} = CWR_{z,s} - P_{Eff} + IR_{LOSS} \quad (4)$$

$$CWUI_{z,s} = IWR_{z,s} * iaf_{z} \quad (5)$$

where,

$CWUI_{z,s}$ is irrigation water use of paddy in in z[th] zone in season s (m^3/ha);

$IWR_{z,s}$ is irrigation water requirement (m^3/ha);

P_{Eff} is effective rainfall in the zone;

iaf_z is fraction of total area of paddy under irrigation in z[th] zone; and

IR_{LOSS} is infiltration and conveyance losses of irrigation water assessed assuming irrigation efficiency of 40% from surface water and 70% from groundwater irrigation system (CWC 2014).

Using the crop rainwater use ($CWUR_{zs}$, estimated in Equation 3) and crop irrigation water use *(*$CWUI_{zs}$, estimated in Equation 4), we estimate the total crop water use using Equation 6.

$$CWUT_{zs} = CWUR_{zs} + CWUI_{zs} \quad (6)$$

where, $CWUT_{zs}$: total crop water use by a crop c (m^3/ha);

Finally, the water footprint was estimated as the volume of water consumed per unit of the crop produce (cubic metre per metric ton, m^3/t). The blue water footprint (BWF) refers to the volume of surface and groundwater utilized to produce a unit of crop, while the total water footprint (TWF) includes rainwater (Chapagain and Hoekstra 2011).

Sustainability benchmarks

Focusing on reducing the BWF to decrease the pressure on the irrigation water, and based on the different combinations of BWF and TWF, we categorized the zones into highly sustainable (low BWF and TWF), sustainable (low BWF and high TWF), low sustainable (high BWF and low TWF), and unsustainable (high BWF and TWF) (Table 2). To categorize the zones, we used two sets of water footprint benchmarks. In Scenario 1, we used the average water footprint of all the zones estimated in the study (820 m^3/t for BWF and 3,324 m^3/t for TWF) as the benchmark. In Scenario 2, we used the estimates of Chapagain and Hoekstra (2011) (826 m^3/t for BWF and 2020 m^3/t for TWF) as the benchmark.

Water footprint of rice production

The TWF of rice varies from 1,030 m^3/t in the high altitude and hilly zone of Tamil Nadu to 8,355 m^3/t in the Jhabua hills of Madhya Pradesh and 13,515 m^3/t in the central plateau of Maharashtra (Figure 1a). In general, the water footprint of rice is lower in the ACZs of eastern states (West Bengal, Assam, Bihar, and Jharkhand) than in the zones in central and western India (Madhya Pradesh, Rajasthan, Maharashtra, the Central Maharashtra Plateau and Western Maharashtra Plains of Maharashtra, Jhabua Hills and Bundelkhand of Madhya Pradesh, and the Humid Southern Plains

Figure 1a Water footprints of rice across agroclimatic zones: total water footprint
Source Authors' estimates

Table 2 Benchmarking sustainability classes

Blue water footprint (BWF)	Total water footprint (TWF)	
	Low	High
Low	Highly sustainable	Sustainable
High	Low sustainable	Unsustainable

Note Values of water footprints ≤ reference value were considered low while ≥ reference values were considered as high.

of Rajasthan). The TWF in these zones is high largely because productivity is low (< 1.0 t/ha) (Figure 2b), as also indicated by Kampman (2007).

The study highlights the wide inter-zonal variation. In Maharashtra, for example, the TWF ranges from 1,898 m^3/t in South Konkan Coastal to 13,515 m^3/t in the Central Maharashtra Plateau. In Madhya Pradesh, the TWF ranges from 2,932 m^3/t in Satpura Plateau to 8,355 m^3/t in Jhabua Hills of the state. In Andhra Pradesh, the TWF in the Scarce Rainfall Zone is 3,210 m3/t, almost double that in the Southern Zone (1,793 m^3/t).

The scattered regional estimations by researchers show wide variation in the TWF. In the Gomti river basin the water footprint of paddy is estimated at 3,018 m^3/t; in the Betwa river basin it is estimated at 8,209 m^3/t (Mali et al. 2018). Though there is a slight difference in the geographical boundaries of the basins with our delineation of the ACZs, our corresponding estimations for the Central Plains and Bundelkhand zones of Uttar Pradesh were along the same lines. Appendix A2 lists the water footprints by ACZ.

We separated the TWF into blue and green. A high BWF signifies the use of freshwater resources for growing a particular crop. High blue water usage leads to stress on the groundwater in zones where water resources are scarce, and it may deplete the groundwater level and eventually threaten agricultural sustainability. In the arid and semi-arid zones of the country the BWF is very high (Figure 1b). The top five BWF zones are the Scarce Rainfall zone of Andhra Pradesh, Cauvery Delta of Tamil Nadu, Central Maharashtra Plateau of Maharashtra, Central Dry Zone of Karnataka, and the Irrigated North-Western Plains of Rajasthan.

West Bengal and Uttar Pradesh have three ACZs each, Bihar has two, and Chhattisgarh and Punjab have one each. Together, these 10 ACZs account for 33% of the total rice area in the country (Figure 2a), and 50% of these zones reported a water footprint of over 1,000 m^3/t. In the ACZs of the Trans-Gangetic Plains, the BWF exceeds 1,600 m^3/t, and the sustainability of rice cultivation is in question. The intensification of rice cultivation has taken place largely because of high input subsidies and the assured procurement of rice at the minimum support price (MSP). The share of paddy in the gross cropped area (GCA) in Punjab increased from 18% (1980–81) to 38% (2015–16) (GoP 2018), and paddy procurement at MSP exceeded 80% of the total production concurrently from 2010 to 2015. The increasing area under the water-intensive paddy crop in the Trans-Gangetic Plains threatens sustainability, as also pointed out by Jain et al. (2017).

Figure 1b Water footprints of rice across across agroclimatic zones: blue water footprint
Source Authors' estimates

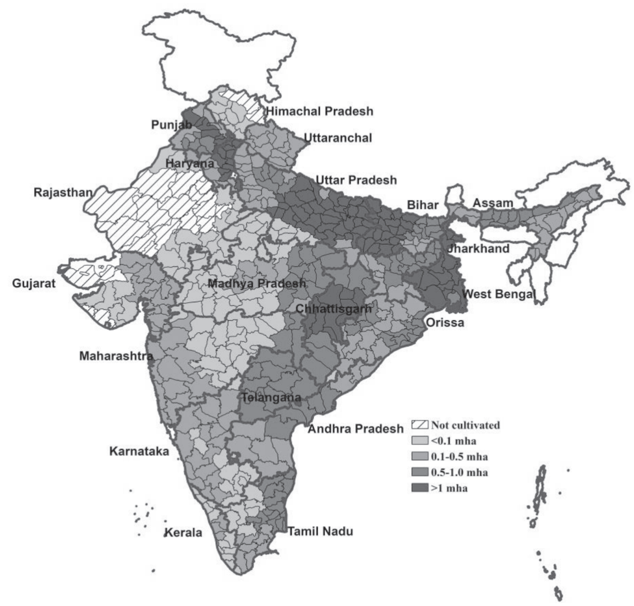

Figure 2a Area under rice by agroclimatic zone

In most of the ACZs in Assam, Chhattisgarh, Madhya Pradesh, and Odisha, the effective rainfall exceeded

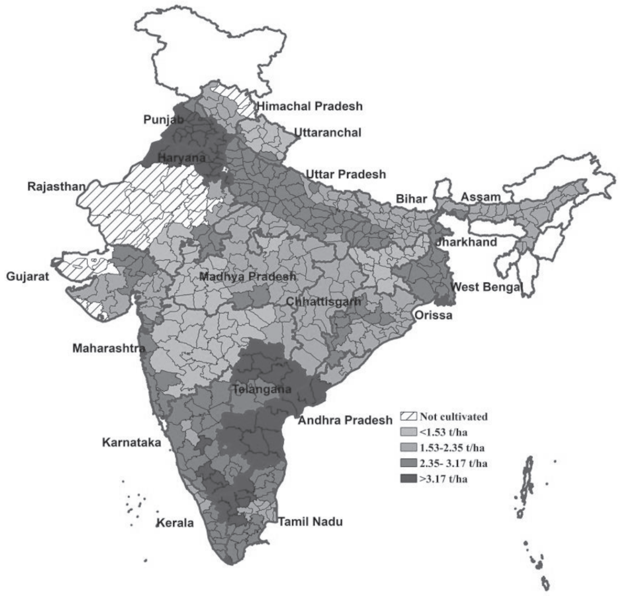

Figure 2b Rice yield by agroclimatic zone
Source Authors' estimates

the water requirement of the crop, and the BWF is zero (Figure 1b). Of the rice-growing zones in the 113 ACZs, the green component of water was higher than blue water in nearly 70%, and in 51% of these the blue water fraction was either zero or negligible. The findings of Chapagain and Hoekstra (2011) indicate that green water constitutes a large fraction of the TWF of rice production, and the stress on water resources is low compared to that in the USA and Pakistan. If the BWF of a zone is zero, the zone has the potential for further intensification of rice cultivation and for easing the burden of water-scarce regions. The BWF constitutes more than 70% of the TWF in the arid and semi-arid zones of the country, reflecting the alarming decline in the groundwater table. In most of these zones, the groundwater resources of over 50% of the sub-districts (blocks, talukas, mandals) are either overexploited or critical (CGWB 2017). These zones make up the rice bowl of the country, and stopping or reducing the cultivation of rice would impede food security, and therefore the government should focus on promoting efficient agricultural practices and water-saving technological interventions.

Seasonal variations in water footprint

In India, rice is predominantly a kharif crop, but a considerable amount is grown in the rabi and summer seasons also. We analysed the seasonal variation in the water footprint of rice across the ACZs (Figures 3–5). The water footprint pattern of kharif rice production is similar to that of the overall water footprint (Figures 3a and 3b). Rabi and summer rice account for around 13% of the rice production in the country. Rabi rice is grown mainly in the eastern states (West Bengal, Assam, Odisha, Mizoram, Bihar, and Jharkhand) and in the southern states (Andhra Pradesh, Telangana,

Figure 3a Total water footprint of kharif rice

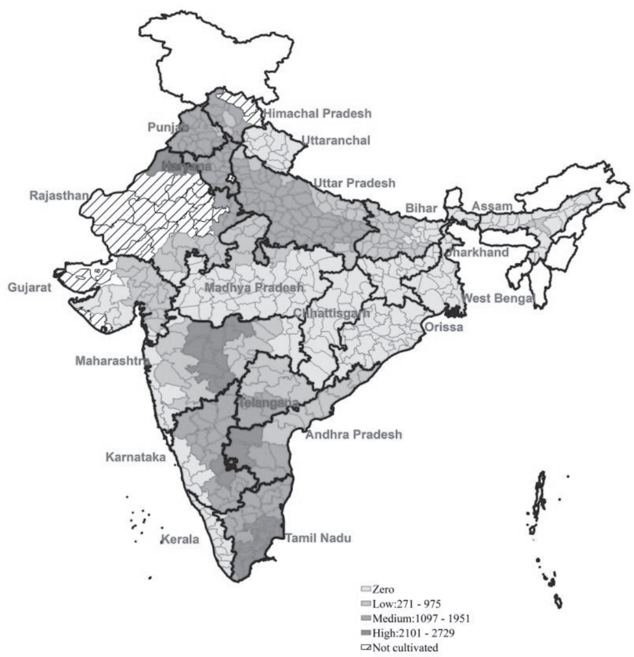

Figure 3b Blue water footprint of kharif rice
Source Authors' estimates

Tamil Nadu, Kerala, and Karnataka). Summer rice is grown mainly in the eastern states of West Bengal, Assam, Bihar, and Odisha; the southern states of Karnataka and Kerala; and in some pockets of Uttar Pradesh (GoI 2017).

The water footprint of winter rice production is lower than that of kharif rice because evapotranspiration is low. In most of the ACZs in Assam, Bihar, and Jharkhand, the water footprint of winter rice production is 50% of that of kharif rice. In the ACZs of Tamil Nadu, Kerala, Karnataka, Telangana, and Andhra Pradesh, the seasonal difference in the water footprint was little (Figures 3–5). In the ACZs of Assam, West Bengal, and Odisha, rabi rice is grown entirely using green water but in Karnataka, Andhra Pradesh, and Telangana it is dependent mostly on irrigation water (Figure 4). Though the TWF of summer rice production was lower than that of the kharif rice production, the blue water component exceeded 3,000 m^3/t in most ACZs (except in the eastern states, the Bhabar and Terai Zone of Uttarakhand, and the High Rainfall Costal Zones of Maharashtra (Figure 5).

Suitability of the agroclimatic zones for sustainable water use

In Scenario 1, the rice cultivation zones were found to be highly sustainable in most of the ACZs in Assam, West Bengal, Odisha, and Jharkhand; the Coastal and High Rainfall Hilly Regions of Karnataka, Andhra

Figure 4a Total water footprint of rabi rice
Source Authors' estimates

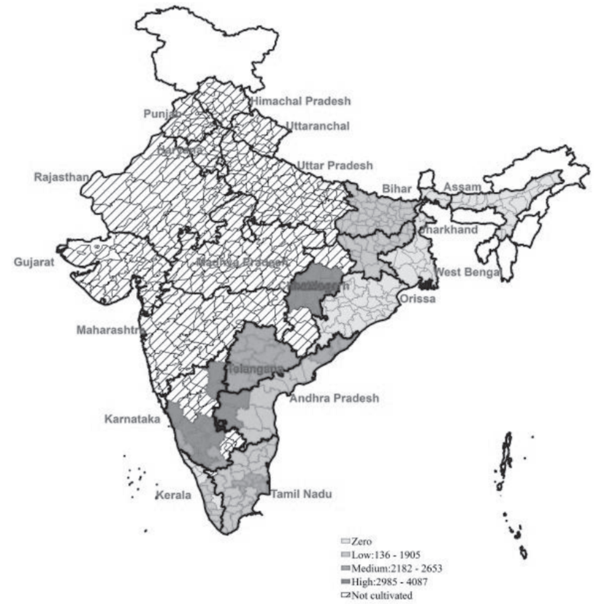

Figure 4b Blue water footprint of rabi rice
Source Authors' estimates

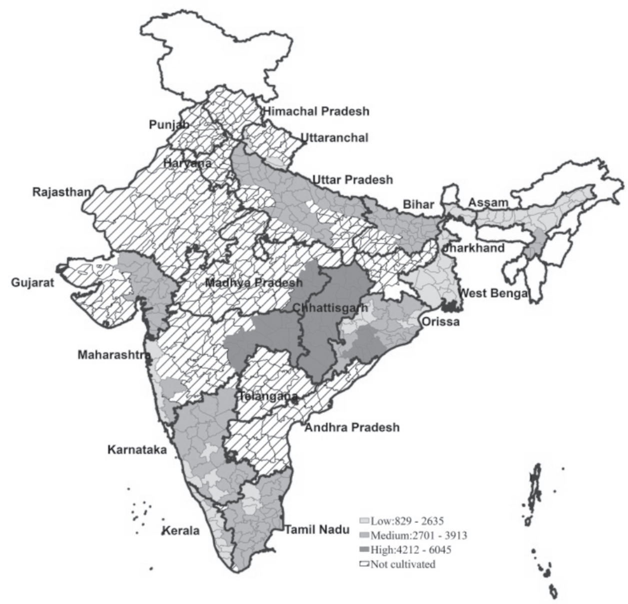

Figure 5a Total water footprint of summer rice
Source Authors' estimates

Pradesh, Tamil Nadu, Maharashtra, and Kerala; the Terai (low-lying wet zones) of Uttarakhand and Uttar Pradesh; and the Satpura Plateau, Grid, and Central Narmada Valley zones of Madhya Pradesh.

The unsustainable zones were in the Scarce Rainfall zone of Andhra Pradesh, dry zones of Karnataka, Central Plateau zone of Maharashtra, Bundelkhand of

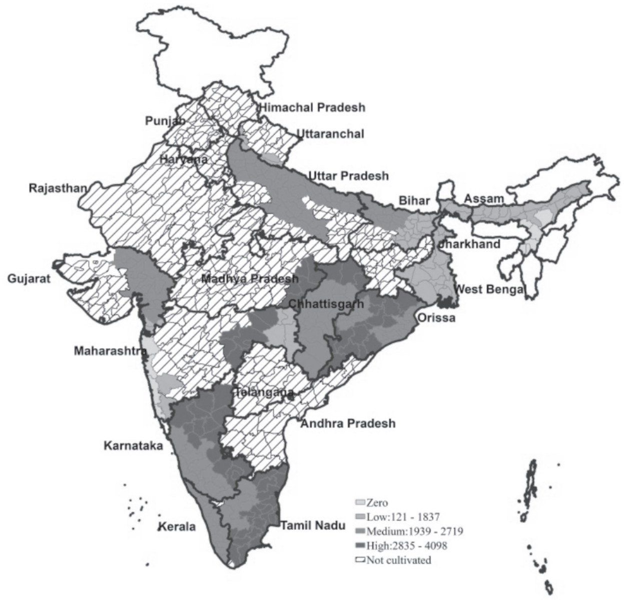

Figure 5b Blue water footprint of summer rice
Source Authors' estimates

Uttar Pradesh, western zones of Punjab, Northern and Southern Alluvial zones of Bihar, and northern zones of Rajasthan (Figure 6a).

In view of the groundwater depletion and water stress, growing rice in these zones is justifiable only with resource-saving technologies such as direct seeded rice (DSR), laser land levelling, alternative wetting, and the drying, short-duration, and water stress resistant varieties. The application of these technologies can bring down water use by 17–37 cm and improve paddy yield by up to 1 metric ton per hectare (Kakumanu et al. 2019; Ravichandran et al. 2015; Tripathi et al. 2014; Adusumilli and Laxmi 2011; Sidhu et al. 2010; Jat et al. 2006).

We estimated the water footprint of paddy production under some of these technologies based on the data in these studies (Table 3). Using a laser land leveller can reduce the TWF by 53% compared to conventional practice and the BWF by 64%. The adoption of the System of Rice Intensification in Telangana and Tamil Nadu can reduce the BWF from 58% to 66%.

In Scenario 2, more than 67% of the ACZs (high irrigation zones) are unsustainable (Figure 6b). Only a few zones are highly sustainable—in Assam, West Bengal, and Jharkhand; the coastal zones of Maharashtra and Karnataka; and the Terai and Hill Zones of Uttarakhand. The productivity of paddy is low in most of the ACZs of central India, and that is why these zones are in the low sustainable category. Technology-assisted productivity enhancement techniques should be promoted in these zones.

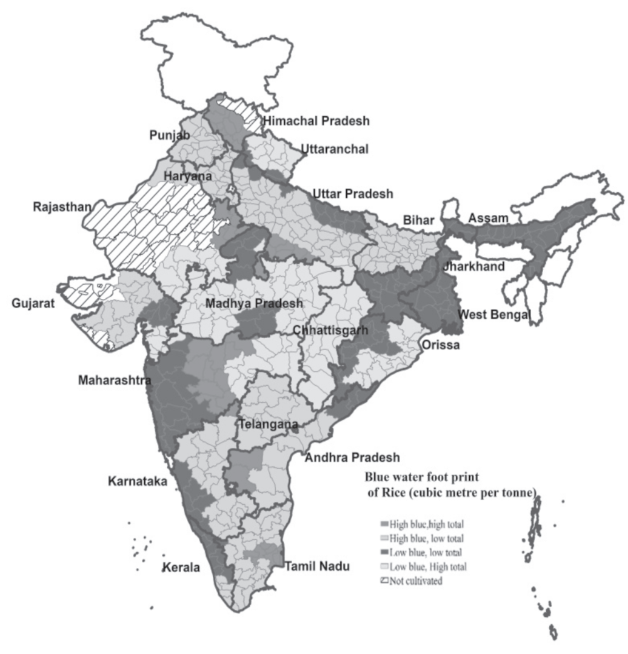

Figure 6a Agroclimatic zones identified for rice production based on water use, Scenario 1
Source Authors' estimates

Figure 6b Agroclimatic zones identified for rice production based on water use, Scenario 2
Source Authors' estimates

Table 3 Water footprints of paddy production under different water-saving technologies

(m^3/t of paddy)

State	Agroclimatic zone	Total water	Blue water
Central plain zone of Punjab	Conventional method	2,199	1,708
	Laser land levelling	1,028	621
	Tensiometer	1,218	728
Eastern zone of Haryana	Conventional method	2,329	1,700
	Direct Seeded Rice	1,837	1,169
Southern zone of Telangana	Conventional method	2,875	2,089
	System of Rice Intensification	1,720	711
North-eastern zone of Tamil Nadu	Conventional method	2,766	1,856
	System of Rice Intensification	1,319	780

Conclusions and policy implications

The water footprint for rice is lower in the ACZs of West Bengal, Assam, Bihar, and Jharkhand, and higher in Madhya Pradesh, Rajasthan, and Maharashtra. The highly sustainable zones are Barak Valley, Lower and Central Brahmaputra, Hill Zone of Assam; laterite, new, and old alluvial, hill, and Terai zones of West Bengal; Eastern Ghat, western, and mid-central table land, north-western, and western undulating zones of Odisha; the north and south Konkan zones of Maharashtra; and the central, north-eastern, south-eastern, and western plateau zones of Jharkhand. This study suggests that the cropping patterns in the ACZs need to be realigned.

In 80 ACZs, the green component of water was higher than blue water; these traditional rice cultivation zones are sustainable from the water resources perspective. The BWF constitutes over 70% of the TWF in the irrigated north-western zones of Punjab and Haryana and in the arid and semi-arid zones of the country. In these zones, rice cultivation under the existing practice of puddling and standing water is no longer sustainable; resource-saving technologies like DSR, alternate wetting and drying, and short-duration and water stress resistant varieties must be used. The policy focus in these zones should be on incentivizing water-saving practices/technologies and payment for water ecosystem services.

Winter rice is more water-productive than kharif rice wherever cultivated. Except in the ACZs of eastern states, the Konkan coastal zones of Maharashtra, the northern zone of Kerala, Bhabar, and the Terai zone of Uttarakhand, the cultivation of summer rice would exploit the groundwater resources further and make agriculture unsustainable. To understand the underlying cause of the current imbalance of cropping pattern and water availability, the pricing aspect (both input and output) needs to be scrutinized.

In the rice–wheat belts, cereal-based cropping systems are profitable mainly because inputs (water and power) are subsidized and procurement is assured. The study recommends the subsidies in the overexploited regions be reduced gradually, to reduce the burden on the north-western belts, and the procurement system in the eastern regions strengthened.

Acknowledgements

The authors acknowledge the funding support provided by the Indian Council of Agricultural Research (ICAR) for the Resource Use Planning for Sustainable Agriculture project, from which this paper originates. We also thank the anonymous reviewer of the journal for their constructive comments.

References

Adusumilli, R and S B Laxmi. 2011. Potential of the system of rice intensification for systemic improvement in rice production and water use: the case of Andhra Pradesh, India. *Paddy and Water Environment* 9: 89–97. https://doi.org/10.1007/s10333-010-0230-6

Allen, R G, L S Pereira, D Raes, and M Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper No 56, Food and Agriculture Organization, Rome. http://www.fao.org/tempref/SD/Reserved/Agromet/PET/FAO_Irrigation_Drainage_Paper_56.pdf

Central Ground Water Board (CGWB), Government of India, 2017. Dynamic ground water resources of India. Faridabad. http://cgwb.gov.in/Documents/Dynamic%20GWRE-2013.pdf

Central Water Commission (CWC), Government of India. 2014. Guidelines for improving water use efficiency in irrigation, domestic & industrial sectors. Performance Overview and Management Improvement Organization, New Delhi. http://jalshakti-dowr.gov.in/sites/default/files/Guidelines_for_improving_water_use_efficiency_1.pdf

Chapagain, A K and A Y Hoekstra. 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. *Ecological Economics* 70: 749–758. https://doi.org/10.1016/j.ecolecon.2010.11.012

Dhawan, V. 2017. Water and agriculture in India. Background paper for the South Asia expert panel GFFA, German Asia-Pacific Business Association, Hamburg. https://www.oav.de/fileadmin/user_upload/5_Publikationen/5_Studien/170118_Study_Water_Agriculture_India.pdf

Directorate of Economics and Statistics (DES), Government of India. 2017. Agricultural statistics at a glance., New Delhi https://eands.dacnet.nic.in/PDF/Agricultural%20Statistics%20at%20a%20Glance%202017.pdf

Economic and Statistical Organisation, Government of Punjab, 2018. *Statistical Abstract of Punjab*. Chandigarh. https://www.esopb.gov.in/Static/PDF/Abstract2018.pdf

Food and Agriculture Organization (FAO). 1977. Guidelines for predicting crop water requirement. *Irrigation and Drainage Paper 24*, Rome. http://www.fao.org/3/a-f2430e.pdf

Ghosh, S P. 1991. *Agro-climatic zone speciûc research: Indian perspective under NARP*. 1st edition, Indian Council of Agricultural Research, New Delhi.

Hoekstra, A Y and A K Chapagain. 2007. Water footprints of nations: water use by people as function of their consumption pattern. *Water Resource Management* 21: 35–48. https://doi.org/10.1007/s11269-006-9039-x

Humphreys, E, S S Kukal, E W Christen, G S Hira, B Singh, S Yadav, and R K Sharma. 2010. Halting the groundwater decline in north-west India—which crop technologies will be winners? In *Advances in Agronomy*, volume 109, ed D Sparks, 155–217. Academic Press, Cambridge. https://doi.org/10.1016/B978-0-12-385040-9.00005-0

Jain, R, I Kingsly, R Chand, A Kaur, S S Raju, S K Srivastava, and J Singh. 2017. Farmers and social perspective on optimal crop planning for ground water sustainability: a case of Punjab state in India. *Journal of the Indian Society of Agricultural Statistics* 71(1): 75–88. http://isas.org.in/jsp/volume/vol71/issue1/10-RajniJain.pdf

Jat, M L, P Chandna, R Gupta, S K Sharma, and M A Gill. 2006. Laser land levelling: a precursor technology for resource conservation. Technical Bulletin Series 7, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi. http://www.knowledgebank.irri.org/csisa/images/FactsheetsAndReferences/Techbulletins/lasertechbull.pdf

Jayaram, K and V C Mathur. 2015. Valuing water used for food production in India. *Economic Affairs* 60: 409–414. https://doi.org/10.5958/0976-4666.2015.00058.3

Kakumanu, K R, G R Kotapati, U S Nagothu, K Palanisami, and S R Kallam. 2019. Adaptation to climate change and variability: a case of direct seeded rice in Andhra Pradesh, India. *Journal of Water and Climate Change* 10(2): 419–430. https://doi.org/10.2166/wcc.2018.141

Kampman, D A. 2007. The water footprint of India: a study on water use in relation to the consumption of agricultural goods in the Indian states. Master thesis, University of Twente, Enchede, The Netherland. https://essay.utwente.nl/537/1/scriptie_Kampman.pdf

Luo T, D Krishnan, and S Sen. 2018. Parched power: water demands, risks, and opportunities for India's power sector. Working Paper, World Resources Institute, Washington, DC. https://www.wri.org/publication/parched-power

MacDonald, A M, H C Bonsor, K M Ahmed, W G Burgess, M Basharat, R C Calow, A Dixit, S S D Foster, K Gopal, D J Lapworth, R M Lark, M Moench, A Mukherjee, M S Rao, M Shamsudduha, L Smith, R G Taylor, J Tucker, F van Steenbergen, and S K Yadav. 2016. Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. *Nature Geoscience* 9: 762–766. https://doi.org/10.1038/ngeo2791

Mali, S S, D K Singh, A Sarangi, and S S Parihar. 2018. Assessing water footprints and virtual water flows in Gomti river basin of India. *Current Science* 115(4): 721–728. https://doi.org/10.18520/cs/v115/i4/721–728

Mohan, S and N Arumugam. 1994. Irrigation crop coefficients for lowland rice. *Irrigation and Drainage Systems* 8(3): 159–176. https://doi.org/10.1007/bf00881016.

Rao, B B, V M Sandeep, V U M Rao, and B Venkateswarlu. 2012. Potential evapotranspiration estimation for Indian conditions: improving accuracy through calibration coefficients. Tech. Bull. No 1/2012, National Innovations on Climate Resilient Agriculture, ICAR-Central Research Institute for Dryland Agriculture, Hyderabad. http://nicra-icar.in/nicrarevised/images/Books/Potential%20Evapotranspiration%20estimation.pdf

Rao, V U M, A V M S Rao, M A S Chandran, P Kaur, P V Kumar, B B Rao, I R Khandgond, and Ch S Rao. 2015. District level crop weather calendars of major crops in India. Central Research Institute for Dryland Agriculture, Hyderabad. http://www.crida.in/Pubs/Crop%20Weather%20Calendars_technical%20bulletin.pdf

Ravichandran, V K, V Nayar, and K C Prakash. 2015. An evaluation of the SRI on increasing yield, water productivity and profitability; experiences from TN-IAMWARM project. *Irrigation & Drainage Systems Engineering* 4:137, https://doi.org/10.4172/2168-9768.1000137

Rodell, M, I Velicogna, and J Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460: 999–1002. https://doi.org/10.1038/nature08238

Sidhu, R S, K Vatta, and H S Dhaliwal. 2010. Conservation agriculture in Punjab: economic implications of technologies and practices. *Indian Journal of Agricultural Economics* 65(3): 413–427. https://doi.org/10.22004/ag.econ.204693

Tripathi, R S, R Raju, and K Thimmappa. Economics of direct seeded and transplanted methods of rice production in Haryana. *Oryza* 51(1): 70–73.

Tyagi, N K, D K Sharma, and S K Luthra. 2000. Determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter. *Agricultural Water Management* 45(1): 41–54. https://doi.org/10.1016/s0378-3774(99)00071-2

Received: May 2019 Accepted: January 2020

Appendix Table A2 ACZ-wise blue water footprint (BWF) and total water footprint (TWF)

ACZ codes	Name of ACZs	Blue water footprint (BWF)				Total water footprint (TFW)			
		Kharif	Rabi	Summer	Total	Kharif	Rabi	Summer	Total
1	AP: Godavari	721.3	1,359.8	na	1,101	3,029.4	1,456.3	na	2,070.5
2	AP: Krishna	974.9	1,632.1	na	1,133.4	2021.7	1,753.4	na	1957.1
3	AP: North Coastal	630.8	2,543.3	na	702.9	3,085.3	2,835.4	na	3,063.5
4	AP: Scarce Rainfall zone	2,591.2	2,984.7	na	2,676.1	3,232.6	3,128.8	na	3,210.2
5	AP: Southern zone	1,367.3	1,504.7	na	1,465.8	1989.4	1,717.1	na	1,793.1
6	AS: Barak Valley	0	0	0	0	3,090.6	1966.1	3,187.9	2,092.6
7	AS: Central Brahmaputra Valley	625.6	0	237.3	102.4	2,537.6	2,187	828.8	1,660.3
8	AS: Hills	0	0	0	0	3,625	2,484.7	1,472.1	2,573.2
9	AS: Lower Brahmaputra Valley	0	0	129.9	0	4,636	2,253.7	1,726	2,177.7
10	AS: North Bank Plains	0	0	333.8	0	4,287.5	2,228.2	1,413.6	2,209.6
11	AS: Upper Brahmaputra Valley	0	0	120.6	0	4,174.3	2035.5	2,099.6	2,069.3
12	BR: North-Eastern Alluvial	0	1,277.3	1,452.2	1,125.3	4,554	1,589.8	3,275.6	2,246.6
13	BR: North-Western Alluvial Plains	418.3	1,331.6	2,428.6	1,013.6	3,731.4	1,684.4	3,797.3	2,311.7
14	BR: South-Eastern Alluvial Plains	291.4	1,528.9	1,416.1	1986.5	3,921.4	1,756.5	2,842.9	2,299.9
15	BR: South-Western Alluvial Plains	950.2	1,763.8	na	1,840.8	4,326.8	1912.8	na	1998.9
16	CG: Bastar Plateau	0	na	2,083.7	0	3,403	na	5,569.9	3,404.2
17	CG: Chhattisgarh Plains	0	3,559.8	2,543.2	0	3,658.5	3,719.9	4,422.8	3,622.4
18	CG: North Hills of Chhattisgarh	0	na	4,097.9	0	4,232.2	na	6,045.3	4,219.3
19	GJ: Middle Gujarat	609.2	na	2,218.2	768.2	3,186.4	na	2,980	3,008.5
20	GJ: North Gujarat	351.1	na	2,211.1	1,078.7	2,362.1	na	2,947.3	2,993.9
21	GJ: North Saurashtra	0	na	na	1,452.4	1,427	na	na	2,872.3
23	GJ: South Gujarat Heavy Rainfall zone	0	na	1,150.9	0	3,473	na	3,146.5	3,306.7
24	GJ: South Gujarat	270.9	na	2,138.8	426.2	3,414.7	na	3,183.6	3,329
26	HR: Eastern Zone	1,699.7	na	na	1,699.7	2,328.7	na	na	2,328.7
27	HR: Western Zone	1951.2	na	na	1951.2	2,352.1	na	na	2,352.1
29	HP: High-Hills Temperate Wet	1,706.9	na	na	1,706.9	3,998	na	na	3,998
30	HP: Mid-Hills Sub-Humid	903.5	na	na	903.5	4,212.9	na	na	4,212.9
31	HP: Sub-Mountain & Low Hills Sub-Tropical	1,206.9	na	na	1,206.9	4,359	na	na	4,359
32	JR: Central and North-eastern plateau	0	155.8	na	143.7	7,684.6	694.8	na	1,128.3
33	JR: South-eastern Plateau sub-zone	0	136.1	na	139.5	9,923.4	939.3	na	1,194.6
34	JR: Western plateau sub-zone	0	407.2	na	234.6	7,294.8	1,055.4	na	2,484.8
35	KA: Central Dry Zone	2,101.3	3,086.5	3,604.2	2,322.1	2,974.8	3,319.5	3,912.6	3,101.3
36	KA: Coastal Zone	0	2,452.6	2,193.4	182.2	1,865.4	2,757.7	2,593.6	1,629
37	KA: Eastern Dry Zone	1,572	na	2,928.1	1,679.4	2,636.1	na	3,261.8	2,710.1
38	KA: Hilly Zone	0	3,050.6	2,718.6	0	3,115.8	3,317.5	3,027	2,967.7
39	KA: North-Eastern Dry Zone	1,756.1	4,087.5	3,315.9	2,223.2	2,868.2	4,227.4	3,464.6	3,067.5
40	KA: North-Eastern Transition Zone	1,725.1	na	na	1,725.1	5,694.9	na	na	5,694.9

Contd...

ACZ codes	Name of ACZs	Blue water footprint (BWF)				Total water footprint (TFW)			
		Kharif	Rabi	Summer	Total	Kharif	Rabi	Summer	Total
41	KA: Northern Dry Zone	1,685.9	na	3,343.5	2,122.9	2,442	na	3,493.5	2,735.4
42	KA: Northern Transition Zone	1,465.5	na	3,229.5	1,620	3,211.4	na	3,494.4	3,161.7
43	KA: Southern Dry Zone	1,756.7	2,181.7	2,452	1,860.2	2,353.1	2,402.6	2,720	2,406
44	KA: Southern Transition Zone	1,545.5	3,360.3	2,334.3	1,712.9	2,451	3,667.3	2,604.6	2,473.6
45	KL: Central zone	0	219.3	2,088.3	250.2	2,209.8	2,988.6	2,209.9	2,495.6
46	KL: High altitude zone	0	0	2,568.8	280.4	2,287.9	3,099.2	2,727.8	3,050.5
47	KL: Northern zone	0	0	2,187.5	243.5	2,449.4	4,199.9	2,246.3	3,133.5
48	KL: Onattukara, Kuttannad and Kole	0	570.6	2,277.9	1,300.4	1930.2	2,682.4	2,544.3	2,381.5
49	KL: Southern zone	0	256.8	2,236.6	1,196.4	1912.7	2,978	2,484.1	2,484.5
50	MH: Central Maharashtra Plateau	2,366.3	na	na	2,366.3	13,514.7	na	na	13,514.7
51	MH: Eastern Vidarbha	0	na	1,524.5	0	4,942	na	4,249	4,856
52	MH: North Konkan Coastal	0	na	0	0	2,160.4	na	2,458.5	2,179.2
53	MH: South Konkan Coastal	0	na	0	0	1,862.3	na	2,474.2	1,897.9
54	MH: Western Ghat and Sub-Mountain	0	na	1,450.7	0	3,128.6	na	3,284.6	2,657.9
55	MH: Western Maharashtra Dry	273.6	na	na	273.6	2,997.6	na	na	2,997.6
56	MH: Western Maharashtra Plains	0	na	na	0	6,005.5	na	na	6,005.5
57	MH: Western Vidarbha	383.6	na	3,238.7	364.6	4,836.1	na	5,013.5	4,482.9
58	MP: Bundelkhand	438.5	na	na	438.5	7,751.1	na	na	7,751.1
59	MP: Central Narmada Valley	0	na	na	0	3,000.3	na	na	3,000.3
60	MP: Chhattisgarh plains	0	na	2,835.5	0	3,926.9	na	5,670.7	3,926.3
61	MP: Gird Region	496.6	na	na	496.6	3,075.6	na	na	3,075.6
62	MP: Jhabua Hills	0	na	na	0	8,355.4	na	na	8,355.4
63	MP: Kymore Plateau & Satpura Hills	0	na	na	0	4,023.2	na	na	4,023.2
64	MP: Malwa Plateau	0	na	na	0	7,462.1	na	na	3,734.8
65	MP: Nimar Plains	0	na	na	0	5,583.9	na	na	5,583.9
67	MP: Satpura Plateau	0	na	na	0	2,931.6	na	na	2,931.6
68	MP: Vindhya Plateau	0	na	na	0	4,043.4	na	na	4,043.4
69	OD: East and South-Eastern Coastal Plain	0	0	2,496.2	101.4	4,281.5	3,988.7	2,803.2	3,750.6
70	OD: Eastern Ghat High Land	0	0	3,147.4	0	4,726.1	2,854.1	3,397	2,903.7
71	OD: Mid-Central Table Land	0	0	3,210.5	0	4,248.2	2,764.7	3,481.9	2,844.9
72	OD: North Central Plateau	0	0	3,344.6	0	4,979.3	3,979.8	3,868.8	4,029.5
73	OD: North-Eastern Coastal Plains	0	0	2,121.6	107.7	6,601.5	4,724.8	2,495.8	4,172.8
74	OD: North-Eastern Ghat	0	0	3,725.7	0	6,015	4,149.3	4,212	4,175.6
75	OD: North-Western Plateau	0	0	3,418.1	0	3,702.9	2,751.4	3,584.3	3,017
76	OD: South-Eastern Ghat	0	0	3,175.1	0	6,518.7	3,978.2	3,481.9	4,062.9
77	OD: Western Central Table Land	0	0	2,144.8	149.5	3,692.9	2,513.5	2,237.5	2,356.2
78	OD: Western Undulating	0	0	2,981.6	168.2	4,053.8	2,835.6	3,229.2	2,836.8
79	PB: Central plains	1,708	na	na	1,708	2,198.8	na	na	2,198.8
80	PB: Sub-Mountain Undulating	1,444.8	na	na	1,444.8	2,637.2	na	na	2,637.2
81	PB-Undulating Plains	881.8	na	na	881.8	1,875.3	na	na	1,875.3
82	PB-Western Plains	1,700.4	na	na	1,700.4	2011.4	na	na	2011.4

Contd...

ACZ codes	Name of ACZs	Blue water footprint (BWF)				Total water footprint (TFW)			
		Kharif	Rabi	Summer	Total	Kharif	Rabi	Summer	Total
83	PB: Western Zone	1,605.7	na	na	1,605.7	1910.5	na	na	1910.5
85	RJ: Flood Prone Eastern Plains	1,097	na	na	1,097	3,399.8	na	na	3,399.8
86	RJ: Humid South-Eastern Plains	369.3	na	na	369.3	3,389	na	na	3,389
87	RJ: Humid Southern Plains	0	na	na	0	7,166.8	na	na	7,166.8
88	RJ: Irrigated North-West Plains	2,245.5	na	na	2,245.5	2,611.1	na	na	2,611.1
90	RJ: Sub-Humid Southern Plains and the Aravalli Hills	321.7	na	na	321.7	4,518.8	na	na	4,518.8
93	TN: Cauvery Delta	2,195.7	2,648	3,023.9	2,563	2,445.1	4,312.1	3,221	3,822.6
94	TN: High Altitude and Hilly Zone	0	na	na	0	1,030	na	na	1,030
95	TN: High Rainfall Zone	1,262.3	1,270.7	na	1,265.9	1,872.9	2,260	na	2037.4
96	TN: North-Eastern Zone	1,802.6	1,548.1	2,979.7	1,856.1	2,087.2	3,079.2	3,269.5	2,766.1
97	TN: North-Western Zone	1,620.7	1905.4	2,571.9	1926.8	1908	2,693.2	2,634.8	2,484.4
98	TN: Southern Zone	2,729	1,574.1	2,927.7	1,669.7	3,063.4	2,503.6	3,118	2,539.2
99	TN: Western Zone	1,657.1	1,681.6	2,627.8	1,752.4	1900.3	2,302.7	2,700.7	2,241.2
100	TG: Central Telangana	709.4	2,461.5	na	1,215.7	2,627.9	2,581.1	na	2,579.5
101	TG: North Telangana	593.4	2,265.8	na	1,242.9	2,406	2,392	na	2,392.9
102	TG: Southern Telangana	1,648.8	2,652.5	na	2,089.3	2,954.3	2,783.9	na	2,874.8
103	UP: Bhabar and Terai	582	na	1939.4	620.6	2,705.5	na	3,132.8	2,711.6
104	UP: Bundelkhand	1,577	na	na	1,577	4,202.7	na	na	4,202.7
105	UP: Central Plains	1,493.6	na	2,507.5	1,495.3	2,928	na	3,291.7	2,928.6
106	UP: Eastern Plains	1,245.1	na	na	1,245.1	3,108.3	na	na	3,108.3
107	UP: Mid-Western Plains	1,182.4	na	2,364.6	1,203.4	3,043.3	na	3,516.8	3,051.7
108	UP: North-Eastern Plains	345.1	na	2,207.2	345.3	2,614.2	na	3,535.9	2,614.2
109	UP: South-Western Semi-Arid	1,848.6	na	na	1,848.8	2,995.5	na	na	2,995.5
110	UP: Vindhyan zone	288	na	na	288	3,190.6	na	na	3,190.6
111	UP: Western Plains	1917.7	na	2,550.9	1918.8	2,763.1	na	3,039.6	2,763.6
112	UK: Bhabar and Terai	0	na	204.2	0	2,052.8	na	2,141.2	2016.6
113	UK: Hills	0	na	na	0	3,956.1	na	na	3,956.1
114	WB: Coastal and saline zone	0	0	877.6	186.6	2,713.7	2,618.3	1,242.4	2007.3
115	WB: Hills	0	0	992	0	3,004	2,527.4	2,273.9	2,526.1
116	WB: Laterite and red soil Zone	0	0	1,836.6	137.4	2,110.3	2,110.3	2,152.4	2039
117	WB: New Alluvial	0	0	1,481.7	416	2,399.6	2,069.1	1,801.2	1,854
118	WB: Old Alluvial	0	0	1,722.5	319.1	2,386.3	2,071.5	2032.2	1,886.3
119	WB: Terai Zone	0	0	1,053.6	163.2	3,624.5	2,438.7	2,058.5	2,236.8

Note ‘na’ denotes to no cultivation of rice in the zone (area < 100 ha); Names prefixing the zones are abbreviated state names where AP-Andhra Pradesh, AS-Assam, BR-Bihar, CG-Chhattisgarh, GJ-Gujarat, HP-Himachal Pradesh, HR-Haryana, JR-Jharkhand, KA-Karnataka, KL-Kerala, MH-Maharashtra, MP- Madhya Pradesh, OD-Odisha, PB-Punjab, RJ-Rajasthan, TN-Tamil Nadu, TG-Telangana, UP-Uttar Pradesh, UK-Uttarakhand, and WB-West Bengal.

Appendix Figure A1 Boundaries of agroclimatic zones

Legends are given in first column of Appendix Table A2

Source Authors' estimates