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SUMMARY

Sustainable rice production is the key to achieving Sustainable Development Goals (SDGs), particularly for country like India. Growing rice in non-conventional and unsuitable ecoregions, however, has generated several environmental problems such as depletion of ground water, pollution of air, degradation of soil and aggravation of climate change. All these degenerative factors are taking toll on the productivity, profitability and sustainability of rice farming. To achieve sustainable and environment-friendly rice farming, the crop should be cultivated in the region where its environmental footprint is the minimum. This can be accomplished with ecoregional approach of rice farming. Ecoregions are geographical regions with similar ecological, soil and climatic conditions. Rainfall, temperature and soil are the three most important biophysical factors determining ecoregions for growing rice. Rice is a water-loving crop. Therefore, its cultivation should be done in the areas where average annual rainfall is more than 1000 mm. Temperature is another key factor influencing growth, development and yield of rice. Rice being a tropical and sub-tropical plant, requires a fairly high temperature, ranging from 20° to 30°C. Clayey loam soil (27-40% clay content) in monsoon land is considered to be the best for rice cultivation as water retention capacity of this soil is high. The paper presents an analysis of delineating suitable ecoregions for rice in India considering rainfall, temperature and soil texture as the major contributing factors. The suitable ecoregions of rice farming have been delineated and site-specific improved technologies have been identified for enhancing productivity, profitability, climate resilience and sustainability of rice farming in the country.

PREFACE

Rice, the world's most important food crop, is the staple food for about four billion people i.e., half of the humankind on the planet. It is cultivated in a wide range of climatic conditions spanning from 44°N in North Korea to 35°S in Australia and from six feet below sea level (such as in Kerala, India) to 2700 feet above sea level in the Himalayas. The crop occupies a significant position in the culture and heritage of many Asian countries. In India, it is the staple food for more than 65% of population, thereby, is pivotal to food and livelihood security of people and directly contributing to attainment of Sustainable Development Goal (SDG). Thus, it is imperative to enhance not only the productivity of rice, but also profitability, input use efficiency and climate resilience in rice systems in order to contribute to other SDGs.

In India, the current land use pattern for agriculture in many states is not based on principles of comparative advantage. Crop pattern in various region are inefficient in terms of resource use and unsustainable from natural resource use point of view. This is resulting into serious misallocation of resources, efficiency loss, indiscriminate use of land and water resources, and adversely affecting long-term production prospects. Due to lack of proper crop planning, problems of soil and water degradation are aggravating. Proper crop planning that it is consistent with natural endowment and resources use efficiency is urgently required to stop the further degradation.

This publication presents the suitable eco-regions for sustainable rice cultivation in India. The eco-regions for rice are developed based not only on the biophysical parameters for rice cultivation, but also on the futuristic demand for rice in the country. The study delineated the area under rice cultivation in India into four broad categories from unsuitable to very suitable; emphasised on optimizing the productivity from the suitable zones and discussed the strategies for enhancing productivity and profitability of rice cultivation.

We wish the research bulletin would be an important document for influencing the future policy on resource allocation for sustainable rice cultivation in the country and thereby contributing to attainment of SDGs.

Authors

CONTENT

1. Introduction

Rice, the world's most important food crop, is the staple food for about four billion people i.e., half of the humankind on the planet (Table 1). Rice fields cover around 160 million hectares (Mha) in a wide range of climatic conditions spanning from 44°N in North Korea to 35°S in Australia. It is cultivated from six feet below sea level (such as in Kerala, India) to 2700 feet above sea level in the Himalayas. The crop occupies a significant position in the culture and heritage of many Asian countries. Most of the rice in tropical countries is produced in irrigated and rainfed lowland areas. Irrigated rice systems account for 78% of all rice production and 55% of total harvested rice area, mostly concentrated in alluvial floodplains, terraces, inland valleys, and deltas in the humid and sub-humid subtropics and humid tropics of Asia. The crop occupies largest area in India followed by China and Indonesia, whereas China has the highest production but Australia has the highest productivity.

Rice is staple food for about 800 million people of India (Table 1). It plays a major role in diet, economy, employment, culture and history. It is the staple food for more than 65% of Indian population contributing approximately 40% to the total food grain production, thereby, occupying a pivotal role in the food and livelihood security of people. India grows rice in 43 Mha with production of 112 million tons (Mt) of milled rice and average productivity of 2.6 t ha^{-1}. The crop is grown in highly diverse conditions ranging from hills to coasts. Primarily a *kharif* crop, it is cultivated round the year in one or the other parts of the country. District wise rice area in proportion to agricultural area in presented in Fig. 1. Over the years, area under rice has increased about 1.5 times, however production has increased more than five times (Fig. 2). With this, India has not only achieved self-sufficiency in rice but also produces surplus to export. The leading rice producing states are West Bengal, Uttar Pradesh, Punjab, Odisha, Andhra Pradesh, Bihar and Chhattisgarh (Table 2).

Area, production and productivity of rice in different agro-climatic zones are presented in Table 3 whereas area and productivity of rice in different seasons and ecosystems of India are presented in Table 4. About 40% of the rice area in India is rainfed and more than 70% of which is in eastern India. Out of the total rainfed area, 23% are rainfed upland and 77% are rainfed lowland. The entire rainfed upland and 52% rainfed lowlands are drought prone. About 17% of rainfed lowlands are flood prone.

Rice production in India has made tremendous progress over the years. However, it is facing unprecedented challenges of environmental degradation and climate change in recent years (Wassmann et al. 2009a, 2009b; Pathak 2015). Low and uncertain income, degraded natural resource base, growing labour and energy shortages and threats of climate change are making Indian agriculture highly vulnerable and unsustainable (Pathak et al. 2018b; 2019a,b,c). Environmentally safe and economically viable disposal of rice straw is another challenge of rice farming in many, particularly the north-western part of the country (Pathak et al. 2012). Indian rice farming thus seems to be in a cross-road once again. Producing enough rice for the increasing population against the backdrop of reducing natural resource base is, therefore, the primary task of Indian rice sector.

Sustainable rice production is the key to achieving Sustainable Development Goals (SDGs), particularly for country like India (Fig. 3). We need to enhance productivity, profitability, input use efficiency and climate resilience in rice systems to achieve the SDGs. Current land use pattern for agriculture in many states are not based on principles of comparative advantage. Crop pattern in various region are inefficient in terms of resource use and unsustainable from natural resource use point of view. This is resulting into serious misallocation of resources, efficiency loss, indiscriminate use of land and water resources, and adversely affecting long-term production prospects. Due to lack of proper crop planning, problems of soil and water degradation are aggravating. Proper crop planning that it is consistent with natural endowment and resources use efficiency is urgently required to stop the further degradation. The paper presents an analysis of delineating suitable ecoregions for rice in India considering rainfall, temperature and soil texture as the major contributing factors. It also identifies technologies for enhancing productivity, profitability, climate resilience and sustainability of rice farming in the country in the suitable ecoregions.

2. Trends in area, production and productivity of rice at national and state levels

Increasing demand for food and various government policies have a significant implication on resource allocation for rice crop and its acreage. Hence, the shift in area, production and productivity of rice was computed with the help of following model.

$$Y = ab^t$$

$$\text{Log } Y = \log a + t \log b$$

where, 'Y' is the time series data of state wise area, production and productivity of rice, 't' is the trend term and 'a' is the constant coefficient. The slope coefficient 'b' measures the relative change in 'Y' for a given absolute change in the value of explanatory variable 't'. If the relative change in Y is multiplied by 100, one can get the percentage change or growth rate in Y for an absolute change in the variable 't'. The slope coefficient 'b' measures the instantaneous rate of growth. The compound growth rate 'r' can be calculated as follows:

$$CGR(r) = [\text{Antilog}(\log b) - 1] \times 100$$

The above equation was solved using Ordinarily Least Square (OLS) method.

During 1950-51 to 2017-18, rice area in India has witnessed an expansion at the rate of 0.20 Mha yr^{-1}, whereas production and productivity have increased at the rate of 2.05 Mt yr^{-1} and 0.04 t ha^{-1} yr^{-1} respectively (Fig. 2) during the same period. These changes are reflecting the cumulative effect of green revolution technologies and various government policies. However, in last three decades, crop specific policies (Procurement Policy, National Food Security Mission and others) have indirectly played a crucial role in resource allocation for few crops which would have certainly affected their production and yield. Between 1990-91 and 2017-18, the area, production and productivity of rice in India have increased at the rate of 0.09, 1.45 and 1.36, respectively (Table 5). However, state level analysis of area, production and productivity for the same period indicates a negative growth in area under rice for 45% of the states. Trend in production was positive in all states except six states *viz.* Kerala, Mizoram, Pondicherry, Tamil Nadu, Sikkim and Goa, where it was negative. Productivity trend has been positive in all the states except Manipur and Mizoram, where it was negative (Table 5).

3. Projection of rice demand in 2030, 2040 and 2050

Rice farming, particularly in the rainfed regions, faces multiple risks from uncertain climate, degraded soil, water deficit and underdeveloped markets. It has come under increasing pressure from intense competition for land and water, a more difficult growing environment because of climate change, higher price for energy and fertilizers, labour shortage, increasing cost of cultivation, declining profit margin and greater demand for reduced environmental footprint (Samal 2009; 2013). The socio-economic dynamics and food habits are also changing adding another dimension to already complex challenges of rice cultivation. Therefore, the goal of rice research and development should be at improving nutritional and income security of rice farmers while addressing environmental sustainability and coping with climate change.

We used household data from 68th round of consumption survey conducted by National Sample Survey Organization (NSSO) for deriving per capita consumption demand of rice per year. The data on annual population for the country for the year 1951 to 2018 was taken from the United Nations (UN), which was further extrapolated to project the population for year 2020, 2030, 2040 and 2050. Income/expenditure elasticity of rice based on Food Characteristics Demand System (FCDS) model for all India has been taken from Kumar et al. (2011). Income growth is another important factor in demand projections. Growth rates in per capita income for 2018-19 (5.9%) is taken from the first advance estimates of national income, 2018-19 (GoI, 2019) from the Ministry of Statistics and Programme Implementation, Government of India. The projected direct food demand was thus given by the following equation:

$$D_t = d_0 \times N_t (1+y_{growth} \times e)^t$$

Where,

D_t= Aggregate demand at time 't'

d_0= Base year per capita consumption demand

N_t= Projected population at time 't'

y_{growth}= Per capita Income growth

e= Income elasticity of demand

t= time period in decades

Besides direct demand, there is also an important component, which includes seed, feed, industrial uses and wastage, and has been termed as 'indirect demand'. Conventionally, the indirect demand is assumed to be 12.5% of the total food grain production. Kumar et al. (2007) computed the shares of seed, feed, wastage and other food uses as 9.5% of the total production of rice. Database from Handbook of Statistics on Indian Economy was used to predict the future production assuming *cetris peribus*. The rice production data from 1951 to 2018 was extrapolated to project the production of rice up to 2050. Following Kumar et al. (2007) the indirect demand for rice was computed for the same period. It was assumed that per capita consumption of rice is 64.1 kg/person/year (NSSO 2011-12); growth in per capita income was taken as 5.9% (GoI 2019) and expenditure elasticity was taken as 0.026 (Joshi and Kumar 2011). Calculated future demand for rice for the year 2020, 2030, 2040 and 2050 is given in Table 6.

4. Rice ecosystems in India

In India, rice is grown under highly diverse conditions with area stretching from 79° to 90°E longitude and 16° to 28° N latitude under varying agro-ecological zones. It is cultivated mostly in wet season with unpredictable rainfall distribution. It is also grown in areas, where water depth reaches 2-3 m or more. Rice culture in Kuttanad district of Kerala is grown below the sea level, while in the state of Jammu and Kashmir, it is grown upto an altitude of 2000 m above sea level; with temperature range of 15-40°C and average annual rainfall range from 30 mm in Rajasthan to more than 2800 mm in Assam. A wide range of rainfall distribution pattern (drought, submergence, deep water) and distinct differences in soils (coastal and inland salinity, alkalinity, acidity), agro-climatic situations (high humidity) and seasons has resulted in the cultivation of thousands of varieties and therefore, one can see a standing rice crop at some parts of the country or the other in any time of the year. Rice is primarily grown under four major ecosystems broadly classified as (i) irrigated, (ii) rainfed lowland, (iii) rainfed upland and (iv) flood prone.

- *Irrigated rice eco-system*: Total area under irrigated rice in the country is about 26.0 Mha accounting for about 60% of the total area under the crop. It includes the areas in Punjab, Haryana, Uttar Pradesh, Jammu & Kashmir, Andhra Pradesh, Telangana, Tamil Nadu, Karnataka, Himachal Pradesh and Gujarat.

- *Rainfed lowland rice ecosystem*: In India, lowland rice covers an area of about 12.0 Mha, which accounts for about 27% of the total area, located mainly in eastern India. The area is characterized by poor soil quality and frequent occurrence of drought/flood due to erratic rains.
- *Rainfed upland rice ecosystem*: Total area under rainfed upland rice in the country is about 4.8 Mha, which accounts for 11% of total area, located mainly in Eastern Zone i.e., Assam, Bihar, Chhattisgarh, Eastern Uttar Pradesh, Jharkhand, Madhya Pradesh, Odisha, West Bengal, and North East Hill Region. The rainfed upland ecosystem is drought prone.
- *Flood-prone rice ecosystem*: It occupies about 1.3 Mha in eastern states i.e., 3% of the country. The crop is grown in shallow (up to 30 cm), semi-deep (30-100 cm) and deep-water (>100 cm) ecosystems in eastern Uttar Pradesh, Bihar, West Bengal, Assam and Odisha.

Among the above ecosystems, further sub-systems are usually identified for location-specific variations such as 'favourable' or 'unfavourable' moisture, soil type, temperature regime, proneness to drought, submergence, both drought and submergence, growth duration (early, medium, late maturity groups) and low light intensity conditions.

Table 3 shows the area, production and productivity of rice in different agro climatic zones (ACZs). Ranking of different ACZs based on area under rice showed that Eastern Plateau zone occupies first position followed by Middle Gangetic Plains, East Coast Plains and Hill Zone. Based on production, however, the Trans-Gangetic Plains zone ranks first followed by East Coast Plains and Lower Gangetic Plains. On productivity basis, the Islands Zone comes first, followed by Trans-Gangetic Plains and Southern Plateau. Ranking of zones based on the average ranking of area, production and productivity showed that the Trans-Gangetic Plains comes first followed by East Coast Plains and Lower Gangetic Plains. East Coast Plains zone stands 3^{rd} in area, 2^{nd} in production and 3^{rd} in overall ranking.

5. Constraints in rice production in different ecosystems

The constraints of rice production vary from ecosystem to ecosystem. Some of these constraints are related to soil, some are technological and cultural, others are of extension and development; and a few are of institutional and/or infrastructural in nature. Major constraints of rice production in various ecosystems are listed below.

5.1. Upland ecosystem

- Soil moisture stress and drought due to erratic and inadequate rainfall pattern. Poor grain setting on account of heavy rainfall at flowering and germination of matured grains on the panicles (Adhya et al. 2008).

- Al and Mn toxicity, low availability of P and high P fixation capacity and N, Zn and Fe deficiency, low nutrient and water retention capacity, low organic carbon, crust formation and poor crop stand (Mahajan and Gupta 2009).
- Severe weed problem and phasic emergence of weeds.

5.2. Lowland Ecosystem

- Delayed onset of monsoon, early drought, early cessation of monsoon often results delayed transplanting and sub-optimum plant population.
- Imbalanced use of fertilizer, acid soils of poor fertility, saline soils deficient in N, P and Zn, low to very low fertilizer use, submergence in flood prone areas, early/intermittent dry spells, poor plant stand, disease/pest incidence and ineffective transfer of technology were the major constraints in achieving the potential yield (Siddiq 2000).
- Severe weed problem in dry broadcasted rice. In absence of use of herbicides, farmers practice beushening and unable to maintain optimal plant population.

5.3. Deepwater Ecosystem

- Damage to the seeds and young plants by drought conditions due to direct seeding, competition from weeds, seedling death due to sudden flooding.
- Waterlogging /stagnant flooding reduces the tillering and growth of the normal rice crop. Flash floods leading to crop failure due to slow rates of gas exchange, severe shading by turbid water, mechanical damage from strong flow rates at panicle initiation (Kar et al. 2010).
- Occurrence of multiple waves of floods causes heavy siltation of the fields, resulting in permanent loss of productive agricultural land.
- Suffers adversity from acid sulphate soils and aluminum toxicity (Puckridge et al. 2000).
- Distinctive pest complex i.e., yellow stem borer and brown spot. Farmers commonly employ cultural control methods, and insecticides are used in some areas but diseases are not treated.

5.4. Irrigated Ecosystem

- Over-mining of nutrients and/or faulty irrigation caused salinity/alkalinity, delayed planting due to uncertainty of canal water release in command areas, imbalanced fertilizer nutrient use, sub-optimal plant population, widespread micronutrient (Zn) deficiency and high incidence of pests and diseases constitute the major constraints in southern zone (Siddiq 2000).
- Salinity and deficiency of P, Ca, S, Zn, lack of ideal varieties, low fertilizer use, and submergence/moisture stress at times seriously affect productivity in the eastern and western zones.

- Drop in groundwater, high diesel price; and occasional unavailability of diesel in northern zone. Soil related constraints such as zinc and nitrogen deficiency, infestation of stem borer and false smut andwater-logging were top ranked technological constraints (Makalet al. 2017).

6. Suitable soil and climatic conditions for rice production

Rice is a crop of tropical climate. It grows well in humid to sub-humid regions. In India, rice is grown under different climatic conditions including temperate, tropical and sub-tropical and almost in all types of soil with varying productivity. Rice varieties grown in different agro-climatic regions perform differently based on degree of occurrence of climatic parameters. Climatic variables like maximum and minimum temperature, relative humidity in morning and afternoon hours, rainfall, intensity and duration of bright sunshine hours are important factors that affect phenological phases of crop, plant growth and development. The growth and ultimate yield of rice plants is extremely sensitive to these climatic conditions.

The optimum temperature for rice plant growth is 25°C to 35°C. The areas with mean annual temperature of more than 24°C are best suited for rice production (FAO 1993). The minimum temperature should not be less than 15°C at the time of germination as it is affected below that temperature. In the temperate regions, irrigated rice cultivation starts when spring temperatures are between 13°C and 20°C; the crop is harvested before temperatures drop below 13°C in the autumn wherein the tropics temperature is favourable for rice growth throughout the year and cultivation starts with the rainy season (Yoshida 1981). The optimum aerial temperatures are 22-31°C at germination, 25-30°C during day and 20-25°C during night at flower initiation, 30°C at anthesis and 23°C at ripening (Venkataraman 1987). The optimum daytime temperature is 29°C where as night temperature is 19°C during a fortnight after heading but during subsequent days it is 26°C in the daytime and l6°C at night for effective ripening (Matsushima 1967).

Moist humid weather vegetative growth and dry sunny weather during ripening is most desirable. The optimum relative humidity during rice growth period is 60-80%. A rainfall of 1000 mm to 2000 mm is ideal for rice growing. The maximum rice yield was observed in rainfall range of 1000 and 1150 mm. Variations in sunshine hours caused by varying overcast conditions greatly influence rice production in the country. The yield of rice is influenced by the solar radiation particularly during the last 35 to 45 days of its ripening period. The effect of solar radiation is more profound where water, temperature and nitrogenous nutrients are not limiting factors (Mitin 2009). Abundant sunshine is essential during its growth period, mostly a total of more than 400 h particularly during the last two months of crop growth (Sato 1956). Photo periodically, rice is a short-day plant. Photo insensitive high yielding variety performed well even at low light intensity such as 250-350 hours of bright sunshine

(Samui 1999). High yielding photo insensitive varieties now grown widely in India also respond differently to climatic conditions than that of traditional varieties.

Rice can be grown under upland conditions, under moderately submerged conditions, and in 1.5-5.0 m water (Yoshida 1981). However, flat surface are more suitable for rice cultivation. Land areas with 0-2% slope are best suitable topography for rice cultivation (Praveen et al. 2017). Clayey soils or soil having higher proportion of clay content with good water holding capacity are suitable for growing rice. Paddy soils are usually medium to fine-textured; clay-clay loams, silt loams, and silty clay loams that permit percolation of 10-20 mm water/day for high yields. Poorly drained soils are most preferred ones. Paddy crop grows best at neutral pH, but it can be grown in a pH range of 5-8 without significant reduction in yield (Sahrawat 2005). However, under high temperature, high humidity with sufficient rainfall and irrigation facilities, rice can be grown in any type of soil.

7. Characterizing rice producing areas at district level

7.1. Rice area, production and productivity in India

Rice is cultivated throughout the country (Fig. 4a). Largest *kharif* rice area is in eastern India such as Odisha, West Bengal, Eastern Uttar Pradesh, Bihar and Chhattisgarh. In North-west India, Punjab has the largest rice area. Rice productivity in eastern and north-western India is lower (<3 t ha^{-1}) as compared to southern and north-western Indian states (>3 t ha^{-1}) (Fig. 4b).

Rabi rice in India is cultivated in eastern, north eastern and southern states (Fig. 5a). District wise *rabi* rice area is higher in Andhra Pradesh and West Bengal. In Odisha almost all the districts have some *rabi* rice area. *Rabi* rice productivity in some districts of Andhra Pradesh was >5 t ha^{-1} and it is 3-5 t ha^{-1} in West Bengal and some districts of Odisha and north-eastern states (Fig. 5b). In most of the *rabi* rice growing districts, average productivity is <3 t ha^{-1}. Summer rice area for different districts of India is presented in Fig. 6a. Except few districts the summer rice area in all the districts is less than 25000 ha. Productivity of summer rice in districts of southern states is comparatively higher than eastern states (Fig. 6b). The lowest productivity among the summer rice growing states is found in Odisha.

7.2. Climatic and soil characteristics of rice growing areas in India

Rainfall distribution pattern in India is depicted in Fig. 7. In all the North Eastern states annual rainfall is >1500 mm and Eastern states such as Odisha, West Bengal, Bihar and Chhattisgarh receive 1000-1500 mm rainfall, which is favorable for rice cultivation. The mean air temperature variation is shown in Fig. 8. In most of the eastern, central and northern part, the air temperature is in the range of 27.5-30°C, which is most favorable for rice cultivation.

Most of the eastern and north-eastern states of India have >30% clay in soil (Fig. 9). The northern states have <30% clay in soil. For rice cultivation, high percentage of clay is favorable because it helps in retention of water and minimizes the percolation of water from the soil profile.

8. Delineating the suitable zones for rice production

Rainfall, temperature and soil are the three most important biophysical factors for growing rice. In the analysis of suitable areas for growing rice, these three biophysical factors were considered. Rice is a water-loving crop as a result its cultivation should be done in the areas where average annual rainfall is 1000 mm. Regions with average annual rainfall >1500 mm or more are the most suitable. Temperature is a very important factor influencing growth, development and yield of rice. Rice being a tropical and sub-tropical plant requires a fairly high temperature, ranging from 20° to 30°C. The optimum temperature of 30°C during day-time and 20°C during night time seems to be more favourable for the development and growth of rice crop. Temperature beyond 35°C affects grain filling. Clayey loam soil (27-40% clay content) in monsoon land is considered to be the best for rice cultivation as water retention capacity of this soil is very high.

In the present analysis, rainfall, air temperature and soil texture were considered as the major contributing factors for deciding the area for rice cultivation. District-wise data regarding annual mean rainfall, soil texture and mean air temperature was collected from various sources (IMD; NBSSLUP). Rice suitability index was developed using the following equation.

*Rice suitability index = 0.6 * Annual rainfall (mm) + 0.4 * Clay content of soil (%) - 0.1 * Mean seasonal air temperature (°C)*

Using the suitability index, various suitability classes for growing rice were delineated using the classification given in Table 7. All the districts of the country were grouped into different zones for suitability classes for growing rice using the values mentioned in Table 7. Data was then imported into ArcGIS 10 and rice suitability zone map was prepared (Fig. 10). TheNorth-Eastern states fall under very suitable zones for rice cultivation. Whereas the Eastern states such as Odisha, West Bengal, Chhattisgarh are under suitable or very suitable category. Most of the central India fall under moderately suitable zone and North Western states are in unsuitable rice cultivation zones (Fig. 10).

The number of districts under very suitable, suitable, moderately suitable and unsuitable zones are 145, 196, 115 and 207 representing 21.9%, 29.6%, 17.3% and 31.2%, respectively of all the districts of India. Out of 663, 145 districts covering 19% *kharif* rice area, are under unsuitable category contributing around 23% of the rice production in the country. Whereas 31% rice area coming under very suitable category but contributing to only 29% of the rice production of the country. These unsuitable districts are located in 15 states but only five states (Punjab, Haryana, Gujarat, Rajasthan and Uttar Pradesh) constitute 93% of these unsuitable rice cultivated areas as well as production while 21% of rice production of the country comes from these region.

During green revolution era, the north-west parts of the country shifted from their traditional crops (maize, pearl millet, pulses and oilseeds) to the paddy-wheat cultivation cycle. During those years, the major focus was to ensure the food security for the country but at present groundwater levels have fallen in these parts especially in Punjab and parts of Haryana to alarming levels.

Average water footprint (m^3 ha^{-1}) from the four states i.e., Punjab, Haryana, Gujarat and Rajasthan was around 18% higher than average rice water footprint (WF) for India. Since productivity in these regions are high due to extensive use of fertiliser and chemicals, the water footprint of rice per unit of produce is 4% lesser compared to all India average (Unpublished). While north-west parts of India (Punjab and Haryana) have highest rice productivity (4t ha^{-1}), the Irrigation water productivity (IWP) for these states is relatively low (0.22 kg m^{-3}) reflecting the inefficient irrigation even though 100% irrigation coverage. In contrast, Chhattisgarh and Jharkhand, recorded higher IWP at 0.68 kg m^{-3} and 0.75 kg m^{-3}, even though they had substantially lesser irrigation coverage at 32% and 3%, respectively. But rice productivity in these states is low because of low irrigation and input use. Only four states Punjab, Haryana, Gujarat and Rajasthan (categorised as unsuitable) having 10% of *kharif* rice area of the country, contribute to 19% whereas Punjab alone contributes to 12% of the CF from rice fields (Unpublished). Highest carbon footprint (CF) from rice fields in India was estimated from Punjab (4919 CO_2 eq. ha^{-1}), which is almost double than the average CF (2245 CO_2 eq. ha^{-1}) for Indian rice field.

Shifting the major chunk of rice production to India's central and eastern states like Chhattisgarh and Jharkhand, while diversifying the rice growing areas in the rice-growing regions of Punjab and Haryana, could help India prevent an impending water crisis (Sharma et al. 2018).

9. Optimizing productivity in the suitable zones to meet future rice demand

As discussed above, total rice cultivated area of the country has been divided into four distinct zones. Current rice production in *kharif* from all the zones is 97.10 Mt. If assumed that the cultivation of rice crop in all the unsuitable zones is abandoned at this point of time, the total *kharif* production would slump down to 74.69 Mt only. Therefore, rice production from other three zones must have to be increased to compensate for the production losses so that food security of the country is not disturbed. Moreover, these so called suitable zones should also produce more rice to meet the future demand (Table 8). We assessed the required increase in rice production from these areas to meet these requirements. The assessment showed that 30% increase in production will be required to meet the demand of rice by 2030 (Table 8).

10. Strategies for enhancing productivity and profitability of rice production

The following strategies should be adopted for increasing productivity and profitability of rice farming in the suitable zones.

10.1. Promoting high-yielding varieties and hybrids: Due to unavailability of the quality seeds of high yielding varieties and high seed cost of the hybrids, farmers are unable to get those seeds and they prefer to grow their local seed materials. The yield potential of local seeds is low and they are susceptible to many pests and diseases. Although many government programmes are in operation for making HYV and hybrids seeds available to the farmers, thus there is ample scope of promoting high-yielding varieties and hybrid. Further, improved market support will encourage the farmers for adopting high yielding varieties and hybrids.

10.2. Providing quality seed and enhancing seed replacement ratio: Seed is the critical determinant of agricultural production on which the performance and efficacy of other inputs depends. Quality seeds appropriate to different agro-climatic conditions and in sufficient quantity at affordable prices are required to raise productivity. Availability and use of quality seeds is not a onetime affair. Sustained increase in agriculture production and productivity necessarily requires continuous development of new and improved varieties of crops and efficient system of production and supply of seeds to farmers. Despite a huge institutional framework for seed production both in the public and private sector, availability of good quality seeds continues to be a problem for the farmers. As a result, they prefer to rely on farm saved seeds; seed replacement rate continues to remain low for most crops. As is well known, seed replacement rate has a strong positive correlation with the productivity and production of crops.

10.3. Promoting water harvesting and micro-irrigation: In many farming areas, readily available water is in short supply. Although the total annual rainfall in an area may be enough to sustain farm needs, it is often distributed very unevenly so that long dry periods are interspersed with periods of intense rainfall. In many cases, a crop is unable to use a high proportion of this water, as much of it is lost through run off or leaching. This may also cause soil erosion and loss of soil nutrients. Hence, there is need to promoting water harvesting and micro-irrigation to achieve per drop more crop. Further adoption of water saving technologies such as direct seeding of rice and system of rice intensification can save water. For surface-irrigated areas, a properly levelled surface with the required inclination according to the irrigation method is absolutely essential. Traditional farmers' methods for levelling by eyesight, particularly on larger plots, are not accurate enough and lead to extended irrigation times, unnecessary water consumption, and inefficient water use. With laser levelling, the unevenness of the field is reduced resulting in better water application and distribution efficiency, and improved water productivity.

10.4. Using soil health card and site-specific nutrient management:

The soil health card carries crop wise recommendations of nutrients/fertilizers required for farms, making it possible for farmers to improve productivity by using appropriate inputs. Under current management practices, nutrient use efficiency are low and farmers often fail to apply nitrogen, phosphorous and potash in the optimal ratio to meet the need of crops. Site-specific nutrient management (SSNM) provides an approach for feeding crops with nutrients as and when needed. The SSNM eliminates wastage of fertilizer by preventing excessive rates of fertilizer and by avoiding fertilizer application when the crop does not require nutrient inputs.

10.5. Promoting farm mechanization and solar energy: Intensification of mechanization is one of the most important factor for increasing agricultural activities and production as well. Productivity of farms depends greatly on the availability and judicious use of farm power. Agricultural implements and machines enable farmers to employ the power judiciously for production purposes. Agricultural machines increase productivity of land and labour by meeting timeliness in farm operations. Mechanization has the advantages of proper utilization of resources, reducing drudgery in farm operations, timely execution of various agricultural operations and best use of the available soil moisture, switching over from animal power to mechanical and electrical power for enhanced power availability for various farm operations, reduce cost of operation, and crop diversification. Promoting use of renewable energy in farm equipment segment such as solar-powered pumps may have the immense potential in farm operations and can create alternate source of revenue for the farmer by selling the additional power.

10.6. Adopting plant protection measures: Plant protection continues to play a significant role in achieving targets of crop production. The major thrust areas of plant protection are promotion of integrated pest management (IPM), ensuring availability of safe and quality pesticides for sustaining crop production from the ravages of pests and diseases, streamlining the quarantine measures for accelerating the introduction of new high yielding crop varieties, besides eliminating the chances of entry of exotic pests. Crop losses due to pests and diseases occur despite increased pesticide use, which highlight the need to develop sustainable approaches for pest control with less reliance on chemical inputs. To address concerns regarding human health, environmental safety and pesticide resistance, plant defensive traits could be exploited more widely in crop protection strategies. Further, it is essential to have a pest monitoring system, which will check the spread of disease pest and the crop loss.

10.7. Policy and infra-structure needs

Unless the government policies should target on ecoregion cultivation of rice, this herculean task can never be achievable. Like the subsidies on promotion of new varieties for seed, the government policies should also target on incentivizing the cultivation of rice in zones, which are suitable for cultivation or in the zones where the social cost of rice cultivation is lesser than that of private cost.

The intensity of rice cultivation has direct linkage with the development of market in the region and operation of procurement operation as in case of Western states like Punjab and Haryana which provide major chunk to the central pool of food grains owing to their well developed market infrastructure and procurement policies although these states are unsuitable for rice cultivation. Therefore, the thrust should be given on market development in the suitable zones for reaping the future benefits from these zones. Bisen and Kumar (2018) classified the challenges of market development in terms of implementation of e-NAM as 3I's (Infrastructure, Institution and Information). These 3I's can be a game changer for Indian farmers and key pull factors for attaining the ecoregion concept of rice cultivation.

Moreover, the operation of MSP and procurement operation in Eastern states are not so impressive as in Western states. The NITI Ayog (2016) reported that in a few selected States in Eastern India (for instance, Assam and West Bengal), the poor impact of the MSP scheme may be judged by the fact that none of the selected farmers were even aware. Thus, these regions attract very high priority in terms of awareness creation about such schemes of the government and investments necessary for infrastructure (Primary Procurement Centers, Storage and warehousing and functional agricultural markets) development to enable the ecoregion crop planning in future.

Institutional reforms are necessary to generate collective actions through co-operative avenues to overcome the development deadlock created due to small and uneconomical holding sizes. This is essential not only to enhance collective bargaining power of the farmers but also to inculcate the spirit of submerging the personal interests in collective welfare. Earlier system of co-operative farming, emerging group approaches such as the self-help groups (SHGs) and prospects of creating farmers' corporations need to be explored thoroughly.

The Agri-Business Incubation (ABI) program aim to promote entrepreneurs in public-private partnership mode that maximizes the success quotient of start-up entrepreneurs by offering them best opportunities with minimum risk. Effective communication, coordination and cooperation among the various nodal centres, umbrella consortium and the industry are inevitable for the successful implementation of the schemes.

11. Conclusions

In order to meet future rice demand, increasing production and productivity of rice is essential. This has to be done in the face of growing shortage of land, labour and water for rice farming. As the profit margin in rice cultivation has decreased, there is need to not only increase in yield per se but also bring efficiency in input use in rice production. The goal of rice research should be in developing profitable and resilient rainfed rice farming system with a vision of enhancing productivity, profitability and resilience for ever-green rice farming with high-quality research, partnership and leadership in rice science. The thrust areas research should include (1) genetic enhancement for improving productivity, quality and climate resilience of rice; (2) ecosystem management for higher input-efficiency and lower environmental footprints; (3) value-addition with improved quality, co-farming, processing and marketing and (4) accelerating technology delivery, capacity building and policy formulation. The rice-research in the past has made immense contributions in developing and demonstrating technologies for improved rice farming. It, however, needs to be strengthened to address the emerging challenges of low productivity and low income of rice farmers in the face of environmental changes. A multi-disciplinary and participatory research should be adopted to address the emerging challenges and make rice farming more productive, profitable and climate resilient.

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Annexure

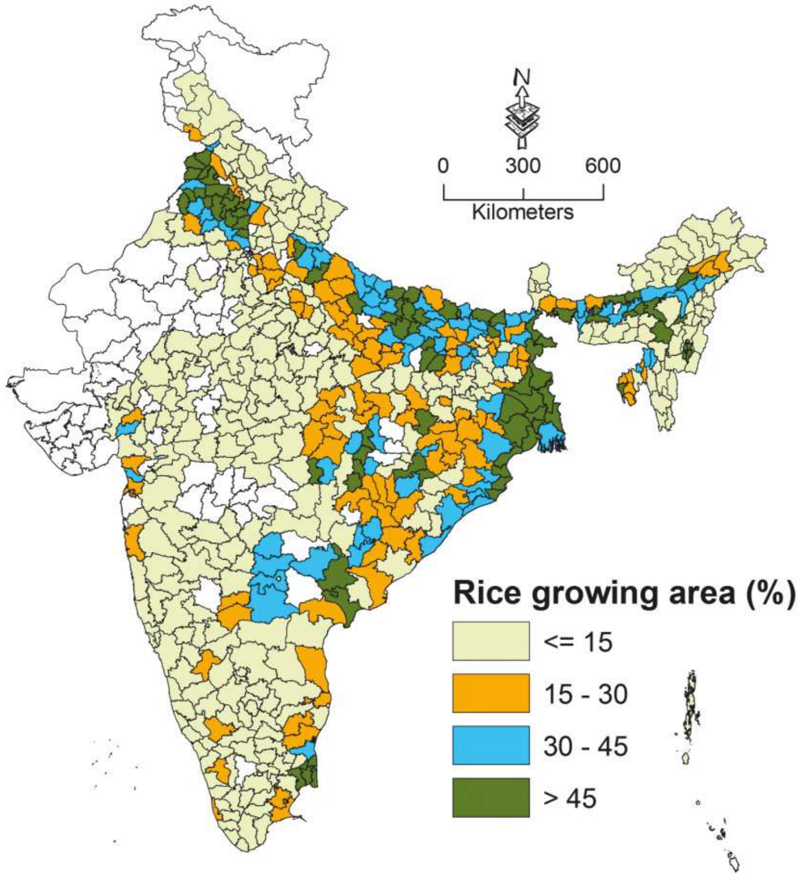

Fig. 1. District-wise rice area in proportion to total agricultural area in India.

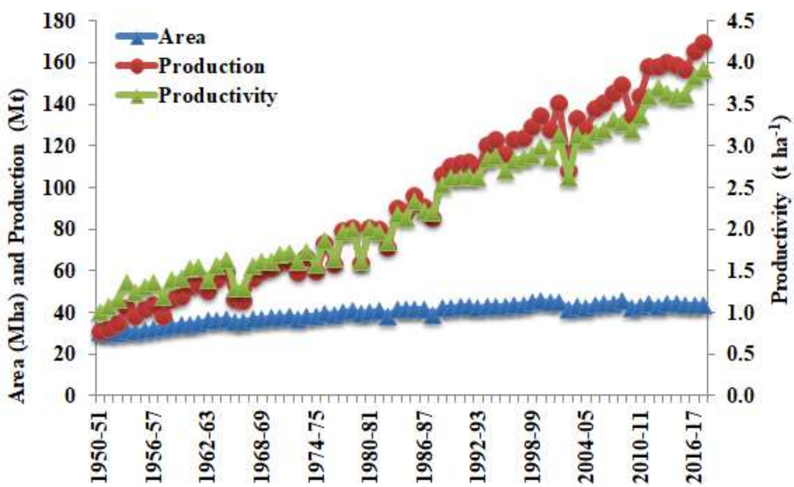

Fig. 2. Area, production and productivity of rice in India over the years. *Source: Pathak et al. (2019)*

Fig. 3. Rice and sustainable development goals. *Source: Pathak (2018)*

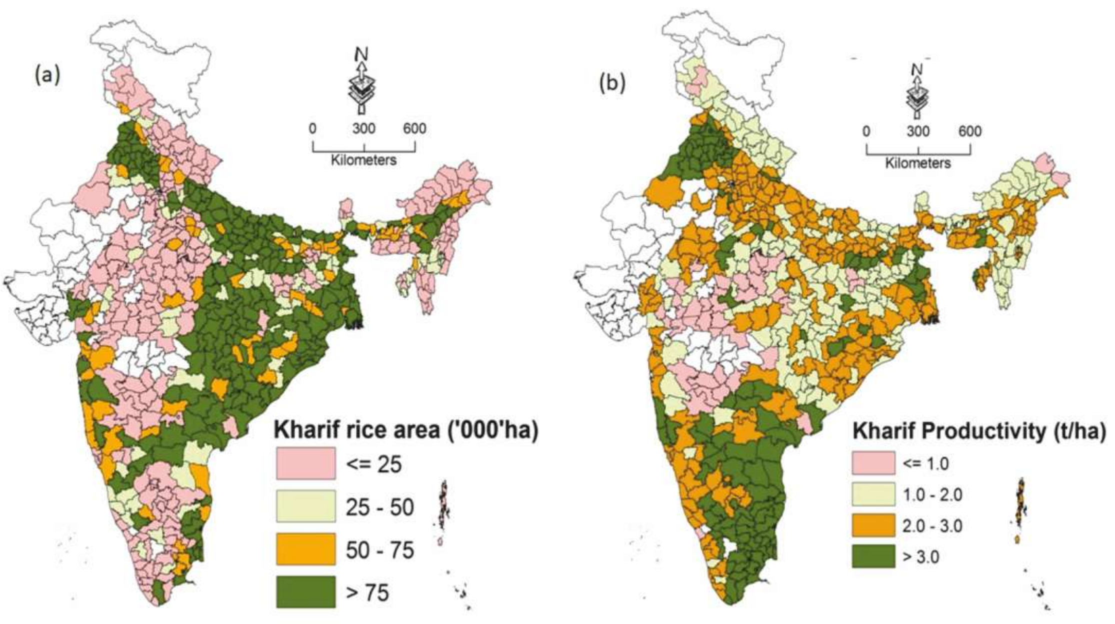

Fig. 4. District wise (a) *kharif* rice area and (b) productivity in India.

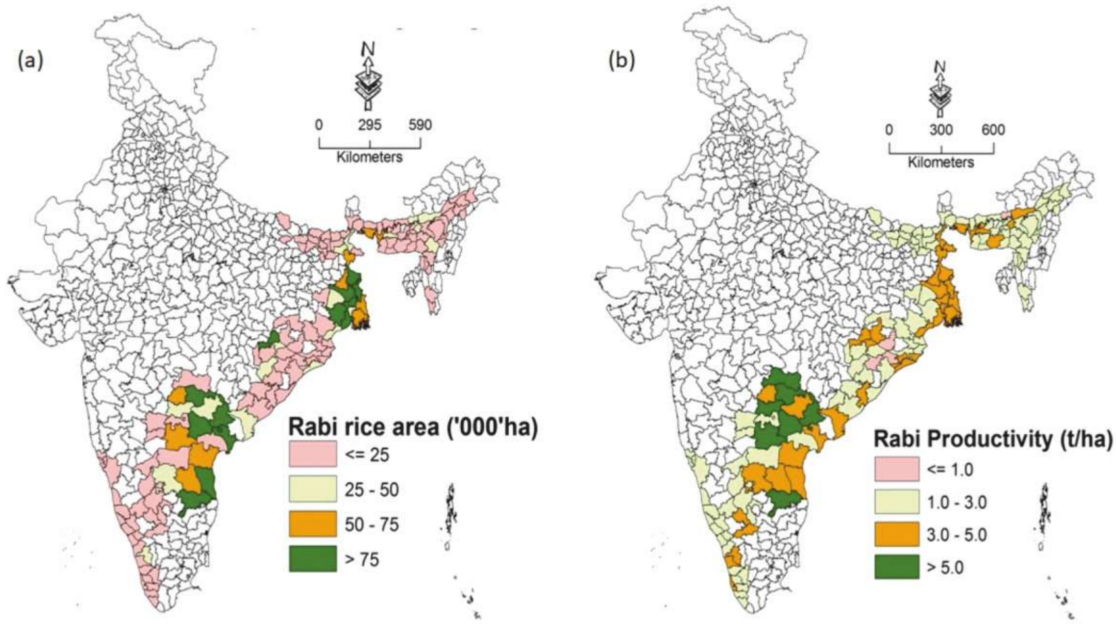

Fig. 5. District wise (a) *rabi* rice area and (b) productivity in India.

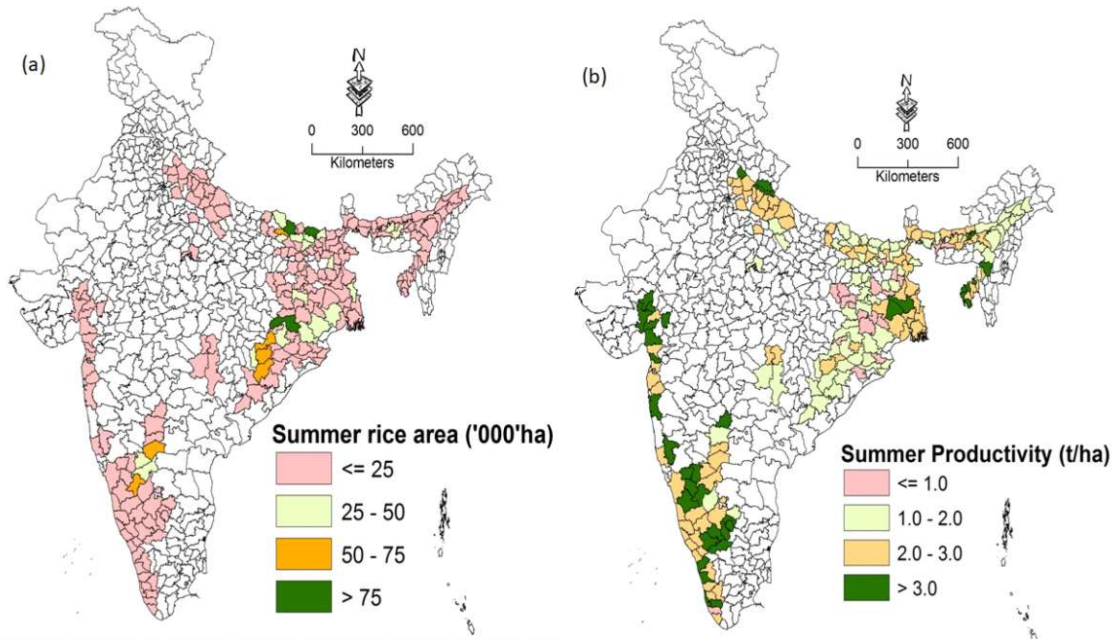

Fig. 6. District wise (a) summer rice area and (b) productivity in India.

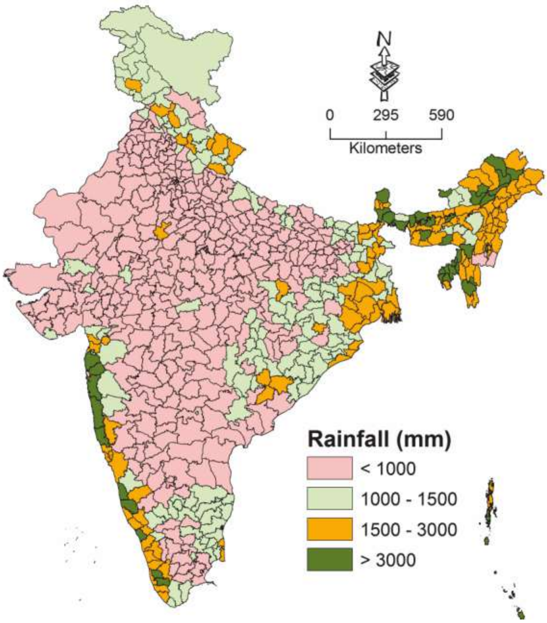

Fig. 7. District-wise rainfall map of India.

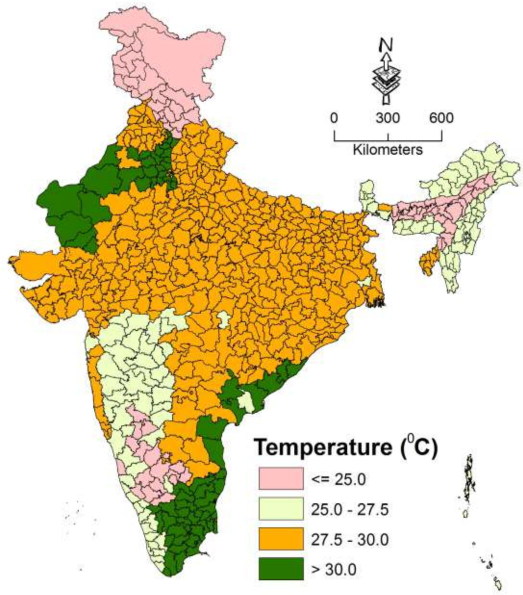

Fig. 8. District-wise temperature map of India.

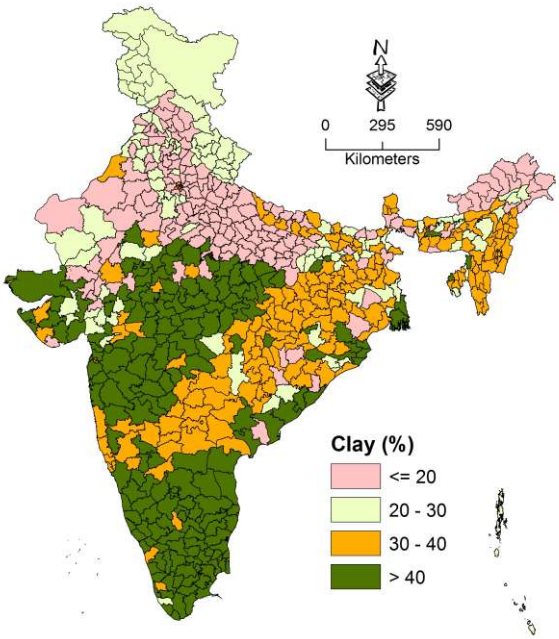

Fig. 9. District-wise clay content of soils of India.

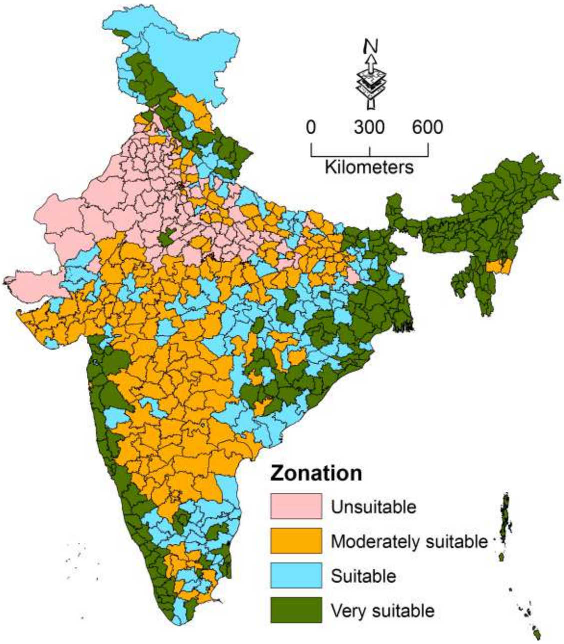

Fig. 10. Suitability of rice areas in India.

Table 1. Global and Indian scenarios of rice.

Parameters		World	India
1.	Production (Mt)	500 (milled rice), 750 (paddy), 1875 (residues)	112 (milled rice), 170 (paddy), 425 (residues)
2.	Feeding people (billion)	4 (56% of population)	0.8 (65% of population)
3.	Area (Mha)	166 (10% crop land)	43 (22% crop land)
4.	Grown by families (million)	144 (25% of farmers)	67 (56% of farmers)
5.	Livelihood to rural poor (million)	400 (40% of poor)	150 (40% of poor)
6.	Annual value (US$ billion)	206 (13% of crop value)	53 (17% of crop value)
7.	Irrigation wateruse (km^3 yr^{-1})	880 (35% of total)	200 (29% of total)
8.	Fertilizer use (Mt yr^{-1})	25 (15% of total)	6.5 (37% of total)
9.	Methane emission (Mt yr^{-1})	25 (12% of agriculture)	3.5 (18% of agriculture)

Source: Pathak et al. (2019a)

Table 2. Area, production and productivity of paddy in different states of India (2017-18).

State	Area (Mha)	Production (Mt)	Productivity (t ha^{-1})
Uttar Pradesh	5.81	19.91	3.42
West Bengal	5.12	22.45	4.39
Odisha	3.77	9.83	2.61
Chhattisgarh	3.76	7.40	1.97
Bihar	3.31	12.14	3.67
Punjab	3.07	20.07	6.55
Assam	2.43	7.93	3.26
Andhra Pradesh	2.16	12.25	5.68
Madhya Pradesh	2.04	6.19	3.04
Telangana	1.96	9.39	4.79
Tamil Nadu	1.83	9.96	5.45
Jharkhand	1.74	6.12	3.53
Maharashtra	1.45	4.10	2.82
Haryana	1.42	6.79	4.77
Karnataka	0.99	4.53	4.56
Gujarat	0.86	2.84	3.31
Others	2.07	7.27	3.51
India	43.77	169.14	3.86

Source: Department of Agriculture, Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India (2019)

Table 3. Area, production and productivity of rice in different agro-climatic zones.

Agro-climatic Zones	Area (Mha)	Production (Mt)	Productivity (t ha^{-1})
Western Himalayan	0.69	1.68	2.43
Eastern Himalayan	3.98	13.16	3.31

Lower Gangetic Plains	4.73	21.14	4.47
Middle Gangetic Plains	5.94	17.97	3.03
Upper Gangetic Plains	3.19	11.12	3.48
Trans-Gangetic Plains	4.27	23.81	5.57
Eastern Plateau & Hills	8.03	16.04	2.00
Central Plateau & Hills	1.70	4.34	2.55
Western Plateau & Hills	0.51	1.23	2.41
Southern Plateau & Hills	2.41	11.30	4.69
East Coat Plains & Hills	5.31	23.46	4.42
West Coast Plains & Ghats	0.98	3.86	3.93
Gujarat Plains & Hills	0.72	2.30	3.19
Western Dry	0.03	0.14	4.67
The Islands	0.01	0.03	3.00
India	42.5	151.6	3.86

Source: Updated from Pathak et al. (2019c)

Table 4. Area and productivity of rice in different seasons and ecosystems.

Ecologies	Area (Mha)	Productivity (t ha^{-1})
Kharif Irrigated Area	21.1	5.0-6.0
Kharif Rainfed Upland	4.8	1.5-2.0
Kharif Rainfed Lowland	11.8	3.0-4.0
Kharif Deepwater	1.3	2.0-2.5
Rabi/Summer Irrigated	4.5	3.5-4.5
India	43.5	1.5-6.0

Table 5. Changes in area, production and productivity of rice in different states during 1990-91 to 2017-18.

State	Area (%)	Production (%)	Productivity (%)
Andhra Pradesh	0.06	1.30	1.23
Arunachal Pradesh	0.33	2.89	2.55
Assam	-0.08	1.74	1.82
Bihar	-0.40	1.98	2.39
Goa	-1.01	-0.73	0.28
Gujarat	1.46	3.59	2.10
Haryana	2.65	3.38	0.71
Himachal Pradesh	-0.55	0.72	1.27
Jammu & Kashmir	0.02	0.58	0.56
Karnataka	0.03	0.90	0.87
Kerala	-4.43	-3.05	1.45
Madhya Pradesh	0.38	2.28	1.90
Maharashtra	-0.02	0.93	0.95

Manipur	1.29	0.98	-0.31
Meghalaya	0.24	3.49	3.25
Mizoram	-2.27	-2.77	-0.51
Nagaland	1.73	3.96	2.19
Orissa	-0.43	1.09	1.53
Punjab	1.45	2.39	0.92
Rajasthan	0.26	3.49	3.22
Sikkim	-1.82	-0.66	1.18
Tamil Nadu	-0.82	-0.80	0.02
Tripura	0.04	2.08	2.04
Uttar Pradesh	0.46	1.32	0.85
West Bengal	-0.32	1.22	1.54
Dadra & Nagar Haveli	0.18	0.78	0.61
Pondicherry	-1.92	-1.09	0.85
India	**0.09**	**1.45**	**1.36**

Source: DAC (2019)

Table 6. Demand for rice for the year 2020, 2030, 2040 and 2050.

Year	Population (Billion)	Demand for rice (Mt)		
		Direct	Indirect	Total demand
2020-21	1.38	99.39	10.61	110.00
2030-31	1.51	125.39	11.90	137.29
2040-41	1.60	153.45	13.20	166.65
2050-51	1.65	182.90	14.49	197.40

Table 7. Delineation of suitability classes for growing rice.

Suitability class		Suitability Index
1.	Very suitable	>800
2.	Suitable	600-800
3.	Moderately suitable	400-600
4.	Unsuitable	<400

Table 8. Current and required production scenarios of kharif rice in India.

Production scenario		Production (Mt)
1.	Current production	97.10
2.	Current production in suitable areas	74.68
3.	10% increase in production in suitable areas	82.15
4.	20% increase in production in suitable areas	89.62
5.	30% increase in production in suitable areas	97.08
6.	40% increase in production in suitable areas	104.55

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150 YEARS OF CELEBRATING THE MAHATMA

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