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New district-level maps of rice cropping in India: A foundation for scientific input into policy assessment☆

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Abstract

We combined several district-level and state-level data sets of rice cropping in India to develop a single dataset of district-level rice cropping systems for all of India in 1999–2000. The data set contains district-level areas for 34 different single-, double-, and triple-cropping combinations (e.g., rice–rice, rice–rice–pulse, rice–pulse–fibrecrop, rice–wheat, and rice–fallow). The dataset specifies cropping by season (e.g., Kharif and Rabi) and area in two water management systems (irrigated or rainfed) for each cropping system in each district. The total rice sown area is 44.9 million hectares (Mha), 91% in the Kharif (wet) season. Total rice land area was 41.6 Mha, with upland rice accounting for 13% of this area. Rainfed rice (including upland and deepwater) accounted for 44% of the total rice sown area, and rice–fallow for 38% of the total rice sown area. The total multiple cropping area with rice occupied 17.6 Mha, with dominant systems being rice–wheat (8.8 Mha), rice–pulse (3.2 Mha), rice–rice (2.2 Mha), and rice–oilseed (1.2 Mha, including rice–groundnut). We combined these maps with a simple, monthly time-step water balance model to estimate irrigation water demand for irrigated rice by district; total national demand was 200 $km^3\ y^{-1}$. A complete national, district-level set of maps and data of rice cropping systems and water management will be useful as inputs to a range of studies on agricultural productivity, resource use, and environmental impacts of rice agriculture.

Keywords: Rice paddy; Cropping area; Irrigation; Rainfed; Multiple cropping; Water use

1. Introduction

Agriculture is a dominant form of human land use, with crop and pasture land occupying nearly 40% of the earth's land surface (FAOSTAT, 2005). Conversion of natural landscapes to managed agriculture can have significant environmental impacts, including effects on floral and faunal biodiversity, the surface energy balance and weather, water use and the water cycle, nutrient cycling and nutrient leaching to groundwater and surface water, greenhouse gas emissions, and soil degradation (e.g., Vitousek et al., 1997; Matson et al., 1997; Goudie, 2000). With human population expected to increase by about 3 billion in the coming 50 years (Lutz et al., 2001), agriculture's impact on the environment will continue to be large (Tilman et al., 2001). Quantifying and predicting these impacts requires both an understanding of and ability to model the relevant processes. Reliable and detailed multi-scale geo-spatial datasets of the distribution of agriculture and agricultural management practices are required.

Rice is a dominant crop; about 20% of global total human food calories are supplied by rice (Maclean et al., 2002). More than 150 million hectares were sown with rice in 2002, 90% of that in Asia (Maclean et al., 2002). Demand for rice in Asia is projected to increase by 70% over the next 30 years (IRRI, 2002; Hossain, 1997). Rice agriculture is a major consumer of water. Agricultural water use accounts for about 70% of global freshwater consumptive demand globally, and 86% of Asia's freshwater demand (FAO, 1999; IRRI, 2002). More than 90% of rice production in Asia is from flooded paddy fields (Huke and Huke, 1997). Flooded rice paddies contribute about ~10% of total global emissions to the atmosphere of the greenhouse gas methane (Prather et al., 2001).

☆ Upon publication, the maps and data will be made freely available in several formats over the internet at http://www.eos-webster.sr.unh.edu.

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At ∼45 million hectares, India has the largest national area of rice cropping (FAOSTAT, 2005). Much of this rice area is multi-cropped, and cropping patterns are very diverse; Yadav and Subba Rao (2001) report, for 17 of India's 27 states, district-level areas for 105 crop rotations that include rice. While most rice is grown in the Kharif-season (wet-season, roughly July–December), rice is also grown in the Rabi-season (dry-season, roughly January–June) in many states (Yadav and Subba Rao, 2001). Approximately 55% of India's rice crop is irrigated, up from about 45% in 1990; the fraction of rice area that is irrigated varies by state from <50% irrigated in Madhya Pradesh, Maharashtra, and Bihar, to >90% in Punjab, Tamil Nadu, Andhra Pradesh, and Haryana (Chanda et al., 2003).

These varied cropping systems occur across a varied environment (e.g., weather, soils, topography), so quantitative assessment of a number of the 'outputs' of agriculture (e.g., crop yield, water use, soil erosion, nutrient leaching, greenhouse gas emissions) will benefit from detailed geospatial datasets of cropping systems and environmental variables. Existing national level individual rice datasets do not contain sufficient information on the nature of the cropping systems (seasonality of cropping, water management, non-rice crops in the rotation) to quantitatively evaluate environmental impacts.

In this paper we synthesize a number of statistical or census data sets to generate a new map of rice cropping in India for the cropping year 1999–2000, using district- and state-level data from datasets with complete national coverage wherever possible. The synthesis of several data sets also identifies inconsistencies, likely errors, and/or inadequacies of the individual data sets. We use more current and more general datasets to update a dated but more specific dataset, making only very general assumptions and applying them to the entire dataset. We add complexity to a single dataset by combining features of different datasets. We constrain the new data product to match the most reliable estimates of the extent of rice cropping. The outcome of this type of data synthesis is a new geospatial data set that provides essential input data for regional analyses. The new dataset is consistent with as many of the primary source data sets as possible, but provides an internally consistent data set that extends the individual input data set it was built from.

2. Data and methods

2.1. Datasets and gap-filling

Our district-level GIS base map came from the International Rice Research Institute (IRRI) database for India (Huke and Huke, 1997), has 467 districts across 26 states, and represents the political boundaries from the early- to mid-1990s (Fig. 1). Since that time, political reorganizations have occurred, with new states (Uttaranchal separated from Uttar Pradesh, Chhattisgarh separated from Madhya Pradesh, and Jharkhand separated from Bihar) and new districts. Generally district boundary changes occurred when a single district was split into two districts. We matched all district-level data lists to our base map districts list, combining two or more new districts into one old district as necessary, based on comparison of new maps of political boundaries from Maps of India (http://www.mapsofindia.com) with our base map.

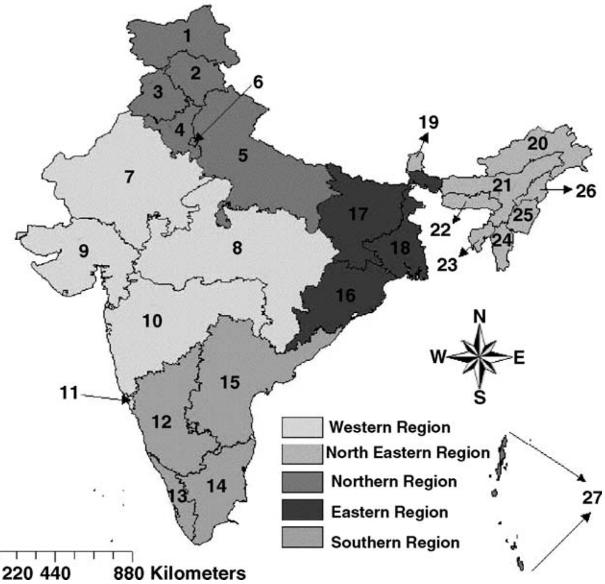


Fig. 1. States and regions of India. Northern region: (1) Jammu & Kashmir; (2) Himachal Pradesh; (3) Punjab; (4) Haryana; (5) Uttar Pradesh; (6) Delhi. Western region: (7) Rajasthan; (8) Madhya Pradesh; (9) Gujarat; (10) Maharashtra; (11) Goa. Southern region: (12) Karnataka; (13) Kerala; (14) Tamil Nadu; (15) Andhra Pradesh; (27) Union Territories (only Andaman and Nicobar shown). Eastern region: (16) Orissa; (17) Bihar; (18) West Bengal. North-eastern region: (19) Sikkim; (20) Arunachal Pradesh; (21) Assam; (22) Meghalaya; (23) Tripura; (24) Mizoram; (25) Manipur; (26) Nagaland.

We used five primary data sources to develop district-level rice crop rotations for all of India (Table 1):

- Huke and Huke (1997) (hereafter H&H) provided district-level rice sown areas by water management: upland, deepwater, wet-season irrigated, dry-season irrigated, and rainfed rice, based on data from the early- to mid-1990s; total rice sown area for India was 42.8 Mha.
- The Directorate of Rice Development (DRD, 2004) provided district-level rice sown area in 1999–2000 (total of Kharif plus Rabi seasons); total rice sown area for India was 44.9 Mha.
- Yadav and Subba Rao (2001) (hereafter Y&SR) provided areas of the three primary crop rotations of most districts in most states of India, but no information on less dominant rotations. Altogether they provide district-level areas for 105 different rice cropping systems (e.g., rice–rice–rice, rice–wheat, rice–fallow), as well as numerous non-rice rotations (e.g., wheat–maize) for 400 districts in 17 states. Total reported sown area of rice was 27.6 Mha. We first simplified the list of crop rotations by combining

Table 1
Datasets used to generate the new district-level maps of rice cropping in India

Datasets	Year	Domain	Source	Notes
1. District-level rice area by water management	c. 1990	All India	Huke and Huke (1997)	Baseline dataset, includes rice sown area of several water management classes: upland, deepwater, irrigated wet (Kharif) season, irrigated dry (Rabi) season, and rainfed
2. District-level total rice area	1999–2000	All India	DRD (2004)	Used to update dataset #1 to 1999–2000, maintaining same fractional area in each water management class as in dataset #1. Also filled ∼10 data gaps in dataset #1
3. District-level major crop rotations	1999–2000	17 states[a]	Yadav and Subba Rao (2001)	Used to specify areas of up to three dominant rice cropping systems in each district (e.g., rice–rice, rice-wheat, etc.). Areas were constrained not to exceed total district area or total Rabi-season area from datasets #1 and #2
4. District-level crop area by season	1999–2000	7 states[b]	NERDB (2005)	Used to supplement dataset #3 for major crop rotations in north-eastern states (see text)
5. State-level rice area by season	1999–2000	All India	FAO-RAP (2005)	Used to update Rabi-season area of dataset #1 (‘dry-season irrigated’). Increases (decreases) in Rabi-season area were offset by decreases (increases) in rainfed area. There was no change in total, upland, or deepwater areas
6. State-level irrigated fraction of rice area	1999–2000	All India	FAO-RAP (2005)	Used to update irrigation fraction from dataset #1. All increases (decreases) in irrigation area were offset by losses (gains) in rainfed area. There was no change in total, upland, or deepwater areas

[a] Andhra Pradesh, Assam, Bihar, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, and West Bengal.
[b] Sikkim, Arunachal Pradesh, Nagaland, Mizoram, Meghalaya, Tripura, and Manipur.

similar crops into single classes (e.g., all grams and other pulses into a single ‘pulse’ class), so the final crop types were rice, pulse, wheat, potato, oilseed, fibrecrop, groundnut, millet, vegetable, barley, sorghum, sugarcane, and fallow. There were no data for some districts within states for which Y&SR reported data. We filled these gaps by assigning the district’s total rice area from DRD data across all Y&SR crop rotations based on the state average proportions in each rotation for districts that had reported values. The total rice area allocated in this manner was 1.75 Mha in 14 districts. Finally, we aggregated together similar rotations in which one representative had much less area than the other. For example, rice–rice–pulse had 40,761 ha in Y&SR, while rice–pulse–rice had 904 ha; we combined this into 41,665 ha of rice–rice–pulse. This reduced the total number of Y&SR rotations to 34 (Table 2). In all cases, we have assumed that the first rotation listed is Kharif-season, although this is not specified in Y&SR.

- There were no Y&SR data for the complete states of Sikkim, Arunachal Pradesh, Nagaland, Mizoram, Meghalaya, Tripura, Manipur, Goa, the Union Territories, and the Andaman and Nicobar Islands. In the DRD database, these states contain a rice area of 0.9 Mha. We supplemented the Y&SR dataset with estimates of areas of three dominant crop rotations for these remaining states. For states in north-eastern India (Sikkim, Arunachal Pradesh, Nagaland, Mizoram, Meghalaya, Tripura, and Manipur), we used season-wise crop area data from the North Eastern Region Databank of India (NERDB, 2005) to estimate crop rotations. We first scaled district-wise rice area from H&H to the DRD district-wise total areas. We then identified the dominant three crop rotations based on season-wise crop data from the NERDB database. We sorted seasonal crop data by area, and created double-cropping rotations based on the dominant crops in each season. The dominant rotation would be a Kharif–Rabi rotation of the two seasonal dominant crops, with an area equal to the smaller of the two seasonal dominant crops. These areas were then subtracted from the seasonal crop data, and the second dominant double crop rotation was determined in the same manner, and then the third. For Goa and the Union Territories (Dadra & N. Haveli, Diman, Diu, Karaikal, Mahe, Pondicherry, and Yanam), we used the same major crop rotations as their neighboring, and much larger states, scaling areas to the same proportion of total rice sown are. For the Andaman and Nicobar Islands we assumed that all rice was in a rice–fallow rotation, as we had no independent data. This complete dataset is hereafter called Y&SR*.
- The Regional Data Exchange System of the FAO Regional Office for Asia and the Pacific (FAO-RAP, 2005) reported two additional state-level data sets for 1999–2000: Rabi-season rice area and fraction of total rice area that is irrigated. The data (hereafter DAC-MoA) are from the Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India.

Table 2
Rice cropping systems occurring in Indian states (Yadav and Subba Rao, 2001; Huke and Huke, 1997)

State	Rice cropping system[a]
Andhra Pradesh	Upland, deepwater, rice–rice, rice–groundnut, rice–oilseed rice–pulse, rice–fallow, fallow–rice
Assam	Upland, deepwater, rice–rice–rice, rice–rice, rice–oilseed–rice, rice–vegetable–rice, rice–fibrecrop–rice, fibrecrop–rice–oilseed, rice–oilseed, rice–potato, rice–pulse, rice–vegetable, rice–fallow, fallow–rice
Bihar	Upland, deepwater, rice–rice, rice–pulse–pulse, fibrecrop–rice, rice–oilseed, rice–pulse, rice–sugarcane, rice–wheat, rice–fallow, fallow–rice
Gujarat	Rice–sorghum, rice–sugarcane, rice–vegetable, rice–wheat, rice–fallow
Haryana	Rice–wheat, rice–fallow
Himachal Pradesh	Rice–wheat, rice–fallow
Jammu & Kashmir	Rice–barley, rice–barley, rice–pulse, rice–wheat, rice–fallow
Karnataka	Upland, rice–rice, rice–groundnut, rice–pulse, rice–fallow, fallow–rice
Kerala	Upland, rice–rice–rice, rice–rice, fallow–rice–rice, rice–rice–pulse, rice–fallow, fallow–rice
Madhya Pradesh	Upland, rice–millet, rice–oilseed, rice–pulse, rice–wheat, rice–fallow
Maharashtra	Upland, rice–rice rice–groundnut, millet–rice, rice–pulse, rice–pulse, rice–vegetable, rice–wheat, rice–fallow, fallow–rice
Orissa	Upland, deepwater, rice–rice, rice–groundnut, rice–oilseed, rice–pulse, rice–vegetable, rice–fallow
Punjab	Rice–wheat, rice–fallow
Rajasthan	Rice–wheat, rice–fallow
Tamil Nadu	Upland, deepwater, rice–rice, rice–rice–groundnut, rice–rice–pulse, rice–rice–sorghum, rice–fibrecrop–vegetable, rice–fibrecrop, rice–groundnut, rice–oilseed, rice–pulse, rice–sugarcane, rice–vegetable, rice–fallow, fallow–rice
Uttar Pradesh	Upland, deepwater, rice–oilseed, rice–potato, rice–pulse, rice–vegetable, rice–wheat, rice–fallow
West Bengal	Upland, deepwater, rice–rice, rice–oilseed–rice, rice–rice–pulse, rice–potato–rice, rice–vegetable–rice, rice–wheat–rice, rice–oilseed–fibrecrop, rice–vegetable–fibrecrop, rice–potato-vegetable, rice–wheat–fibrecrop, rice–wheat–vegetable, rice–fibrecrop, rice–potato, rice–wheat, rice–fallow, fallow–rice
Goa	Rice–oilseed, rice–pulse, rice–vegetable, rice–fallow
A&N Islands	Rice–fallow
Arunchal Pradesh	Upland, rice–groundnut, rice–millet, rice–pulse, rice–fallow
Manipur	Upland, deepwater, rice–millet, rice–oilseed, rice–sorghum, rice–fallow
Meghalaya	Upland, rice–rice, rice–fallow
Mizoram	Upland, deepwater, rice–fallow
Nagaland	Upland, rice–fallow
Union Territories[b]	Rice–rice, rice–fallow, fallow–rice
Sikkim	Upland, rice–fallow
Tripura	Upland, deepwater, rice–rice, fallow–rice
Delhi	Rice–fallow

[a] Similar crops (e.g., all pulses, all fibrecrops) aggregated from data of Yadav and Subba Rao (2001); upland and deepwater data from Huke and Huke (1997).
[b] Dadra and N. Haveli, Diman, Diu, Karaikal, Mahe, Pondicherry, and Yanam.

2.2. Methods to combine datasets into new product

2.2.1. Baseline dataset

We based our analysis on the district-level data of Huke and Huke (1997), reporting sown area by water management for the early- to mid-1990s. We updated the H&H data set in three steps to year 2000 areas, and then partitioned this data into rainfed and irrigated crop rotations in two additional steps (Table 3).

2.2.2. Updating district-wise total sown area to year 2000 values

First we scaled district total rice area from the H&H value, generally representing the early 1990s, to the 1999–

Table 3
Procedure for combining datasets for district-wise maps of rice cropping area

Analysis step[a]	Datasets used[b]	Year	Water management[c]	Crop rotations
1 (Section 2.2.1)	H&H	Early-1990s	IW, ID, RF, UP, DW	Not specified
2 (Section 2.2.2)	Above + DRD	2000	As above, all scaled by district area ratios	Not specified
3 (Section 2.2.3)	Above + DAC-MoA-1	2000	ID adjusted (area of RF compensated)	Not specified
4 (Section 2.2.4)	Above + DAC-MoA-2	2000	IW adjusted (area of RF compensated)	Not specified
5 (Section 2.2.5)	Above + Y&SR*	2000	As above	34 specified, including UP and DW
6 (Section 2.2.6)	Above	2000	19 Kharif-season-rice-only crop rotations partitioned into irrigated and rainfed areas.	53 specified, including UP and DW

[a] Discussed in text in section noted in parentheses.
[b] H&H: district-wise sown area by water management (Huke and Huke, 1997); DRD: district-wise sown area (DRD, 2004); DAC-MoA-1: state-wise Rabi-season sown area (FAO-RAP, 2005); DAC-MoA-2: state-wise total irrigated sown area (FAO-RAP, 2005); Y&SR*: district-wise land area by crop rotation (Yadav and Subba Rao, 2001; NERDB, 2005).
[c] IW: irrigated wet-season; ID: irrigated dry-season; RF: rainfed; UP: upland; DW: deepwater.

2000 district total rice area reported in DRD. The H&H area in each water-management class, $A_{i,\mathrm{H\&H}_j}$, was multiplied by the ratio of the DRD district-level total rice area, DRD_i, divided by the H&H district total rice area.

$$A_{i,j} = A_{i,\mathrm{H\&H}_j} \frac{\mathrm{DRD}_i}{\sum_j A_{i,\mathrm{H\&H}_j}} \quad (1)$$

where the subscript i identifies a district, and the subscript j identifies a water-management (e.g., rainfed, deepwater, etc.). Overall, this increased the total rice area of India by 4.9% (2.1 Mha), though for individual districts the increase could be larger or smaller, or could be a decrease.

For about 10 districts DRD did not report values, so we used the H&H values without scaling.

2.2.3. *Updating district-wise Rabi-season sown area to year 2000 values*

Second, we adjusted the district-level H&H area in Rabi-season rice ('dry-season irrigated' in H&H) so that state-level Rabi-season totals matched the DAC-MoA values. To do this, for each state, we adjusted district-level Rabi-season rice area as follows:

$$A^{*}_{i,\mathrm{Rabi}} = A_{i,\mathrm{Rabi}} \frac{A_{\mathrm{state,DAC-MoA_{Rabi}}}}{\sum_i A_{i,\mathrm{Rabi}}} \quad (2)$$

where $A_{\mathrm{state,DAC-MoA_{Rabi}}}$ is the state total Rabi-season rice area reported in the FAO database, and the summation is over all districts, i, within the state. During this analysis, we concluded that H&H mis-reported irrigated areas for the state of Tamil Nadu, swapping dry-season irrigated and wet-season irrigated. H&H reported 1990 areas of 1.50 Mha of Rabi ('dry-season irrigated') and 0.33 Mha of Kharif ('wet-season irrigated') for Tamil Nadu, while the FAO database reported 1999–2000 areas 0.25 Mha of Rabi-season rice and 1.91 Mha of Kharif-season rice. We therefore swapped the H&H dry-season irrigated and wet-season irrigated area values for all districts in Tamil Nadu before applying Eq. (2). For all states, we assumed that district-level gains (losses) in Rabi-season rice area were offset by district-level losses (gains) in rainfed rice area, and not by changes in district-level upland or deepwater rice. Nationally, this added 0.78 Mha of Rabi-season area, and reduced the rainfed area by 0.78 Mha.

2.2.4. *Updating district-wise Kharif-season irrigated sown area to year 2000 values*

Finally, since rice irrigated area in India increased in the 1990s from 19.4 to 24.3 Mha (Chanda et al., 2003), we adjusted the district-level Kharif-season irrigated rice ('wet-season irrigated' in H&H) so that the total state-level irrigated rice (wet-season + dry-season) matched the total Ministry of Agriculture values reported in Chanda et al. (2003). We assumed that district-level gains (losses) in Kharif-season irrigated rice area were offset by district-level losses (gains) in rainfed rice area, and not by changes in district-level upland or deepwater rice.

$$A^{*}_{i,\mathrm{Kharif-irrigated}} = A_{i,\mathrm{Kharif-irrigated}} + (f_{\mathrm{irrig,DAC-MoA}} - f_{\mathrm{irrig,H\&H^*}}) \sum_j A_{i,j},$$
$$A^{*}_{i,\mathrm{Kharif-rainfed}} = A_{i,\mathrm{Kharif-rainfed}} - (f_{\mathrm{irrig,DAC-MoA}} - f_{\mathrm{irrig,H\&H^*}}) \sum_j A_{i,j} \quad (3)$$

The fraction of rice that is irrigated, f, is given for each dataset by

$$f_{\mathrm{irrig,MoA}} = \frac{A_{\mathrm{irrigated,DAC-MoA}}}{A_{\mathrm{total,DAC-MoA}}},$$
$$f_{\mathrm{irrig,H\&H^*}} = \frac{\sum_i (A_{i,\mathrm{Kharif-irrigated}} + A_{i,\mathrm{Rabi-irrigated}})}{\sum_{i,j} A_{i,j}} \quad (4)$$

We limited changes in area so that neither final area was negative. We did not apply Eq. (3) to the state of Assam because the data reported in Chanda et al. (2003) were from 1953–1954. We did not apply Eq. (3) to the Union Territories (districts of Dadra and N. Haveli, Diman, Diu, Karaikal, Mahe, Pondicherry, and Yanam) because no data were reported in Chanda et al. (2003). For some states this decreased Kharif-season irrigated area (i.e., DAC-MoA irrigated fraction was less than H&H irrigated fraction), while for other states this increased Kharif-season irrigated area. The biggest increases were in the states of Uttar Pradesh (0.8 Mha), West Bengal (0.7 Mha), Madhya Pradesh (0.3 Mha), and Bihar (0.2 Mha). Nationally, this added 2.2 Mha of irrigated area, and reduced the rainfed area by 2.2 Mha.

2.2.5. *Partitioning sown area into crop rotations*

To disaggregate the district-level rice areas into different crop rotations, we used the dataset of Yadav and Subba Rao (2001), supplemented by NERDB (2005). We scaled the Y&SR* district-level rice cropping system rotation areas as follows. First, if the total district-level rice area for the three crop rotations reported in Y&SR* was greater than the DRD district-level total, the Y&SR* values were all reduced proportionally so that their total matched the DRD total; otherwise they were kept unchanged. Second, if the total district-level Rabi-season rice area for the three crop rotations reported in Y&SR* was greater than the Rabi-season total in the updated database, these rotations were scaled to match that total, otherwise they were unchanged.

We then assigned rice areas to upland, deepwater, and all Y&SR* rotations based on the scaled values discussed above. The remaining district-level rice area, which might be zero, was assigned to three rotations: rice–rice, rice–fallow, and/or fallow–rice rotations. First, an area equal to the minimum of the remaining areas of Rabi-season and Kharif-season rice was added to the rice–rice rotation (note that this minimum could be zero if all of the rice from one season had already been assigned to Y&SR* rotations), and the remaining areas of Rabi-season and Kharif-season rice were reduced by this amount, bringing the smaller value to zero. Then the remaining area in Kharif-season rice, which might be zero, was added to the rice–fallow rotation and the remaining area in Rabi-season rice, which might be zero, was added to the fallow–rice rotation.

2.2.6. Partitioning crop rotations into rainfed and irrigated areas

Most districts had more total rice sown area than total irrigated rice area, so the final step was to partition some rotations into irrigated and rainfed subsets. We assumed that all upland and deepwater rice was rainfed. We assumed that all rice crops in rotations with Rabi-season rice were irrigated (i.e., rice–rice–rice, rice–rice, the eight rice–rice–other and rice–other–rice rotations, the one other–rice–other rotation, the two other-rice rotations, and fallow–rice). Depending on areas of these rotations and of Kharif-season irrigated rice, this allocation accounted for none, some, or all of the Kharif-season irrigated rice area in a given district; any remaining Kharif-season irrigated area was allocated to the remaining Kharif-season-only rotations in that district, with the following prioritization: first, to all seven triple-crop rotations (rice–other–other), proportional to their areas in the district; second, to all 11 double-crop rotations (rice–other), proportional to their areas in the district; and finally, any remaining Kharif irrigated area was allocated to rice–fallow. Thus, these 19 Kharif-season-only rice crop rotations could have irrigated and rainfed areas, while all other rotations were irrigated-only, except upland and deepwater, which were rainfed-only.

2.3. Application: estimating irrigated paddy rice water demand

We used the district-wise, season-wise area of irrigated rice and a simple monthly water balance model to estimate monthly, district-wise paddy rice irrigation water requirements for all of India. Irrigation water demand, IRR, was calculated on a monthly basis for irrigated rice as follows. The change in soil water storage (ΔSW) is given by

$$\Delta SW = P + IRR - PET - DR \quad (5)$$

where P is precipitation, PET the potential evapotranspiration, and DR is drainage or percolation losses, all in mm per

Table 4
State-level rice areas (ha) by season and water management

State	Total rice		Irrigated		Rainfed[a]	Kharif			Rabi
	Land area	Sown area	Land area	Sown area	Land and sown area	Sown area[b]	Irrigated	Non-irrigaed[b]	Sown area
Andhra Pradesh	3087151	3875700	2942607	3731156	0	2973788	2829244	144544	901912
Assam	2414402	2646600	580149	812347	994460	2374956	540703	1834253	271644
Bihar	5068655	5086600	2092872	2110817	2051164	4957900	1982117	2975783	128700
Gujarat	759014	759014	466384	466384	292631	759014	466384	292631	0
Haryana	1087000	1087000	1087000	1087000	0	1087000	1087000	0	0
Himachal Pradesh	80200	80200	49483	49483	30717	80200	49483	30717	0
Jammu & Kashmir	271520	271520	244368	244368	27152	271520	244368	27152	0
Karnataka	1202803	1446300	842673	1086170	242499	1161300	801170	360130	285000
Kerala	305610	349400	166614	210404	119179	291400	152404	138996	58000
Madhya Pradesh	5315200	5315200	1318170	1318170	2900206	5315200	1318170	3997030	0
Maharashtra	1470662	1492211	390301	411850	740324	1451211	370850	1080361	41000
Orissa	4211500	4593300	1526291	1908091	1720934	4211500	1526291	2685209	381800
Punjab	2519000	2519000	2519000	2519000	0	2519000	2519000	0	0
Rajasthan	200094	200094	123258	123258	76836	200094	123258	76836	0
Tamil Nadu	1931929	2163600	1793807	2025477	80880	1912200	1774077	138123	251400
Uttar Pradesh	5933000	5933000	3670153	3670153	1467449	5933000	3670153	2262847	0
West Bengal	4911483	6150400	1734395	2973311	2032235	4686413	1509325	3177089	1463987
Goa	56700	56700	16216	16216	40484	56700	16216	40484	0
A&N Islands	12200	12200	0	0	12200	12200	0	12200	0
Arunchal Pradesh	124700	124700	32748	32748	0	124700	32748	91952	0
Manipur	127100	127100	55422	55422	31775	127100	55422	71678	0
Meghalaya	103368	106200	53029	55861	33347	103368	53029	50339	2832
Mizoram	49700	49700	7505	7505	29040	49700	7505	42195	0
Nagaland	148500	148500	64449	64449	17756	148500	64449	84051	0
Union Territories[c]	28777	41572	14623	27418	14154	28776	14622	14154	12796
Sikkim	15900	15900	13181	13181	0	15900	13181	2719	0
Tripura	177859	232200	57700	112041	0	174500	54341	120159	57700
Delhi	3282	3282	3282	3282	0	3282	3282	0	0
All India	41617309	44887193	21865679	25135563	12955422	41030423	21278792	19751631	3856770

[a] Excluding areas in upland and deepwater rotations (see Table 5).
[b] Including areas in upland and deepwater rotations (see Table 5).
[c] Dadra and N. Haveli, Diman, Diu, Karaikal, Mahe, Pondicherry, and Yanam.

month. PET was estimated using the Shuttleworth and Wallace (1985) modification of the Penman-Monteith PET function, a physically-based method recommended by the Food and Agricultural Organization of the United Nations. Monthly precipitation data was based on the 1950–1995 climatology of the University of East Anglia Climate Research Unit (New et al., 1998); this gridded product was linearly interpolated to the center point of each district (Douglas et al., 2006). Eq. (5) can then be solved for irrigation water demand by district and by month as

$$\mathrm{IRR} = \Delta\mathrm{SW} + \mathrm{PET} + \mathrm{DR} - P \quad (6)$$

Percolation losses are primarily a function of soil texture. Guerra et al. (1998) report percolation rates of 1–5 mm d^{-1} for puddled clay and 24–29 mm d^{-1} for sandy loam or loamy sand. Kawaguchi and Kyuma (1977) used a mean value of 100 mm mo^{-1} for a pan-tropical Asia analysis. FAO (2004) report generic low and high-percolation losses for paddy rice of 200 and 700 mm $crop^{-1}$. We determined the value for each district based on its ratio of average sand content to average clay content; soil texture properties were taken from a gridded ($1^\circ \times 1^\circ$) global soil texture dataset (Webb et al., 2000). The highest district-level sand:clay ratio across India (8.9) was given a percolation rate of 600 mm mo^{-1}, the lowest sand:clay ratio across India (0.1) was given a percolation rate of 30 mm mo^{-1}, and all other districts were linearly interpolated between these two values, based on sand:clay ratios. The mean percolation rate was 142 mm mo^{-1} ($n = 439$).

In planting months, the paddy soil is wetted from field capacity to saturation plus flooding; FAO (2004) provides a range of 150–250 mm water for land preparation. We approximated ΔSW as +250 mm for the district with the highest sand:clay ratio, +150 mm for the district with the lowest sand:clay ratio, and linearly interpolated between these values for all other districts. In the harvest month, soils are drained and allowed to dry, so we

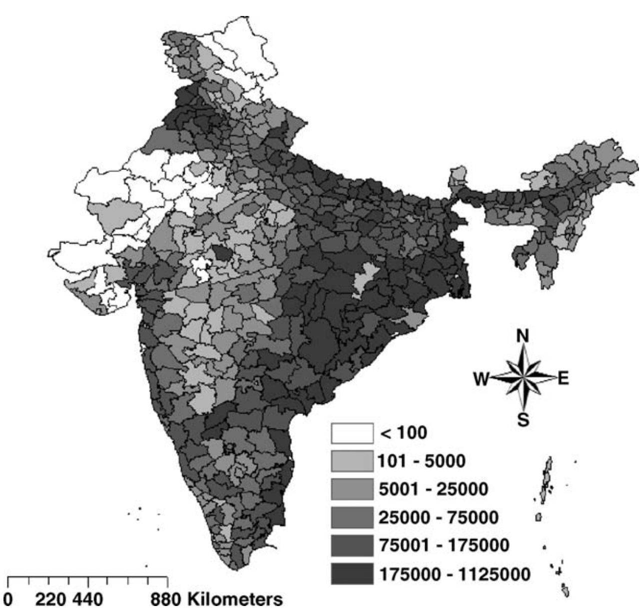
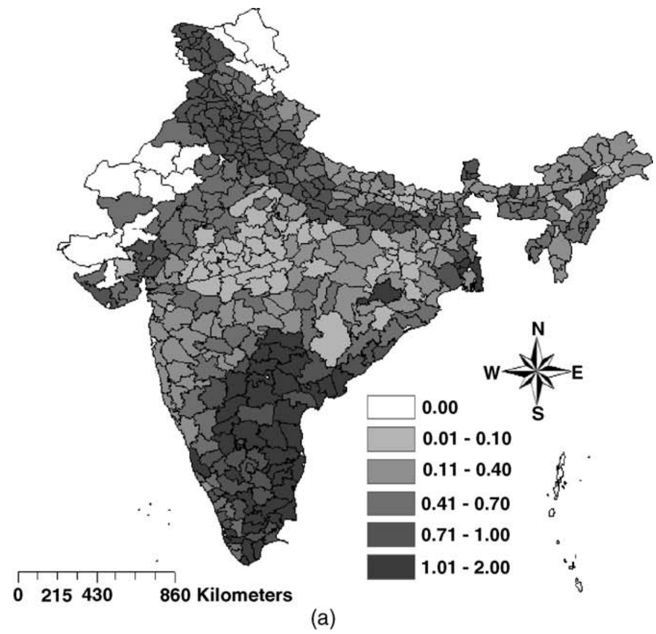


Fig. 2. District-level map of total rice sown area in 1999–2000 (ha/district). Total rice sown area triple-counts rice–rice–rice area and double-counts rice–rice and rice–rice–other areas.



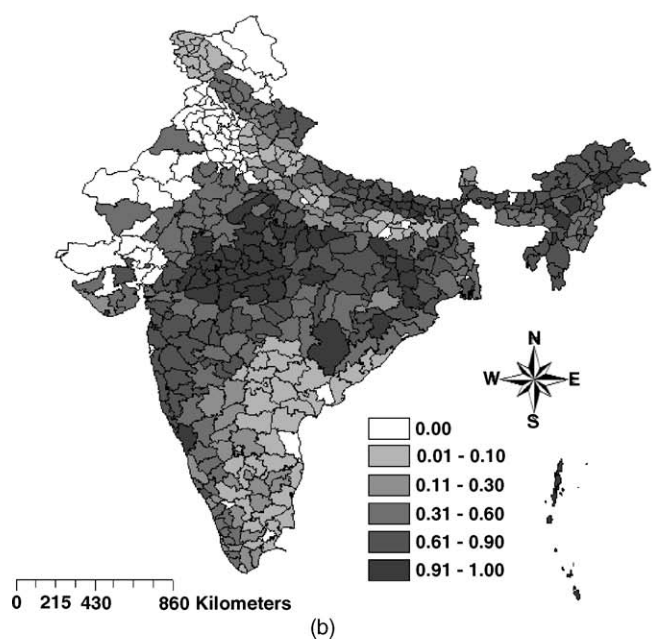


Fig. 3. District-level map of (a) fraction of total rice that was irrigated and (b) fraction of total rice that was rainfed in 1999–2000. The irrigated fraction was calculated as the total irrigated rice *sown* area (i.e., triple-counting rice–rice–rice area and double-counting rice–rice and rice–rice–other areas) divided by the total rice *land* area in the district. For a district with only rice–rice, all irrigated, the ratio would be 2. The maximum district ratio in the map is 1.97. The rainfed fraction was calculated as the total rainfed rice *sown* area, divided by the total rice *land* area in the district. Since we have classified only single-rice cropping (i.e., rice–other and rice–fallow) as rainfed, the maximum value for the rainfed ratio would be 1.0. Note that the scales differ between the two panels.

approximated ΔSW in those months as −150 to −250 mm, based on the water required for preparation. During rice growth months, the soil was maintained in a flooded state, and ΔSW was zero.

A generalized cropping season was used: Kharif-season rice – planting in July and harvest in November; Rabi-season rice – planting in January and harvest in May; double rice – Kharif and Rabi; triple rice – planting in January, May, and September, harvest in April, August, and December (Chanda et al., 2003). District-wide, monthly paddy rice irrigation water demand was then calculated as the product of IRR and the area of irrigated rice growing in each month. During fallow months and months with non-rice cropping, irrigation water demand was assumed to be zero (i.e., we calculated demand only due to rice cropping). Irrigation water demand was then aggregated spatially from district to state, regional, and national totals, and temporally from monthly to annual totals.

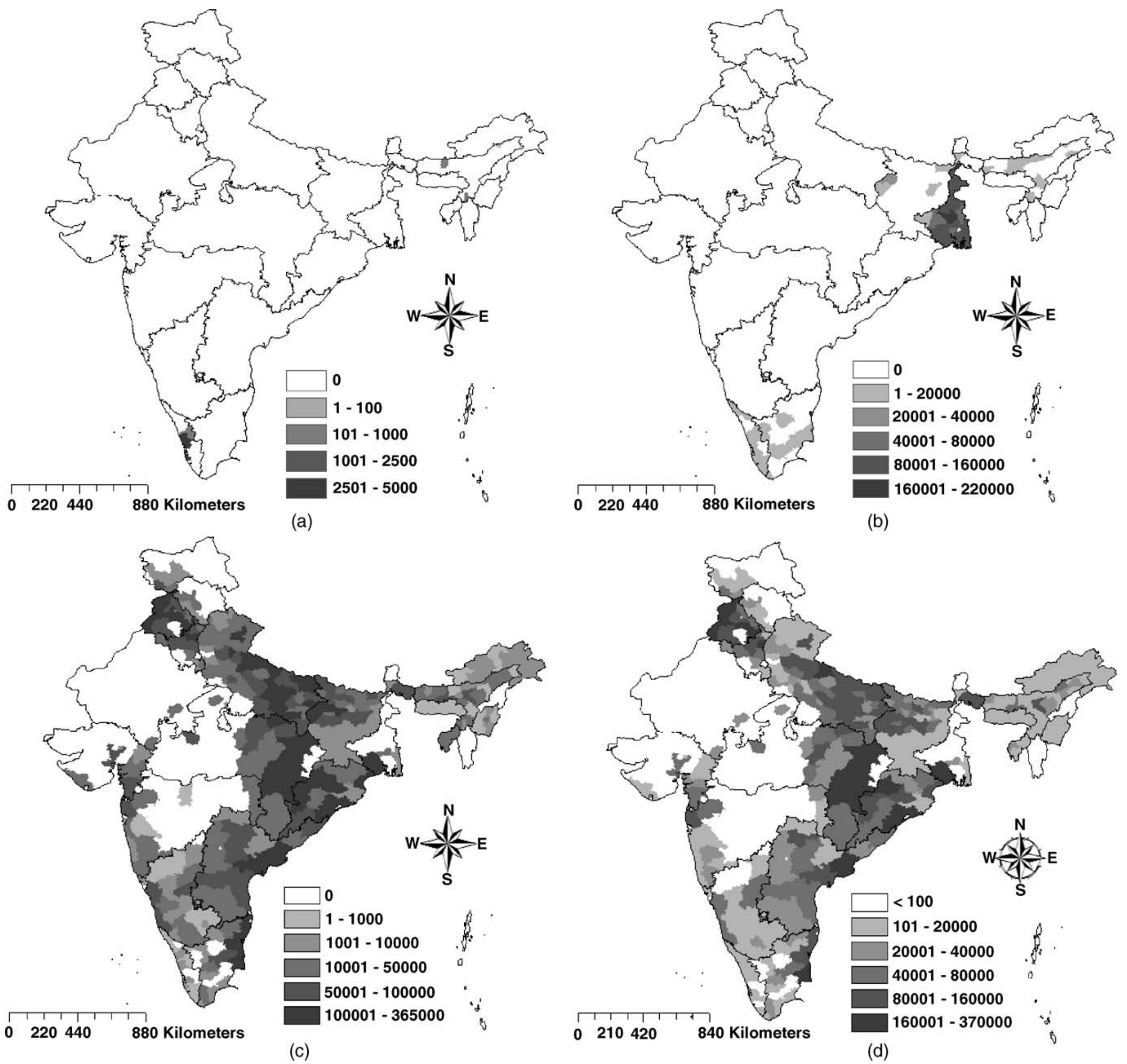


Fig. 4. District-level maps of 1999–2000 land areas (ha/district) in (a) triple-rice (i.e., rice–rice–rice); (b) rice-based triple-cropping (i.e., rice–rice–rice + rice–rice–other + rice–other–other); (c) double-rice (i.e., rice–rice + rice–rice–other); (d) rice-based double-cropping (i.e., rice–rice + rice–other); (e) single-rice (i.e., rice–fallow + rice–other–other + rice–other); (f) rice-based single-cropping, excluding upland and deepwater (i.e., rice–fallow); (g) upland rice (i.e., non-flooded); and (h) deepwater rice (i.e., flooded depth >1 m; Huke and Huke, 1997). All maps represent total land area for all seasonal combinations (e.g., total rice–other equals rice–other plus other-rice). Note that only state boundaries are drawn on these maps.

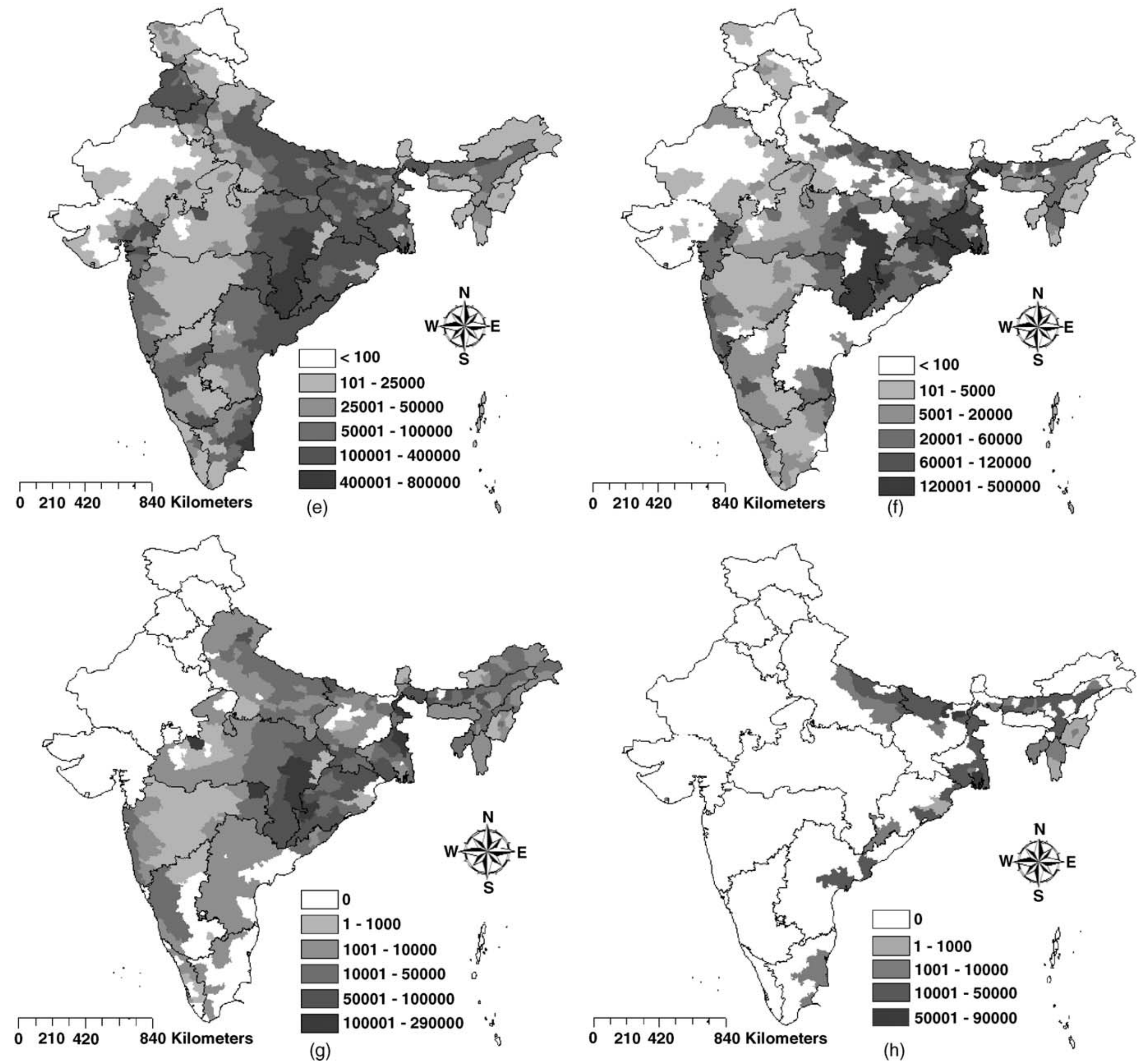


Fig. 4. (*Continued*).

3. Results

3.1. Rice cropping map

The map specifies the area in each district in 17 triple-cropping systems (e.g., rice–rice–rice, rice–rice–pulse, and rice–potato–vegetable), 13 double-cropping systems (e.g., rice–rice and rice–wheat), two single-cropping systems (rice–fallow and fallow–rice), plus upland and deepwater rice. Our naming convention for the double- and single-cropping systems is Kharif–Rabi; for triple-cropping systems, it is winter–summer–autumn, where 'winter' is equivalent to 'Kharif'. The map also specifies, at the district-level, what fraction of each cropping system is irrigated.

The total sown rice area for India in 2000 was 44.9 Mha; the total land area was 41.6 Mha (Table 4). Rice cropping is widespread throughout India, with significant area in about 95% of all districts (Fig. 2). Zero or negligible ($\leq$100 ha in a district) rice cropping was reported for districts in the mountainous far north of Jammu & Kashmir, the Thar Desert area of Rajasthan and Haryana, the Rann of Kachchh saline mudflats in northern Gujarat, a few other districts in Madhya Pradesh and Gujarat, and several urban districts (Bombay, Calcutta, Hyderabad, Madras). Rice cropping areas are large in states along the east coast (Tamil Nadu, Andhra Pradesh, Orissa, eastern Madhya Pradesh – now Chhattisgarh, southern Bihar – now Jharkhand, and West Bengal), districts along the west coast (in Karnataka, Maharashtra, and Gujarat), and in the Indo-Gangetic Plain in the north (Punjab, Haryana, Uttar Pradesh, northern Bihar), and the Brahmaputra Valley in the north-east (Assam).

We calculated the district-level irrigated fraction of rice area as the total *sown* area of irrigated rice divided by the total *land* area in rice; a district with only irrigated double-rice would have an irrigated fraction of 2. Values ranged from <0.01 to 1.97, with a mean value of 0.58 (Fig. 3). The majority of rice cropping is irrigated in southern India (Andhra Pradesh, Tamil Nadu, Kerala, and Karnataka), the northwest (Punjab, Haryana, Rajasthan, and Gujara) and the Ganges River Valley (Uttar Pradesh and northern Bihar) (Fig. 3a and Table 4). The majority of rice cropping is rainfed in central and eastern states (Maharashtra, Madhya Pradesh, West Bengal, Orissa, and Bihar) and in the north-east (Fig. 3b and Table 4). Overall, rainfed rice occupied 13 Mha, plus 5.45 Mha of upland rice and 1.35 Mha of deepwater rice (>1 m flooding depth; Huke and Huke, 1997) (Table 4). Kharif-season rice occupied 41.0 Mha, with just over half of that irrigated; Rabi-season rice sown area was 3.86 Mha, all classified as irrigated (Table 4).

Triple-rice occurred on 0.014 Mha in only a few districts in Kerala and Assam (Fig. 4a) based on data from Yadav and Subba Rao (2001), while triple-cropping with rice (rice–rice–rice + rice–rice–other + rice–other–other) occupied 1.36 Mha, mostly in West Bengal and the southern states of Tamil Nadu and Kerala (Fig. 4b and Table 5). Total double-rice (rice–rice + rice–rice–other) occurred on 2.21 Mha, and was widespread throughout eastern and southern India (Fig. 4c). Double-cropping with rice (rice–rice + rice–other) occupied 16.2 Mha, and occurred throughout southern and eastern India as well as in the Ganges River and Brahmaputra River Valleys in the north and north-east (Fig. 4d and Table 5). Total single-rice (rice–fallow + rice–other) occupied 31.6 Mha, and is common throughout India except for the high mountains of Jammu & Kashmir and the desert areas of Rajasthan and Gujarat (Fig. 4e). The dominant rice–other rotations were rice–wheat (8.8 Mha, mostly in the northern states of Punjab, Haryana, Bihar – now also Jharkhand, and Uttar Pradesh, and in Madhya Pradesh), rice–pulse (3.2 Mha, mostly in the eastern states of Orissa, Bihar – now also Jharkhand, and Andhra Pradesh, and in eastern Madhya Pradesh – now Chhattisgarh), rice–oilseed (0.64 Mha, mostly in eastern Madhya Pradesh – now Chhattisgarh, Tamil Nadu, and Assam), and Rice–groundnut (0.57 Mha, mostly in Tamil Nadu and Andhra Pradesh). Rice–fallow was assigned to 17.2 Mha throughout India, but particularly in the eastern states of Bihar (now also Jharkhand), Madhya Pradesh (now also Chhattisgarh), Orissa, and West Bengal (Fig. 4f and Table 5). Upland rice was common in Orissa, Madhya Pradesh

Table 5
State-level rice land areas (ha) by cropping system[a]

State	Upland	Deepwater	Triple-rice	Rice–rice	Rice–rice–other	Rice–other–other	Rice–other	Rice–fallow
Andhra Pradesh	100684	43860	0	788549	0	0	700129	1453929
Assam	555160	284633	416	209649	21717	1969	251157	1089701
Bihar	501834	422785	0	17945	0	41694	1742179	2342217
Gujarat	0	0	0	0	0	0	239861	519154
Haryana	0	0	0	0	0	0	867000	220000
Himachal Pradesh	0	0	0	0	0	0	58300	21900
Jammu & Kashmir	0	0	0	0	0	0	109700	161820
Karnataka	117630	0	0	243497	0	0	66535	775140
Kerala	19817	0	13512	13045	3720	0	0	255516
Madhya Pradesh	1096824	0	0	0	0	0	2261833	1956543
Maharashtra	340037	0	0	21549	0	0	274593	834483
Orissa	890822	73452	0	381800	0	0	1098600	1766826
Punjab	0	0	0	0	0	0	1750000	769000
Rajasthan	0	0	0	0	0	0	65000	135094
Tamil Nadu	28731	28511	0	175333	56337	15870	478905	1148241
Uttar Pradesh	601953	193445	0	0	0	0	3790951	1346651
West Bengal	872461	272393	0	284655	954261	249840	224900	2052973
Goa	0	0	0	0	0	0	2598	54102
A&N Islands	0	0	0	0	0	0	0	12200
Arunchal Pradesh	91952	0	0	0	0	0	22735	10013
Manipur	31775	8128	0	0	0	0	29233	57964
Meghalaya	16992	0	0	2832	0	0	0	83544
Mizoram	10230	2925	0	0	0	0	0	36545
Nagaland	66295	0	0	0	0	0	0	82205
Union Territories[b]	0	0	0	12795	0	0	0	15981
Sikkim	2719	0	0	0	0	0	0	13181
Tripura	104734	15425	0	54341	0	0	0	3359
Delhi	0	0	0	0	0	0	0	3282
All India	5450651	1345559	13929	2205991	1036035	309373	14034209	17221562

[a] All areas represent total land area for all seasonal combinations (e.g., total rice–other equals rice–other plus other–rice).
[b] Dadra and N. Haveli, Diman, Diu, Karaikal, Mahe, Pondicherry, and Yanam.

Table 6
State-level paddy rice irrigation water demand

State	Paddy rice irrigation water requirement ($km^3\ y^{-1}$)
Andhra Pradesh	25
Assam	2.7
Bihar	15
Gujarat	2.7
Haryana	17
Himachal Pradesh	0.52
Jammu & Kashmir	3.7
Karnataka	8.5
Kerala	0.53
Madhya Pradesh	3.3
Maharashtra	1.5
Orissa	8.1
Punjab	44
Rajasthan	0.78
Tamil Nadu	19
Uttar Pradesh	33
West Bengal	14
Goa	0.12
A&N Islands	0
Arunchal Pradesh	0.06
Manipur	0.20
Meghalaya	0.02
Mizoram	0.04
Nagaland	0.04
Union Territory	0.22
Sikkim	0.08
Tripura	0.53
Delhi	0.03
All India	200

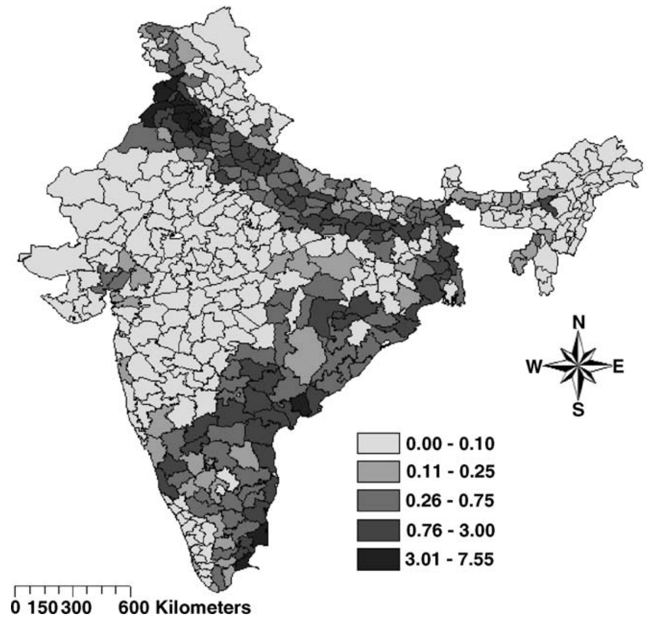


Fig. 5. District-level map of paddy rice annual irrigation water requirement in $km^3\ y^{-1}$. Irrigation water requirement is a function of weather (precipitation and potential evapotranspiration), soils (percolation rate), and district area of irrigated rice. Note that this calculation does not account for irrigation inefficiencies (except percolation losses), nor for water resources limitations.

(now also Chhattisgarh), and West Bengal (Fig. 4g), and covered 5.45 Mha (Table 5), while deepwater rice occurs in the Ganges and Brahmaputra River Valleys and along the east coast in the major river deltas (Fig. 4h), covering 1.35 Mha (Table 5).

Dominance of very few rotations could create serious market clearance problems and also possibly unfavorably affect the ecological condition of the agricultural land. Identification of the diversity in agricultural practices in different regions is of value to policy analyses. Diversity in rice cropping systems is highest in West Bengal, followed by Tamil Nadu, Assam, and Bihar (Table 2), while the lowest diversity was observed in Punjab, Haryana, Himachal Pradesh and Rajasthan.

3.2. Irrigated paddy rice water demand

The total paddy rice irrigation water requirement was estimated to be about 200 $km^3\ y^{-1}$, predominantly in northern and eastern India (Table 6, Fig. 5). High requirements in northern India are primarily due to high-percolation rates and a drier climate, while in eastern India, high demand is due more to extensive irrigation and double rice cropping (Figs. 2 and 4c). About 90% of the total requirement is needed during the Kharif (wet) season (Table 7), when most rice is grown (Table 4).

Table 7
Monthly paddy rice irrigation water demand for all India

Month	Paddy rice irrigation water requirement ($km^3\ mo^{-1}$)
January	14
February	7.6
March	9.0
April	8.7
May	2
June	0
July	59
August	18
September	26
October	44
November	13
December	0
Annual total	200

4. Discussion and conclusions

We have combined several existing datasets to generate a new district-level data set and maps of the area and water management of a number of rice cropping systems in India in 1999–2000. These maps are the first to portray a spatially-explicit distribution of 53 single- and multi-crop, irrigated and rainfed rice cropping rotations in India. The district-level total rice sown area is consistent with the 1999–2000 areas reported by the Directorate of Rice Development (DRD, 2004). We have required the district-level fractions of rice cropping keep upland or deepwater rice to be consistent with the values reported in Huke and Huke (1997). We have required the state-level values of the fraction of rice cropping that is irrigated and the state-level areas of Rabi-season rice to be consistent with data from the Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India (http://www.faorap-pcas.org/india/index.htm). We have also set district-level rice cropping rotations to be consistent with those reported in Yadav and Subba Rao (2001), with the addition of rice–rice and rice–fallow for many districts, and with three dominant rotations (plus rice–rice and rice–fallow) for those regions not covered in Yadav and Subba Rao (2001) data set.

Woodhead and Singh (2002), citing earlier FAO publications, report 3.4 Mha of rice–rice cropping in India, primarily in southern and north-eastern states; this is 50% higher than our estimate for rice–rice, but only 6% greater than our estimate for rice–rice plus rice–rice–other. Woodhead et al. (1994) reported the 1989–1990 area of rice–wheat in India was 9.5 Mha, 8% higher than our estimate. The Rice–Wheat Consortium for the Indo-Gangetic Plains estimates that there are 10.0 Mha of rice–wheat cropping in India (RWC, 2005), 13% more than our estimate.

Yadav and Subba Rao (2001) report only 27.6 Mha of rice cropping area, 61% of the total rice area reported by the Directorate of Rice Development. We supplement this with 1.75 Mha of rice area in the 10 small states with no data in the Yadav and Subba Rao report. The remaining 15.3 Mha of rice area were assigned to either the rice–fallow or the rice–rice rotation, since we have no additional information at the district-level. However, since Yadav and Subba Rao reported only the three dominant rice cropping systems in a district; any rice cropping system with less area than the three dominant ones went unreported and is not included in our analysis. This would tend to bias all of our estimates low. The 'extra' rice area not reported in Y&SR* was assigned to rice–fallow and/or rice–rice, which would tend to bias those estimates high.

These maps have an area of 0.56 Mha in fallow-rice, based on district-level areas reported by Yadav and Subba Rao (2001). This may be an overestimate of an uncommon cropping system, resulting from relatively small sampling sizes of about 15 farmers per region (each region consisted of 'four–five or more districts having similar socio-agro-eco situation'). Overall, Yadav and Subba Rao (2001) interviewed about 1500 farmers representing 400 districts, and have generated the best data set available on cropping systems in India. However, even this major effort inevitably under-sampled a country with ~250 million farmers (FAOSTAT, 2005).

The 200 $km^3\ y^{-1}$ estimated total rice irrigation water demand is roughly 40% of total irrigation in India (~500 $km^3\ y^{-1}$ on ~55 Mha), which accounts for ~80–90% of total water use (Central Water Commission, 1998; FAO, 1999). This estimated irrigation demand for rice is likely to be an overestimation for three reasons. First, the analysis assumes that all paddies are continually flooded, including areas with high-percolation rates, even if this would require more water than is actually available for irrigation. If percolation losses are set to zero everywhere, the irrigation water requirement (for soil preparation and to offset precipitation shortfalls) drops to about 75 $km^3\ y^{-1}$, so about 65% of the irrigation requirement is to offset estimated percolation losses and maintain flooded soils. Thus, any periods with non-flooded soils will reduce irrigation water requirements. Second, the calculation does not account for limitations in water availability (e.g., Martin, 2002). Any time there is not sufficient water available to meet irrigation demand, actual irrigation will be less than potential (Amarasinghe et al., 2005). Third, this total does not account for non-functioning irrigation infrastructure. A recent estimate for India is that about 83% of land 'equipped for irrigation' is actually irrigated (AQUASTAT, 2005). It is not clear in the original datasets of irrigated rice area (Huke and Huke, 1997; FAO-RAP, 2005) if the land area reported represents land 'equipped for irrigation' or land actually irrigated (we have assumed the latter).

This 200 $km^3\ y^{-1}$ total irrigation demand could also be an underestimation, at least from the point of view of water managers, as it does not account for some irrigation inefficiencies. The total amount of water supplied from the original sources will have to be greater than that applied to the fields. Roe (1950) defined irrigation efficiency as the total amount of irrigation water transpired by the crop divided by the total amount of water from the original source diverted into a canal, and put the value for good irrigation practice at about 33%. Some of this inefficiency is due to percolation losses (which are included in our calculations), and some due to seepage losses in the canal and on-farm distribution systems (which are not included in our calculations). For continuous flooding on high-percolation rate soils, percolation losses will probably be the dominant inefficiency, but this may not be the case for low-percolation rate soils. Some of this water 'loss' will go to recharge shallow groundwater aquifers, so it can be a partially beneficial inefficiency. Nonetheless, the total amount of water supplied from the original sources will have to be greater than the on-farm demand. The 'average overall' water use efficiency in India's canal irrigation systems was estimated recently at 40% for India (FAO, 1999). Water losses in distribution from surface water sources to the field are estimated at 40–60% in India (Dastane and Hukkeri, 2003).

The combination of these two offsetting uncertainties complicates the interpretation of irrigated rice water demand (at the field) equaling about 40% of India's estimated total irrigation value of 500 $km^3\ y^{-1}$. Rice and wheat are the dominant irrigated crops (each with ~20–25 Mha irrigated). Cropping season water requirements are much higher for rice than for wheat (Dastane and Hukkeri, 2003), but rice is mostly grown during the wet-season (Kharif), so precipitation inputs are relatively high and irrigation requirements are therefore reduced. As irrigation water demand in India is expected to increase by at least

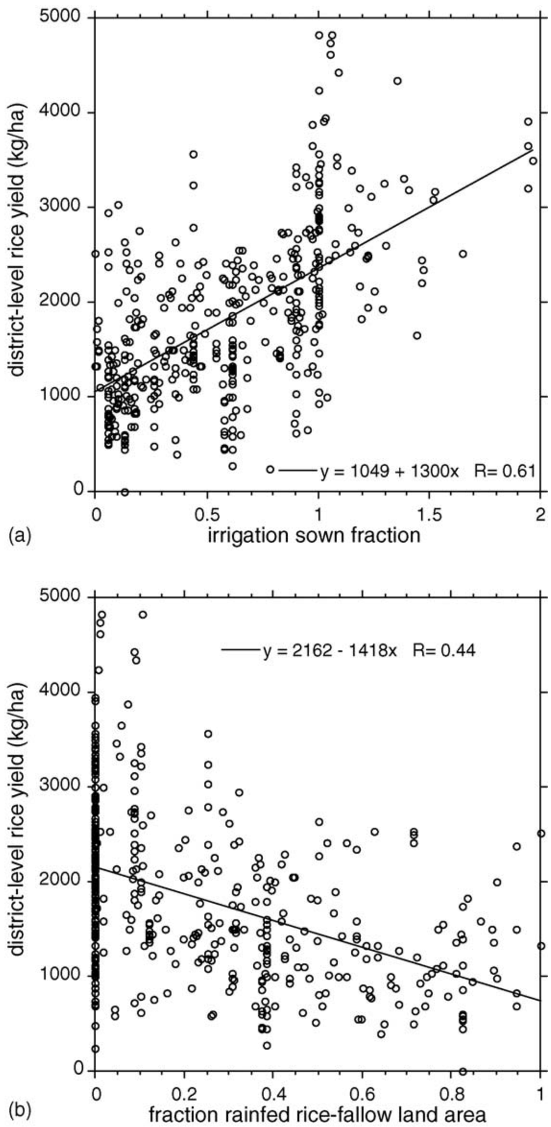


Fig. 6. District-level rice yield (kg ha^{-1}) vs. (a) irrigated sown area fraction, and (b) fraction of total rice land area in the rainfed rice–fallow rotation. Yield data for 1999–2000 from DRD (2004). The irrigated sown area fraction is calculated as the total *sown* area in all irrigated rice rotations in a district divided by the total rice *land* area in the district (see Fig. 3a).

20% over the next 20 years (Central Water Commission, 1998), it is important to refine irrigation demand estimates by (1) including other crops and seasonally-specified crop rotations, (2) including estimates of all irrigation inefficiencies, and (3) including estimates of the fraction of potential irrigation that is actually achieved.

The new dataset we have developed, coupled with an independent dataset on district-level rice yield data from the Directorate of Rice Development (DRD, 2004), point to some clear avenues for increased production. In general, productivity is higher for irrigated than rainfed rice fields (Maclean et al., 2002), and the district-level data shows a strong trend toward increased yield with increased district-level fraction of irrigated rice cropping (Fig. 6a), and a related decreasing yield with increased district-level fraction of rainfed rice–fallow (Fig. 6b). At the same time, it is clear from these figures that irrigation is not the only factor controlling yield, as variability in yield is high across the range of irrigated fraction. The district-level map of rice–fallow cropping (Fig. 4f) indicates where there is the potential for increased food or fibre production through increasing cropping intensity and reducing fallow (e.g., RWC, 2005).

This dataset can serve as a foundation for process-based, national-scale analyses of environmental impacts of rice agriculture. For example, many national-scale assessments of greenhouse gas emissions from croplands use empirical emissions factors, often based on Intergovernmental Panel on Climate Change (IPCC) guidelines (e.g., Bhatia et al., 2004; Anand et al., 2005). However, Li et al. (2002), in an analysis for China, showed that while aggregate national emissions with IPCC emission factors are probably reasonable, as these emissions factors capture mean behavior, the spatial patterns of emissions may not be well-captured by the emissions factor methodology. Because soil characteristics, weather, and agricultural management vary significantly across a large country, and because these factors all influence greenhouse gas emissions, geo-spatial analysis with a process-based model and geo-spatial datasets on soils, weather, and cropping can provide a picture of the spatial variability of emissions, and could help to more efficiently target any mitigation efforts (e.g., Li et al., 2005; Pathak et al., 2005). Similar arguments for the value of geo-spatial datasets could be made for water resources management in agriculture. These new maps can improve our ability to quantify the cycling of carbon, nitrogen, and water in rice agriculture in India.

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References

Amarasinghe, U.A., Sharma, B.R., Aloysius, N., Scott, C., Smakhtin, V., de Fraiture, C., 2005. Spatial Variation in Water Supply and Demand across River Basins of India. Research Report 83. International Water Management Institute, Colombo, Sri Lanka.

Anand, S., Dahiya, R.P., Talyan, V., Vrat, P., 2005. Investigations of methane emissions from rice cultivation in Indian context. Environ. Int. 32, 469–482.

AQUASTAT, 2005. On-line database of the Food and Agricultural Organization of the United Nations. http://www.fao.org/ag/agl/aglw/aquastat/water_use/index.stm, site visited 4 November 2005.

Bhatia, A., Pathak, H., Aggarwal, P.K., 2004. Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. Current Sci. 87, 317–324.

Central Water Commission, 1998. Water and Related Statistics. Delhi, India, pp. 465.

Chanda, T.K., Sati, K., Robertson, C., 2003. Fertilizer Statistics. Fertilizer Association of India, New Delhi, pp. 440.

Dastane, N.G., Hukkeri, S.B., 2003. Water Management in Crop Production, Handbook of Agriculture. Indian Council of Agricultural Research, New Delhi, India, pp. 158–202.

Douglas, E., Niyogi, D.S., Frolking, S., Yeluripati, J.B., Pielke, R.A., Niyogi, N., Vörösmarty, C.J., Mohanty, U.C., 2006. Changes in moisture and energy fluxes due to agricultural land use and irrigation in the Indian Monsoon Belt. Nat. Hazards, submitted for publication.

DRD (Directorate of Rice Development). 2004. Rice in India-A Handbook of Statistics, on-line data (http://dacnet.nic.in/rice/): District-wise Area, Production and Yield of Rice across the States during 1990–2000. Directorate of Rice Development, Ministry of Agriculture, Dept. of Agriculture and Co-Operation, Govt. of India, (visited 10–11 August, 2004).

FAO, 1999. Irrigation in Asia in Figures. Food and Agriculture Organization of the United Nations, Water Report #18, Rome, Italy, pp. 228.

FAO, 2004. Rice Fact Sheet—Rice and Water. (http://www.fao.org/rice2004/en/factsheets.htm).

FAO-RAP, 2005. On-line database of the FAO Regional Office for Asia and the Pacific. (http://www.faorap-apcas.org/india/index.htm), visited March 2005.

FAOSTAT, 2005. On-line statistical database of the Food and Agriculture Organization of the United Nations. http://apps.fao.org/.

Goudie, A., 2000. The Human Impact on the Natural Environment, 5th ed. MIT Press, Cambridge MA, pp. 511.

Guerra, L.C., Bhuiyan, S.I., Tuong, T.P., Barker, R., 1998. Producing More Rice with Less Water from Irrigated Systems, SWIM Paper 5. International Water Management Institute, Colombo, Sri Lanka, pp. 33.

Hossain, M., 1997. Rice supply and demand in Asia: a socioeconomic and biophysical analysis. In: Teng, P.S., Kropff, M.J., ten Berge, H.F.M., Dent, J.B., Lansigan, F.P., van Laar, H.H. (Eds.), Applications of Systems Approaches at the Farm and Regional Levels. Academic Publ., Dordrecht.

Huke, R.E., Huke, E.H., 1997. Rice Area by Type of Culture: South, Southeast, and East Asia. IRRI, Los Baños, Philippines, pp. 59.

IRRI, 2002. Riceweb. http://www.riceweb.org/, produced by International Rice Research Institute (IRRI), West Africa Rice Development Association (WARDA), and Centro Internacional de Agricultura Tropical (CIAT).

Kawaguchi, K., Kyuma, K., 1977. Paddy Soils in Tropical Asia: Their Material Nature and Fertility. Univ. Press of Hawaii, Honolulu, pp. 258.

Li, C., Qiu, J.J., Frolking, S., Xiao, X., Salas, W., Moore, B., Boles, S., Huang, Y., Sass, R., 2002. Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000. Geophys. Res. Lett. 29 (20) doi: 10.1029/2002GL015370.

Li, C., Frolking, S., Xiao, X., Moore, B., Boles, S., Qiu, J., Huang, Y., Salas, W., Sass, R., 2005. Modeling impacts of farming management alternatives on CO_2, CH_4 and N_2O emissions: a case study for water management of rice agriculture of China. Global Biogeochem. Cycl. 19 (3), doi:10.1029/2004GB002341.

Lutz, W., Sanderson, W., Scherbov, S., 2001. The end of world population growth. Nature 412, 543–545.

Maclean, J.L., Dawe, D.C., Hardy, B., Hettel, G.P. (Eds.), 2002. Rice Almanac. 3rd ed. CABI Publ, Oxon, UK, p. pp. 253.

Martin, G.J., 2002. Water requirement for wet seeded rice, recent advances in irrigation management for field crops. In: Chinnamuthu, C.R., Velayutham, A., Ramasamy, S., Sandaraa, N., Sundarsingh, S.D. (Eds.), Centre of Advanced Studies in Agronomy. Tamil Nadu Agricultural University, Coimbatore, India, pp. 155–159.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509.

NERDB, 2005. On-line database of the North Eastern Region Databank of India. (http://databank.nedfi.com), visited March 2005.

New, M., Hulme, M., Jones, P., 1998. Representing 20th century space-time climate variability. Part II: Development of 1901–1996 monthly grids. J. Climate 13, 2217–2238.

Pathak, H., Li, C., Wassmann, R., 2005. Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model. Biogeosci. Discuss. 2, 77–102.

Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P., Wang, M., 2001. Atmospheric chemistry and greenhouse gases. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 239–287.

Roe, H.B., 1950. Moisture Requirements in Agriculture: Farm Irrigation. McGraw Hill, New York, pp. 413.

RWC (Rice-Wheat Consortium for the Indo-Gangetic Plains), 2005. On-line report at http://www.rwc.cgiar.org/Rwc_Crop.asp, visited April 2005.

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops: an energy combination theory. Quart. J. R. Meteorol. Soc. 111, 839–855.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Daniel Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277, 494–499.

Webb, R.W., Rosenzweig, C.E., Levine, E.R., 2000. Global soil texture and derived water-holding capacities, Data set. Available on-line [http://www.daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.

Woodhead, T., Huke, R.E., Huke, E.H., 1994. Areas, locations, and ongoing collaborative research for the rice-wheat systems of Asia. 68-96 in RAP Publication 1994/11 Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.

Woodhead, T., Singh, R.B., 2002. Rice-Based Livelihood-Support Systems, RAP publication 2002/12. Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand, pp. 123.

Yadav, R.L., Subba Rao, A.V.M., 2001. Atlas of Cropping Systems in India. PDCSR Bulletin No. 2001-2, Project Directorate for Cropping Systems Research, Modipam, Meerut, India, pp. 96.