Vol. 51, No. 2, pp 82-94, 2023
Indian Journal of Soil Conservation
https://iaswc.com/ijsc-2023.html

Multi-temporal AWiFS and SAR data for cropping system analysis in Indian Punjab

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ARTICLE INFO

doi: 10.59797/ijsc.v51.i2.123

Article history:
Received : December, 2022
Revised : May, 2023
Accepted : June, 2023

Key words:
AWiFS
Area diversification
Crop intensification
Cropping system analysis
RADARSAT
Remote sensing

ABSTRACT

The analysis of cropping systems using remote sensing is crucial to the long-term sustainability of agricultural productivity, soil and environmental health through diversification and intensification of crop areas. Realizing the importance, medium-resolution satellite data from advanced wide field sensor (AWiFS: 56 m) and synthetic aperture radar (SAR: 50 m) were used to generate land use, cropping pattern and crop rotation maps for the state of Indian Punjab. To evaluate the efficiency of cropping systems at district level, various remote sensing derived efficiency indices were worked out. The spatial analysis revealed that agriculture covered 86% of the total geographical area (TGA) 5.04 M ha, while forests covered only 2.6% of TGA. Rice was the most dominant crop, occupying about 51.2% TAG of the state during the *kharif* season (first harvest: June to Nov). During the *rabi* season (second harvest: Nov to April), wheat was the most dominant crop, occupying about 3.52 M ha of state area (69.8% TAG). Summer crops (April to May), primarily vegetables, were grown in 5.3% TGA of the state. Rice followed by wheat was the main crop rotation in 43.6% of the TGAs. Apart from rice-wheat, other crops-wheat and cotton-wheat rotations also occupied a considerable agricultural area in the state (16.9% and 9.1% of TGA, respectively). In much of the region, crop intensity exceeded 200% (double cropping). The crop area diversity was considerably higher during the *kharif* season (ADIK: 2.23) than during the *rabi* season (ADIR: 1.60) and the land remained in cultivation 292 days yr^{-1}. Incorporation of medium resolution SAR data with AWiFS data of high temporal (5 days) resolution helped to overcome the limitation of the non-availability of multi-spectral optical images during the *kharif* season because of cloud cover. This has improved the precision of the analysis of cropping systems, especially in the mapping of rice growing areas.

1. INTRODUCTION

The Indian Punjab, the country's food basket, was central to the success of the green revolution in terms of self-sufficiency in food grain production. This was possible because of the expansion of irrigated rice followed by the wheat production system (RW), even in unconventional rice growing areas from the early 1970s to the late 1990s (Sood *et al.,* 2009a; Hira *et al.,* 2014; Bal *et al*., 2018). Over those years, rice and wheat production was supported by favourable policies such as input subsidies and minimum support prices for outputs (Barker and Dawe, 2002). Private investment in groundwater pumping expanded the irrigated area and paved the way for the introduction of small, short-duration, high-yielding varieties of rice and wheat. As a result, the green revolution phase has transformed Punjab into a national food basket but at the same time, it has created several new potential threats to sustain the existing level of production. A paradigm shift in cropping pattern, mainly for monoculture (rice-wheat) with high input intensity (water, fertilizers, pesticides, etc.) from multi-crop practices (maize, millet, cotton, pulses and oilseeds) were one of the most significant changes (Sood *et al*., 2009a, Choudhury *et al*., 2013). Its implication is particularly apparent now on the decline of the groundwater from 0-2 m to > 4.0 m over the decades (2012 to 2002) in 77 to 84% of the area (CGWB, 2022), micro-nutrient deficiency, and soil contamination in the state (Sood *et al*., 2009b; Yousuf *et al*., 2022).

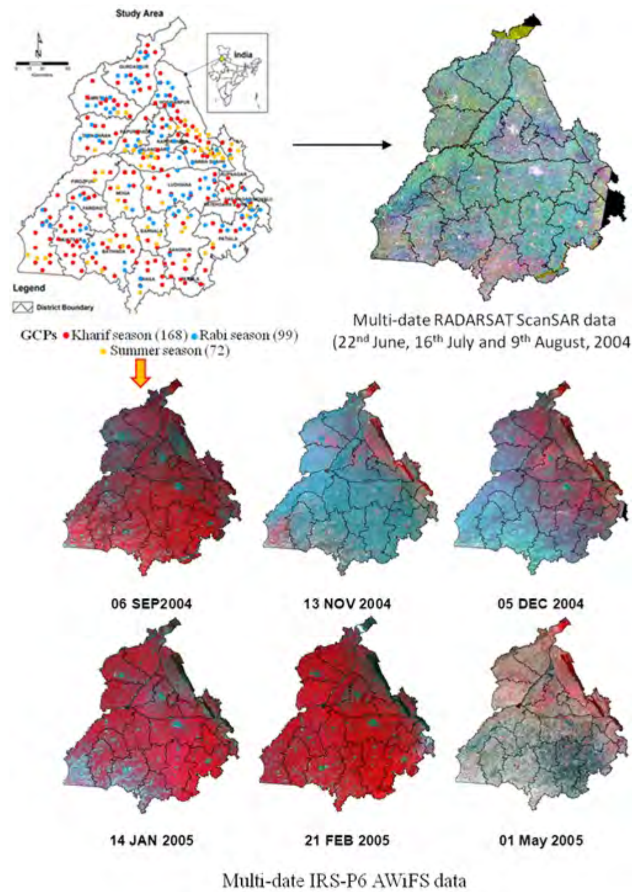
A cropping system can be defined as cropping patterns and their management to maximize the benefits of a given resource base under specific environmental conditions (Yang *et al*., 2020). It plays a key role in agricultural production, socio-economic and significant environmental impacts, namely controlling erosion (Schulte *et al.,* 2017), improving soil health and ecosystem services (Vukicevich *et al*., 2016) and the global carbon footprint (de Araújo Santos *et al.,* 2019). Considering the availability of water, soil health and agrophysical conditions of Indian Punjab, It is now an ecological compulsion to contemplate a cropping system approach to sustain food production through diversification and intensification of crop areas (Bal *et al*., 2018). However, insufficient information on the spatial distribution and efficiency of common cropping systems are the major bottlenecks to support precision management decisions, such as diversification of mono-cropped areas, while intensifying the cropping system enriching soil health.

Remote sensing data offer a great opportunity to generate spatial information at a regional scale (Poojashree and Peladdy, 2022). Because of their point of view, multi-spectral, multi-resolution and frequent monitoring capabilities, satellite data of various resolutions have been widely used to produce agricultural statistics, spatial maps and even yield estimates in many regions of the world (Ibrahim *et al*., 2021; Mahlayeye *et al*., 2022), including India (Panigrahy *et al*., 2003; Singh *et al*., 2011; Rao *et al*., 2021; Prasad *et al*., 2021). However, the unavailability of multi-spectral optical images often during the *kharif* season (June-Sept) due to cloud cover in various parts of India becomes a constraint in the estimation of rice area. However, non-availability of multispectral optical images often during *kharif* season (June-Sept) due to cloud cover in various parts of India (Panigrahy *et al*., 2003, Singh *et al*., 2011) becomes a constrain in *kharif* rice area estimation. Integration of microwave remote sensing data, such as SAR data, may address this gap (Chakraborty and Panigrahy, 2000) and thus, spatial analysis of cropping system will be more refined and cost-effective (Panigrahy *et al*., 2003, Singh *et al*., 2011; Zhao *et al*., 2021). Realizing the needs, in the present study, we used multi-temporal data sets from IRS-P6 AWiFS and RADARSAT SAR (ScanSAR beam mode) to generate a spatial database on the district-wise cropping system of Indian Punjab and then used different indices to evaluate the efficiency of the existing cropping system.

2. MATERIALS AND METHODS

Study Area

The study area (Punjab), lies between 29°33' to 32°31' N latitudes and 73°53' to 76°55'E longitudes at an average elevation of 244 meters above sea level. The state forms a part of the Indus plain with a geographical area of 5.04 M ha and is divided into 20 districts (Fig.1). The climate of the study area is semi-arid and monsoon type. The highest temperature (44.2°C to 44.7°C) is recorded in June and the



**Ground truth points (339) were collected for assessing classification accuracy of cropping pattern*

Fig. 1. Multi-date IRS-P6 AWiFS and RADARSAT Scan SAR data of study area (Indian Punjab)

lowest (0°C to 2.2°C) in Dec. The annual distribution of rainfall varies between 400 mm and less in the south-west and over 1000 mm in the north-east part of the state (Dahiphale *et al.,* 2022). Most of the rain falls in July through Sept. The soils, mostly derived from alluvial deposits, are deep, neutral to alkaline in response (pH 6.5-8.5), low in organic carbon and available nitrogen, low to very high phosphorus and moderate to high potassium (Sood *et al.,* 2009a). The principal crops grown in the state are rice, wheat, cotton, maize, sugarcane and vegetables, with a cropping intensity of 188%. The state has 93% net irrigated area through canals and tube wells (Sood *et al*., 2009b; Choudhury *et al*., 2013; Bal *et al.,* 2018).

Data Used

Two types of remote sensing data, namely multi-temporal optical and microwave data were used. The specifications of IRS-P6 AWiFS and the multi-dates acquired from Sept 2004 to May 2005 to map *kharif* (June-Oct), *rabi* (Nov to Mar) and summer growing seasons (April-May) are shown in Table 1. Optimal coverage scenes were selected through browsing with different path/line

Table: 1
Specifications of IRS-P6 AWiFS sensor and AWiFS data used for analysis

Parameter	Specifications	
Spectral Band (nm)	B2 : 520-590 (Green); B3 : 620-680 (Red); B4 : 770-860 (NIR); B5 : 1550-1700 (SWIR)	
Spatial resolution	56 m	
Radiometric resolution	10 bit	
Temporal Resolution	5 days	
Swath-width	740 km	
	IRS-P6 (AWiFS) Data used	
Season	Dates	Path/Row
Rabi	13/11/2004; 5/12/2004; 14/01/2005; 21/02/2005; 8/03/2005	96/50; 95/50; 94/50; 92/50; 95/50
Kharif	13/11/2004; 6/09/2004; 15/10/2004	96/50; 96/50; 95/50
Summer	1/04/2005; 1/05/2005	95/50; 96/50

combinations on the study area to eliminate cloud-free scenes.

Apart from AWiFS data, RADARSAT Scan SAR Narrow B Beam (SNB) data sets were acquired (Table 2) to estimate the rice area for the *kharif* season, as cloud-free data from the optical sensor are rarely available during this period. First-date data were acquired coinciding with the puddling to transplanting stage. Subsequent data were acquired with a 24-day repeating cycle that covered growth to the maximum vegetative stage of the crop. These dates were deemed appropriate for monitoring field rice crops in India (Chakraborty and Panigrahy, 2000) and detailed specifications are provided in Table 2.

Table: 2
Specifications of sensor RADARSAT Scan SAR Narrow-2 data used for rice crop mapping

Data characteristics	
Incidence angle (Degree)	31-46
Pixel spacing (m)	25×25
Beam mode combinations	W2; S5; S6
Resolution (Range*Azimuth), m	55.1*71.1; 50.1*71.9; 45.7*78.8
SAR band and polarization	C-Band (5.3 GHz), HH-polarisation
Normal swath (km)	350
Repeat cycle (days)	24
Data acquisition	22/06/2004;16/07/2004;9/08/2004

Dataset Preparation

AWiFS data sets of 56 m spatial resolution were resampled to get a 50 m pixel data set and the master scene (Oct, 2004) was registered against the available geo-referenced linear imaging self scanning (LISS)-III sensor data following nearest neighbourhood resampling approach and 2nd order polynomial model. Other images were registered following image-to-image registration using the rectified Oct, 2004 images. The image-to-image registration was done with sub-pixel accuracy of <0.5 root mean square error in second order polynomial. PCI Geomatica 9, ver. 9.1, a commercial image processing software package (PCI Geomatics Inc., Richmond Hill, Ontario, Canada) was used for radiometric corrections, geo-referencing, and classification of the cropping patterns in Punjab.

Three SAR data (June 22, July 16, and Aug 9, 2004) were processed to obtain a stack of geo-referenced data sets co-registered following the Chakraborty and Panigrahy (2000) procedure. The three dates co-registered in one multi-temporal data set reflected the variation in rice planting in the study area. The primary colours of red, green and blue were assigned to multiple dates to generate a multiple date SAR FCC image (Chakraborty and Panigrahy, 2000; Choudhury and Chakraborty, 2006). De-scalloping was performed to remove the image banding followed by speckle suppression using a preset adaptive low-pass filter. Then, converted digital pixel numbers (DN) to backscatter values and encoded 8-bit DN using a predefined scale. Speckle filtered data were calibrated to generate the backscatter image using the orbit information stored in the header (Chakraborty and Panigrahy, 2000; Choudhury and Chakraborty, 2006). After preparing the stack, it was registered with AWiFS data by taking 10 to 12 ground control points (GCP) using the nearest neighborhood re-sampling approach and the second order polynomial model.

Classification and Analysis Approach

Removal of non-agricultural classes

The non-agricultural classes in the image included permanent vegetation, wasteland, water bodies, and urban/settlement. Using three-date SAR data, the water bodies and urban/settlement were classified using a decision rule based classifier. Water bodies have very low DN values and transplanted rice fields have higher DN values. Back scattered values generated for segregation were -20 dB for open water (inland), -6 to -8 dB for saturated fallow fields with exposed soil prior to rice transplantation and -11 to -18 dB for the rice transplanted field. A simple threshold analysis technique was applied to mask these classes (Panigrahy *et al.*, 2003). Nine images of the normalized difference vegetation index (NDIVI) were derived from the nine AWiFS datasets from Sept to March. Similarly, settlement and water body masks were generated from 3-date SAR data. To mask other non-agricultural classes, unsupervised iso-data classes were assigned to the different land cover and land use classes on the NDVI images along with settlement and water body masks. Seasonal fallow land was included in the agricultural zone. Fig's 2 and 3 show a sequential flowchart illustrating the steps taken to mask, non-agricultural classes from multi-date SAR and AWiFS data.

Rice mask generation

A decision rule classifier was used to classify SAR data at three dates for the generation of the rice area map (Chakraborty and Panigrahy, 2000). The decision rule used in this study is:

If, *DN_d1> = 100* and *DN_d1< = 170* and *DN_d2 > DN_d1 + 10* ⟶ Class = Rice;

If, *DN_d2> = 100* and *DN_d2< = 175* and *DN_d2 > DN_d1+10* ⟶ Class = Rice;

If, *DN_d3 > DN_d2 + 10* and *DN_d3 > = 140* and *DN_d3 < 195* ⟶ Class = Rice;

DN_d1, DN_d2, DN_d3 are digital numbers for the dates June 22, July 16 and Aug 9, respectively. The sequential flow of the methodology is shown in Fig. 2.

Generation of cropping pattern and crop rotation maps

Crop classification was done separately for each season (*kharif*, *rabi* and summer). A total of 339 ground truth points representing different land use patterns, including crop growth stages, was collected through periodic field visits. The geographic coordinates of ground truth sites were recorded using global positioning system (GPS) and Survey of India (SoI) topographic maps on a scale of 1:50 K. A two-step classification process was followed *i.e.* derivation of the NDVI image for each data set, followed by unsupervised iso data classification. NDVI images of the 9-date AWiFS data were generated using the following relationship: NDVI = (NIR - R) / (NIR + R); where NIR and R are near infrared DN values and red bands, respectively. Unsupervised classification of iso-data was done on NDVI maps to generate *kharif, rabi* and summer cropping patterns. Crop rotation classes were determined based on the cropping pattern maps generated from the NDVI images. Using rice and the non-agricultural area mask, other crops (cotton, maize, pulses, vegetables, etc.) were extracted from the AWiFS data on 6 Sept, 15 Oct and 13 Nov 2004 and the *kharif* cropping pattern map were generated.

Temporal NDVI profiles among the *kharif* non-rice crops reflected a distinct pattern of maximum and minimum values for crop growing seasons (seeding to harvest). This made it easier to segregate individual crops or crop groups. Maize areas reached a maximum NDVI of 0.78 (average) in early Sept, and then gradually dropped to 0.50 by mid-Oct and reached a low of 0.10 by mid-Nov (already harvested). Conversely, for cotton growing areas, a maximum (average) NDVI value of 0.81 was measured in mid-Oct, then slowly declined to 0.54 in mid-Nov because the standing crop was in the field. Sugarcane, a long-duration crop (March through Feb), NDVI values (mean) steadily increased from 0.45 (early Sept) to 0.60 (mid-Oct) and finally peaked in mid-Nov (0.64). *kharif* short-duration pulses (e.g. green gram, mesh, soybean, etc.), vegetables (e.g. Cucurbits, brinjal, chili, etc.) and other crops (e.g. Groundnut, moon, Mentha, fodder, mixture, etc.) reached maximum NDVI values (0.52-0.57) in mid-Sept and then decreased between Oct and Nov. NDVI values fell sharply in pulse growing areas (0.06 in mid-Nov, already harvested) compared to vegetable growing areas (0.23), which, with detailed information about the ground truth, helped in segregation. When the unsupervised classification was not satisfactory (deviation >10.0% from the Punjab DOA statistics), then only this group of districts was reclassified. In the monoculture (single crop dominating the scene) area, an optimal date was selected by visual examination of all images. This optimal date image was used for supervised classification (using training sites) of the major crop following the maximum likelihood approach to classify the pixels (Fig. 3). Similarly, for *rabi* season, using the agricultural mask, *rabi* crops like wheat, vegetables, potatoes, etc. were extracted from AWiFS data on 13 Nov, 5 Dec 2004 and 14 Jan, 21 Feb, 8 March 2005 and finally, the *rabi* cropping pattern map was generated. In a similar approach, the summer cropping pattern map was generated from AWiFS data from April 1 and May 1, 2005 (Ray *et al.,* 2005).

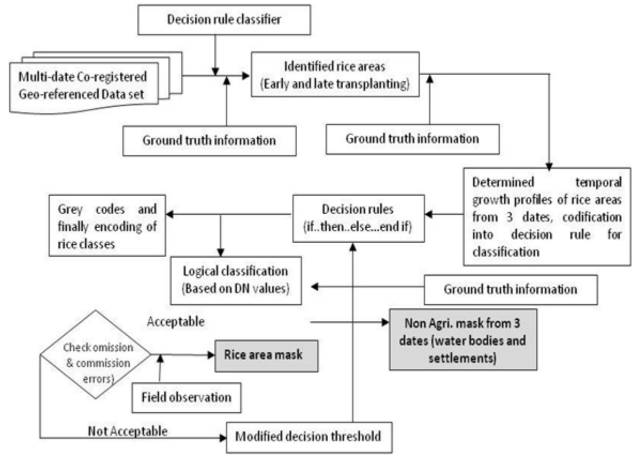


Fig. 2. Flow diagram of rice area mapping from multi-date RADARSAT Scan SAR data

The cropping pattern maps generated for *kharif*, *rabi* and summer seasons for the year 2004-2005 were integrated

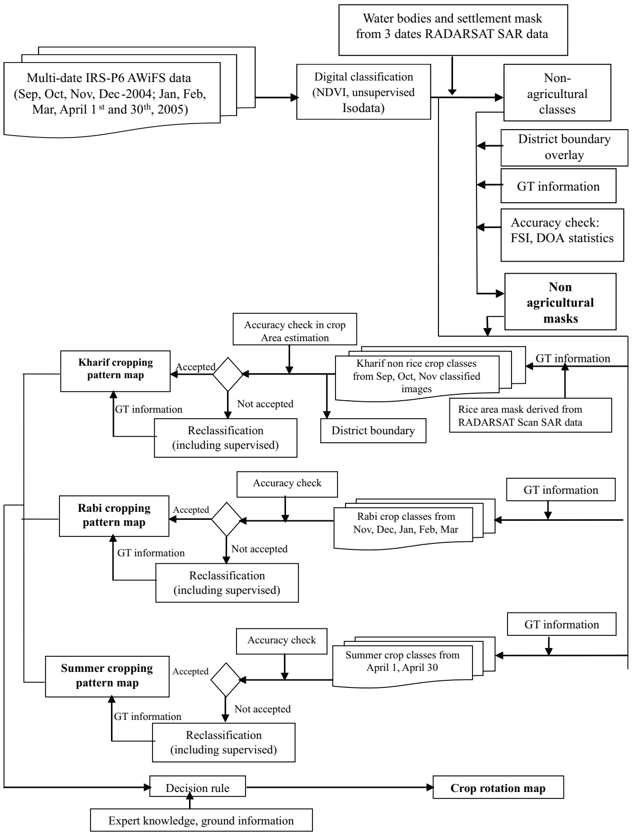


Fig. 3. Flow diagram of non-agricultural area and cropping pattern maps generation

to generate the crop rotation maps. A logical class-code combination algorithm was used to derive the crop rotation map (Panigrahy *et al*., 2003). The class codes used to designate the crop rotations is: rice-wheat is rice in *kharif* season and wheat in *rabi* season while rice-fallow-rice is rice in *kharif* season, fallow in *rabi* and again, rice in summer season. Similarly, others-wheat means green gram / red gram / mash / soybean etc. in *kharif* season and wheat in *rabi* season. Following generations of seasonal cropping pattern and crop rotation maps, an area at the district level was estimated for each category. A series of steps were followed to mask, crop rotation maps from multi-date SAR and AWiFS data (Fig's. 2 and 3).

Cropping system indices

To assess how effective different cropping systems are in terms of land use and crop productivity, three indices, namely multiple cropping, area diversity and cultivated land utilization indices, were computed.

Multiple cropping index (MCI)

This index is a measure of cropping intensity. It is calculated by the sum of the areas planted with different crops and harvested in a single year, divided by the total cultivated area multiplied by 100 (Dalrymple, 1971).

$$MCI = \frac{\sum_{i=1}^{n} ai}{A} \times 100$$

Where, n = total number of crops; ai = area occupied of the i^{th} crop planted and harvested within a year, A = total cultivated land area available. All these values were taken from seasonal cropping pattern statistics generated from the classification of AWiFS data.

Area diversity index (ADI)

ADI measures the multiplicity of crops, which are planted in a single year by computing the reciprocal of sum of squares of the area occupied by each crop. The ADI can be defined as:

$$ADI = \frac{1}{\sum_{i=1}^{n}\left(ai \Big/ \sum_{i=1}^{n} ai \right)^{2}}$$

Where, ai is the area under each crop. In order to depict season wise change in crop diversity, n was used as the number of crops grown in a season. ADI was computed individually for *kharif* (ADI_K) and *rabi* (ADI_R) seasons as well as for the complete growing cycle (annual) of 2004-05 (Panigrahy *et al.*, 2003).

Cultivated land utilization index (CLUI)

CLUI was computed by summing the products of land area planted to each crop, multiplied by the actual duration of that crop and divided by the total cultivated land area times 365 days. This index measures how efficiently the available land area has been used over the year.

$$CLUI = \frac{\sum_{i=1}^{n} ai.di}{A \times 365}$$

Where, n = total number of crops; ai = the area occupied by the i^{th} crop, di = days that the i^{th} crop occupied ai, A = total cultivated land area available during the 365 day period. Here again, ai and A were calculated using crop maps, as specific crop area and total agricultural area (TAA), respectively.

However, for computation of di, duration of each cropping system / rotation was computed using high temporal resolution satellite data of SPOT Vegetation (VGT) sensor. The remote sensing data used included the 10-day maximum value composite of NDVI products derived from VEGETATION sensor of SPOT-4 satellite. The NDVI profile (NDVI plotted against time) for each cropping system in the study area was fitted using a 5th order polynomial. From this fitted model, information on spectral emerging and spectral maturity dates was extracted, which were related to the start and end dates of crop cycles. The component total duration (di) was computed using the

NDVI profile for each crop rotation, where 10 days were added at the start (15 days of rice) and 10 days at the end of each growing season. These days explain the duration of field preparation, the distance between seeding and spectral emergence, and the distance between spectral maturity and crop harvest (Panigrahy *et al*., 2003).

Accuracy assessment

The accuracy of the cultivated area was verified with the help of agricultural statistics at district level, provided by the Bureau of Economics and Statistics (ESO), Govt. of Punjab for the same year (2004-05). The classification was accepted when the area of a particular crop was within 10% of the ESO area. If the classification did not match for a single district or a group of districts within a scene, then the reclassification was carried out only for that district/group of districts. Forest Atlas of India (FSI, 2001) has been used to statistically compare the forest areas of Punjab state and their spatial distribution (FSI, 2001). The accuracy of the crop area maps generated for three seasons (e.g. *kharif, rabi*, and summer) was further assessed by overlaying extensive geo-referenced ground truth points (GCPs: 339 nos.) collected over the study area during 2004-05 representing different land use / cropping system types. This was done by constructing an error matrix and estimating the Kappa coefficient (KC) (Table 3) for each map in the seasonal crop profile. The error matrix is the standard approach used to evaluate classification accuracy whereas Kappa analysis is a discrete multivariate technique that computes the overall accuracy of the producer and users, as well as the Kappa level of accuracy (Congalton and Green, 1999; Phan *et al*., 2020). The matrix was filled with reference points collected during three seasons (GCP of 168 for *kharif*, 99 for *rabi*, and 72 for summer) separately. To determine the accuracy of the classification, a 1 pixel sample was selected for the image classified by season (*kharif / rabi* / summer) and their class identity was compared with the GCP. The overall accuracy of error matrix classification results was above 80% for all

Table: 3
Accuracy assessment matrices for each cropping pattern map with ground truth data collected during 2004-2005

Kharif season	Rice	Cotton	Sugarcane	Maize	Vegetables	Pulses	Other crops
Rice	31	2	0	2	0	0	0
Cotton	1	23	1	0	0	0	0
Sugarcane	0	0	15	1	0	0	0
Maize	2	0	2	16	0	0	1
Vegetables	1	0	0	0	24	2	2
Pulses	0	0	0	0	3	12	2
Other crops*	0	1	0	0	3	2	19
Total GCPs	35	26	18	19	30	16	24
Agreement (AA)	31	23	15	16	24	12	19
Disagreement (DA)	4	3	3	3	6	4	5
Kappa Coefficient (K) = 0.806		Total GCPs = 168 (AA = 140, DA = 28)					
Rabi season	Wheat	Sugarcane	Potato/Vegetables	Pulses	Others crops		
Wheat	29	0	1	0	0		
Sugarcane	0	11	0	0	0		
Vegetables/Potato	0	1	15	2	3		
Pulses	0	0	1	10	2		
Others crops#	2	2	2	1	17		
Total GCPs	31	14	19	13	22		
Agreement (AA)	29	11	15	10	17		
Disagreement (DA)	2	3	4	3	5		
Kappa Coefficient (K) = 0.802		Total GCPs = 99 (AA = 82, DA = 17)					
Summer season	Sugarcane	Summer crops	Pulses	Current Fallow			
Sugarcane	11	0	0	0			
Summer crops^	1	21	2	1			
Pulses	0	3	9	2			
Current Fallow	1	1	1	19			
Total GCPs	13	25	12	22			
Agreement (AA)	11	21	9	19			
Disagreement (DA)	2	4	3	3			
Kappa coefficient (K) = 0.814		Total GCPs = 72 (AA = 60, DA = 12)					

Kappa coefficient (K) = (DA-AA)/(1-AA) three seasons, with KC values varied from 0.802 to 0.814 for *kharif, rabi,* and summer cropping pattern maps (Table 3). This is within the range described by Congalton and Green (1999) as strongly agreeing.

3. RESULTS AND DISCUSSION

Landuse Pattern

Land use statistics from remote sensing showed that 86% (4.33 M ha) of the state's area was used for agricultural purposes, while forests accounted for less than 3% of the area. The reported area under agriculture by traditional survey was 83.4% of TAG (Sood *et al.,* 2009a). There are few opportunities for horizontal agricultural expansion in the state. The water bodies comprising rivers, canals, wetlands and village ponds spread over an area of 27311 ha accounted for only 0.54% of the state's TGA. The main non-agricultural features, including urban and rural settlements and waste-lands, were classified in other categories and covered an area of 10.8% of the state's territory (Fig.4a).

The spatial distribution pattern of land use reflects that forest areas were mainly concentrated in the north-eastern parts (Kandi regions) comprising Gurdaspur (4.4% TGA), Hoshiarpur (18.5%), Rupnagar (15.1%), SAS Nagar (9.7%) and Nawanshehar (6.6%) districts of the state (Fig's. 4a and 5a). Agriculture was the primary land use for 17 of the 20 districts (84.3% to 94.4% TGA) while the remaining 3 districts (SAS Nagar, Rupnagar and Hoshiarpur fall in Kandi region) had less than 65% TGA (60.3-64.8%) in agriculture (Fig. 5a). Contribution of water bodies to non-agricultural features was marginal in all the districts (<1.5%) and were primarily contributed by the main rivers: Ravi, Beas and Satluj which flows through the north-west and central parts of the state. The insignificant amount of forest in the state indicates the urgent need to increase the percentage of forest cover through afforestation programs to maintain the ecological and healthy balance of the environment.

Kharif Cropping Pattern

Rice is the main crop for the *kharif* season, occupying 59.5% of the state's TAA (Table 4). Next to rice, other minor

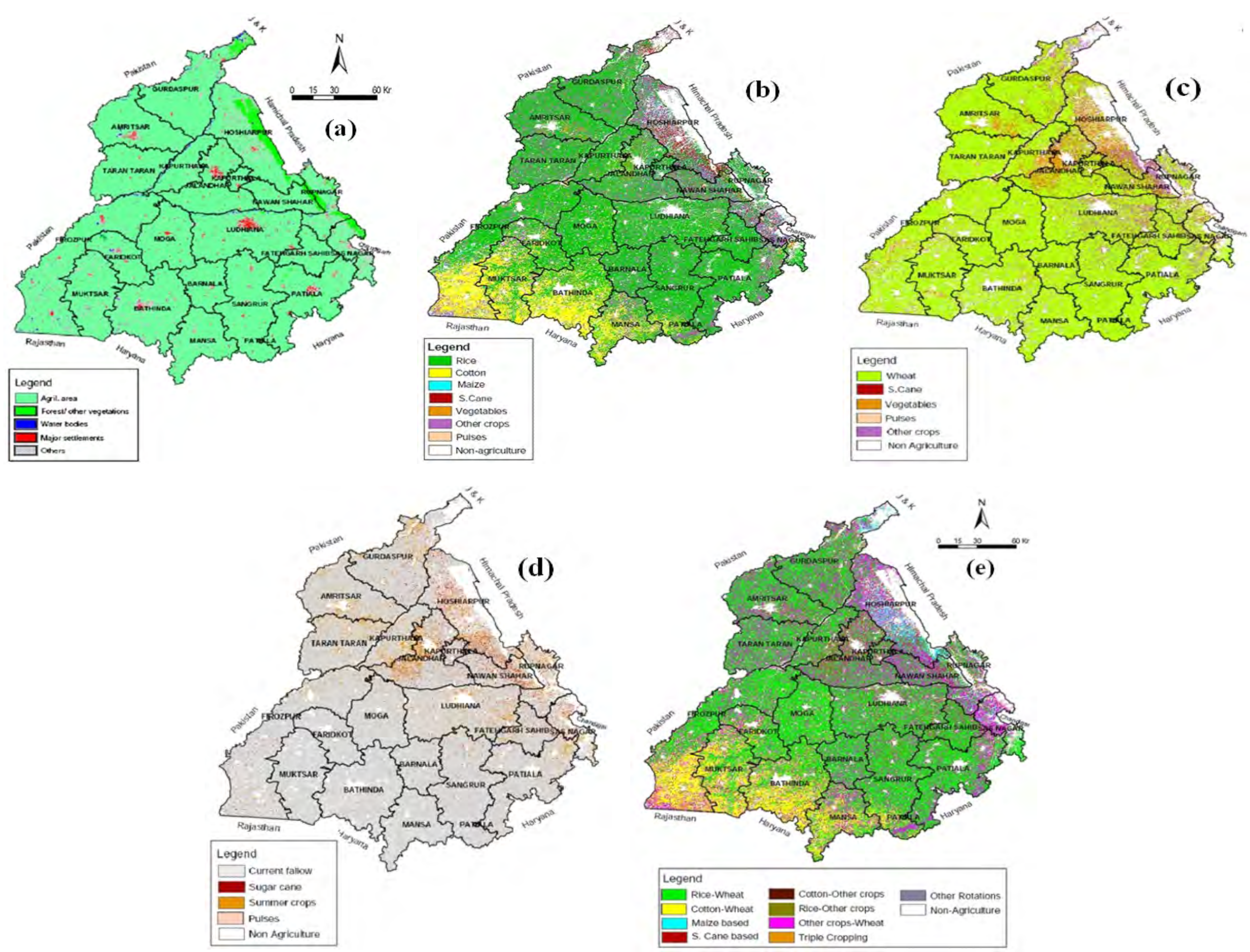


Fig. 4. RS derived spatial distribution pattern of (a) landuse (2004-05), (b) *kharif* cropping, (c) *rabi* cropping, (d) summer cropping, and (e) crop rotations in Indian Punjab

crops grown during the *kharif season* include cotton (11.91% TAA), maize (2.31% TAA), pulses (0.13% TAA), sugarcane (2.14% TAA) and vegetables (2.38% TAA) (Table 4). Dominance of rice crops were mostly due to assure remunerative prices, organized marketing facilities and free power operated irrigation facilities which led the farmers to switch over to rice cultivation from other *kharif* crops (Sood *et al*., 2009). The spatial distribution pattern showed that rice was uniformly cultivated as a major crop in the central parts of the state (Fig. 4b). The major rice-growing districts (more than 70% of TAA under rice) were Tarn Taran, Amritsar, Sangrur, Kapurthala, Patiala, Ludhiana, Barnala, Fatehgarh Sahib and Moga. In the north-eastern part (Kandi region), rice acreage ranged from 26.4% (Hoshiarpur) to 49.1% (Rupnagar). Similarly, in the south-west, the rice area ranged from 35.6% (Muktsar) to 49.3% (Firozpur) (Fig's. 4b and 5b).

However, unlike rice, cotton was grown mainly in the southwest area comprising the districts of Faridkot, Firozpur, Muktsar, Mansa and Bathinda. These five districts accounted for 94% of the total cotton area in the state (0.52 M ha) (Fig. 5b). Similarly, in the north-eastern part comprising districts

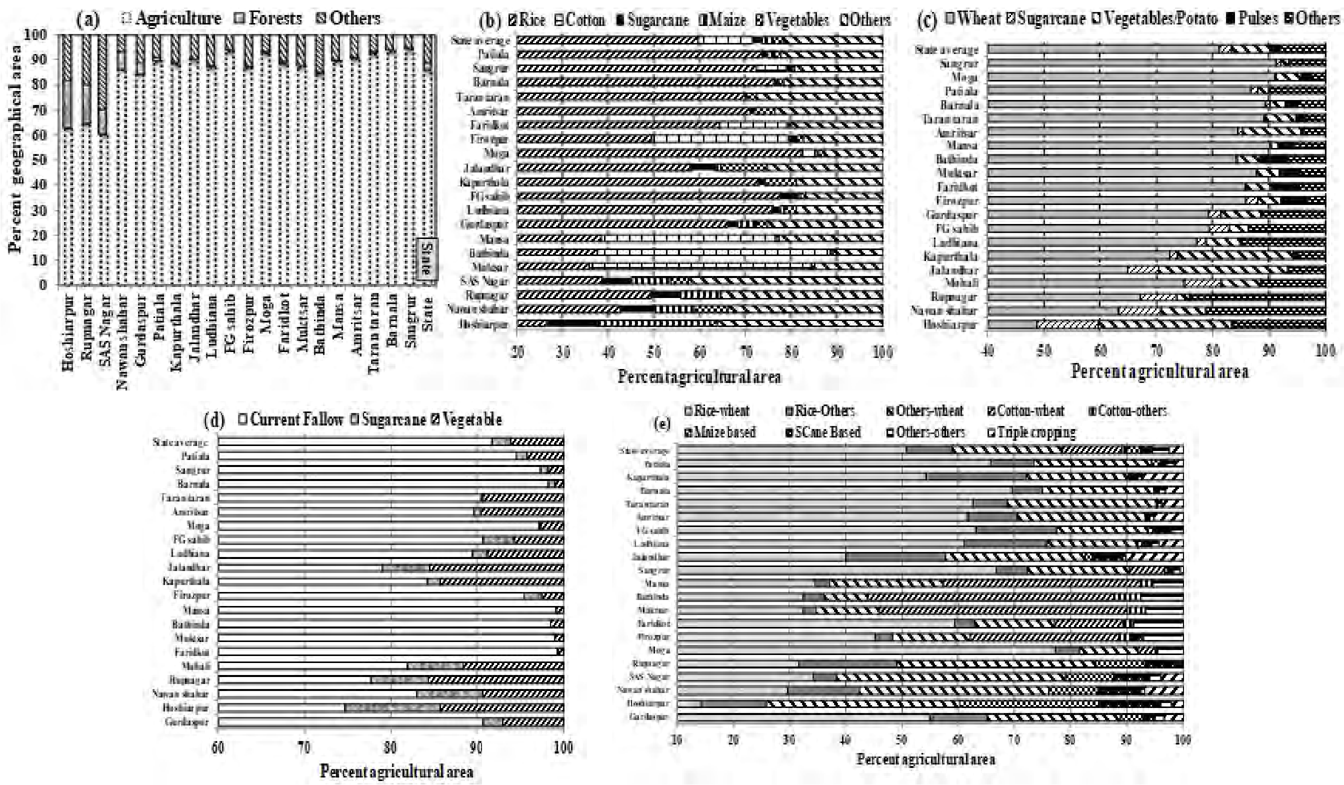


Fig. 5. RS derived district wise (a) land use pattern, (b) percent agricultural area under *rabi* cropping, (c) *kharif* cropping, (d) summer cropping, and (e) different crop rotations in the state of Punjab

Table: 4
RS derived percent agricultural area under different cropping pattern and crop rotation practices

Kharif	TAA$ (%)	*Rabi*	TAA (%)	Summer	TAA (%)	Crop rotation	TAA (%)
Rice	59.53	Wheat	81.21	Current fallow	91.98	Rice-wheat	50.88
Cotton	11.91	Sugarcane	2.14	Sugarcane	2.14	Rice-others	8.07
Sugarcane	2.14	Vegetables / Potato	7	Summer crops^	5.75	Others-wheat	19.60
Maize	2.31	Pulses	1.66	Pulses	0.13	Cotton-wheat	10.62
Vegetables	2.38	Others crops#	7.99	-----	-----	Cotton-others	0.89
Pulses	0.13	-----		-----	-----	Maize based	2.31
Other crops*	21.6	-----		-----	-----	S. cane based	2.14
						Others-others	3.06
						Triple cropping	2.43

*$TAA: total agricultural area; *Moong, Ground nut, mentha, fodder mixture; #Rapeseed and mustard, sunflower, winter maize, fodder mixtures; ^ Vegetables (cucurbits, tomato, potato, lady finger), mentha, sunflower, fodder mixtures*

Hoshiarpur, Gurdaspur, Nawanshehar, Rupnagar and SAS nagar, besides rice, other *kharif* crops like maize, sugarcane and vegetables also occupied a significant proportion of the agricultural area (Fig. 4b). The Hoshiarpur district had the largest area cultivated with maize (24.6% of TAA), followed by the Rupnagar, SAS Nagar and Nawanshehar districts. The state had a sizeable area (21.6% of TAA) under other minor crops like green gram, mash, groundnut, mentha, *susbania* spp. and fodder mixtures, which could not be mapped separately due to the scattered, small patchy distribution and use of medium resolution data (AWiFS-56 m spatial resolution). However, based on ground truth information, these crops were clubbed together into one class *viz.* other crops. The spatial distribution reflects their dispersed distribution in small parcels across the state (Fig. 4b). The Kandi belts had a significant proportion of the area (34.0-42.7% of TAA) under these crops (Fig. 5b).

In previous studies, optical images from IRS-1A LISS-I (1988-89) and IRS-1C WiFS data (1998-99) were used to map rice growing areas, which overestimated the rice area from 13.4% to 16.4% compared to DOA statistics of Punjab (Panigrahy *et al.,* 2003). The unavailability of cloud-free multi-spectral optical data coverage in the *kharif* season is common across India. Therefore, the integration of multi-date SAR microwave data with optical data in the analysis of cropping systems, especially the inventory of rice crops in most of India, including Punjab; had been suggested by a number of previous workers (Panigrahy *et al*., 2003, 2005, Singh *et al*., 2011; Zhao *et al.,* 2021). However, in this study, the use of multi-date AWiFS data at high temporal resolution (5 days) and spatial resolution (56 m) with SAR data; we could indeed map rice areas at district level more accurately. Assessment of classification accuracy using the error matrix and kappa factor greater than 80% and a deviation of <3.0% in the estimated rice area from the DOA statistics also supports the assertion of higher accuracy. Ribbes and Toan (1998) could also map the paddy fields of the alluvial floodplain in Indonesia (Jatisari test site) with a total accuracy of 87% with respect to the coarse land cover map (1:250 K scales). Similarly, in North Vietnam, using the C-band from RADARSAT-2, Hoang *et al.* (2016) could adequately map rice growing areas. This could be possible because the strong temporal backscatter of the rice field above the water surface can be effectively detected by SAR data.

Rabi Cropping Pattern

Wheat was the major crop during *rabi* season, occupied 81.20% TAA (69.81% TGA) of the state (Table 4), though varied spatially from 48.7% (Hoshiarpur) to 91.2% (Sangrur) across the state (Fig's. 4c and 5c). Minor crops were pulses, vegetables/potatoes and sugarcane, which together accounted for about 10.8% of the TAA. Other minor *rabi* crops cultivated in small, scattered plots across the state could not be mapped separately due to the use of medium resolution AWiFS data and clubbed together as single class had a significant presence (8.0% of TAA) (Figs. 4c and 5c). However, these crops were identified using GPS points such as rapeseed and mustard, sunflower, gram, winter maize and fodder. Wheat is spatially distributed all throughout the state while vegetables comprising mainly of potato were adopted in the northern part comprising Jalandhar, Kapurthala, Hoshiarpur, Nawanshehar and Amritsar districts of the state. In the south-western and the central parts of the state, wheat alone occupied more than 80% TAA, while in the Kandi belt (north-eastern part), wheat area was less than 66% of TAA. Sugarcane cultivation was mostly concentrated in the Kandi belts and Jalandhar districts of the state (Fig's. 4c and 5c).

In previous studies from 1988 to 1989 on the analysis of the crop system of Punjab using LISS-I data of coarse multi-temporal optical resolution (72.5 m), Panigrahy *et al.* (1997) could only map rice and wheat crops overestimated (by 10-14%), whereas other large acreage crops (like maize, cotton, sugarcane, potatoes, vegetables etc.) could not be mapped separately. Similarly, after a decade (1998-1999), cropping systems were analyzed using multi-temporal (5-day) optical satellite data from IRS-1C wide field sensor (WiFS) with a spatial resolution of 188 m. This time too, areas under major crops were over estimated (rice by 13.4%, cotton by 12.3% and wheat by 7.5%) compared to DOA statistics for the corresponding years, while minor crops could not be segregate (Panigrahy *et al.,* 2003).

However, as with our study, the US Department of Agriculture (USDA) has frequently used multiple-date AWiFS (56 m resolution) data in crop classification over several growing seasons (Boryan and Craig, 2005). Similarly, Champagne *et al.* (2007) also reported a minimum of three imaging dates for AWiFS data alone may provide a reasonably good classification for each crop within Canadian agricultural fields. They reported that 3-dates AWiFS data relative to finer (30 m) resolution SPOT-5 and Landsat-TM yielded comparable accuracy (80.8% *vs.* 83.2%) in the classification of individual crops, such as canola, sunflower, soybean, maize, etc.

Summer Cropping Pattern

During summer, most of the agricultural land (91.9% of TAA) remained fallow in the state (Table 4). Summer crops such as vegetables, mentha, sunflower, green gram and fodder mixtures were grown (in and around the major cities) on 6.15% TAA of the state. The remaining 2.14% of the district's TAA was grown on sugar cane. The spatial distribution pattern shows that among all the districts of Punjab, Hoshiarpur had a maximum percentage of area under summer crops including sugarcane (25.3%), followed by Jalandhar, SAS Nagar, Nawanshehar and Kapurthala with more than 15% of the TAA under summer crops (Figs. 4d and 5d). Summer pulses (green gram) were mainly cultivated in the central district of Ludhiana (Figs. 4d and 5d). Bal *et al.* (2009) also reported summer crops in approx. 5% of the Punjab's geographical region but they could not separate individual types due to the very coarse resolution (1 km per 1 km) SPOT-vegetation products, cumulative NDVI of 10 days.

Crop Rotation

Rice-wheat rotation was the dominant crop rotation, practiced in 50.9% of the TAA of the state (Fig. 4e). Next to rice-wheat, others- wheat (green gram / red gram / mash / soybean / groundnut-wheat) and cotton-wheat rotations also occupied a considerable area (19.6% and 10.6% of TAA, respectively) of the state (Fig.4e and Table 4). Using very coarse resolution (1 km by 1 km) SPOT-vegetation NDVI produced (10-day cumulative) for the same periods (2004-05), Bal *et al.* (2009) also reported that rice and cotton were the main crops of *kharif*, accounting for 77% of Punjab's agricultural area. Similarly, wheat represented 85% of *rabi's* cropped area, an overestimate of 5% based on our findings. As well, they could not separate minor crops, likely because of the very coarse resolution of the SPOT vegetation sensor. Likewise, Panigrahy *et al.* (2011) also reported that rice wheat was the main crop rotation in India's Indo-Gangetic plains, including Punjab.

The other rotations with significant presence we identified in the state were rice / cotton-others (berseem / winter maize / gram / vegetables / celery / berseem), maize based (maize-wheat / barley / potato / berseem), sugarcane based and triple cropping system (short duration vegetable based, early fodder / rapeseed-wheat, green manure-rice-wheat, rice / maize - potato - green gram) (Fig. 5e). Other minor cropping systems that could not be mapped using AWiFS data as individual classes due to scattering and fragmented distribution occupied 3.1% of the state's TAA (Figs. 4e and 5e). Using ground truth information, they were identified as moong / bajra / jowar / vegetables - barley / gram / vegetables / rapeseed and mustard. Therefore, to map separately the minor crop rotations with marginal area and scattered distribution, finer spatial resolution multi-spectral images compared to AWiFS data are needed. Areal extent and spatial distribution pattern shows that rice-wheat rotation was predominant in 11 out of 20 districts and in the remaining 9 districts, rice-wheat rotation also had a significant presence (Fig's. 4e and 5e). In the south-western part comprising Faridkot, Firozpur, Muktsar, Mansa and Bathinda districts, Cotton-wheat rotation was the dominant one while in the north-eastern part comprising Hoshiarpur, Gurdaspur, Nawanshehar, Rupnagar and SAS Nagar districts, other *kharif* crops like maize, sugarcane and vegetable based triple cropping systems were dominant (Figs. 4e and 5e). Jalandhar and Kapurthala districts located in the north-central part of the state had also a sizeable area under triple cropping system.

Cropping System Indices

Area diversity index (ADI)

The area diversity index over the *kharif* season (ADI_k) was 2.23 for the state, with significant variation at the district level from 1.44 (Moga) to 3.68 (Hoshiarpur (Fig. 6a). The typical rice growing districts (Gurdaspur, Kapurthala, Ludhiana, Patiala, Amritsar, Moga, Tarn Taran, Sangrur and Patiala) had ADI_k lower than 2.0 as rice occupied the major cropped area (>70% TAA). However, the districts which have had one more major crop (e.g. Cotton in Bathinda, Mansa, Faridkot, Firozpur and Muktsar while Maize in Kandi belt comprising Rupnagar, SAS Nagar, Nawanshehar and Hoshiarpur) (Fig. 6a) had higher ADI_k values (>2.0). Nawanshehar and Hoshiarpur districts

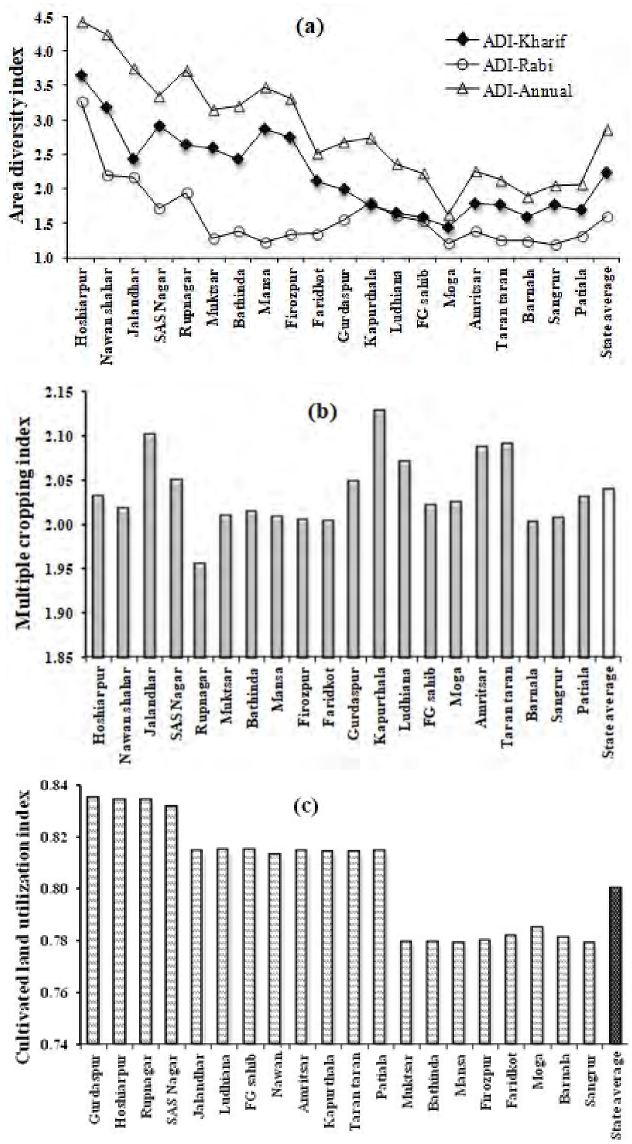


Fig. 6. RS derived district wise cropping system indices, namely (a) area diversity (b) multiple cropping intensity, and (c) cultivated land utilization of Indian Punjab

had even ADI_K values higher than 3.0, mostly due to considerable presence of vegetables (1.5% to 7.2%) and other crops like green gram, sesame, groundnut, etc. in more than 30% cultivated area (Fig. 4).

Due to the dominance of single crop (wheat) in >80% TAA during *rabi* season (Fig. 4c), area diversity was low for the state (ADI_R = 1.6) as well as in most of the districts (ADI_R =<2.0) (Fig. 6a) except Hoshiarpur (3.28), Nawanshehar (2.20) and Jalandhar (2.17) where wheat area was <65% and considerable presence of other crops such as potato, sugarcane, winter maize, rape seed and mustard etc. State average *rabi* ADI_R was also relatively low (29%) compared to *kharif* season (ADI_K), since wheat was the single most dominant crop (>81% TAA) during *rabi* season compared to significant presence of three crops during *kharif* season: rice (59.5% TAA), cotton (11.9% of TAA) and maize (2.3% of TAA) (Fig's. 4b and 4c).

The annual state ADI was slightly less than 3.0, indicating the predominance of more than two field crops in a single year (rotational diversity). This was obviously due to the dominance of rice / cotton-wheat cropping system followed in the state (about 59.6% of the state's TAA). At the district level, the ADI varied considerably (from 1.63 to 4.43), largely due to the variation in the ADI during the *kharif* and *rabi* seasons (Fig. 6a). Districts dominated by rice-wheat rotation had relatively less ADI than districts with three to five rotations such as Hoshiarpur, Nawanshehar and Rupnagar. Input intensive rice- wheat system has a high water requirement, more than 2000 mm. At district level, ADI varied considerably (from 1.63 to 4.43), mostly influenced by variation in ADI during *kharif* and *rabi* seasons (Fig. 6a). Districts with dominance of only rice-wheat rotation had relatively less ADI than in districts with three to five rotations like in Hoshiarpur, Nawanshehar and Rupnagar. Input intensive rice-wheat system has a high water requirement, more than 2000 mm (Choudhury *et al*., 2007).

To meet this requirement, nearly 72.5% of net area sown is irrigated using ground water drawn through tube wells resulting in the over exploitation of ground water resources in the state, especially in central districts where groundwater is declining at a rate of 30 cm annually (Sood *et al*., 2009b; CGWB, 2022). Therefore, some of the area must be diversified to low water requiring crops to arrest the further fall in the water table while increasing the crop area and production diversity in the state. A relatively higher annual ADI for Hoshiarpur and Nawanshehar (>4.0) reflects that, unlike other districts, accelerated diversification of cultivated areas is underway. This could be possible due to the presence of more than five crop rotations, none being the only rotation in those districts.

Multiple cropping index (MCI)

The state-level MCI calculated from remote sensing data was just over 200%. In 19 of the 20 districts of Punjab state, MCI was greater than 200% (200-212%), with the exception of Rupnagar, which had 195% MCI (Fig. 6b). Due to the cultivation of rice, cotton, maize in *kharif* and wheat, other crops during *rabi* seasons resulted in a cropping intensity of more than 200%. Of the 20 districts, Kapurthala and Jalandhar had the highest cropping intensity (>210%) (Fig. 6b). This was primarily due to the significant (14.3 to15.6%) presence of summer vegetables (potatoes, finger sunflower and mentha) apart from rice-wheat, other-rice/wheat system (Fig's. 4d, and 4e). Areas, valued at >200% of MCI are considered to be intensively cultivated (Panigrahy *et al*., 2005). Horizontal expansion and location specific diversification of short duration summer crops (pulses / vegetables) in other parts of the state can further improve the cropping intensity.

Cultivated land utilization index (CLUI)

CLUI indicates how efficiently the available land area has been used over the year. For a cropping pattern, where the land remains unused for a very short time, the CLUI reaches a value close to 100%, while for a completely unused land (all year round), the CLUI is 0.0%. The CLUI value derived from high temporal resolution RS data showed that, in the state of Punjab, the agricultural land was occupied for 292 days in a year by one or other crops (Fig. 6c). All districts had CLUI values greater than 0.77 (>273 growing days), although spatial variability between 0.77 (Sangrur) and 0.84 (Gurdaspur) was observed (Fig. 6c). Inclusion of short duration vegetables / pulses / oilseeds crops of around 60 days duration in the existing cropping systems (long duration rice-wheat) can increase the CLUI in the less utilized agricultural areas of the state.

4. CONCLUSIONS

The results of this study revealed that IRS-P6-AWiFS multi-date data with high temporal resolution (5 days) and medium spatial resolution (56 m) could be used effectively for identifying primary non-rice and minor crops during growing seasons, including characterization of cropping systems at district level. Use of microwave SAR data exclusively for rice area mapping greatly improved the accuracy of the area estimate, a minor variation (2.7%) compared to the DOA statistics of Punjab. The shortcomings related to the unavailability of cloud-free optical images, in particular during the *kharif* season, the difficulties of mapping rice growing areas can be efficiently overcome if multi-date SAR data are used. Similarly, integration of multiple-date SAR data and optical AWiFS data could efficiently characterize cropping systems, including major and minor crops at the district level with greater accuracy. This is illustrated by the marginal differences (<3.0%) in the estimated area of major (rice, wheat, cotton, maize etc.) and minor (pulses, vegetables, potato, sugarcane, etc.) crops relative to the DOA statistics.

A high concordance (>80.0%) of the error matrix and a Kappa estimate against adequate ground truth information also confirmed the accuracy of the classification of seasonal cropping pattern. Therefore, we suggest that SAR data be integrated into multispectral optical data for multi-dates to improve the accuracy of crop classification over the growing season. However, the future scope lies in the use of multi-spectral (spatial) resolution data that is finer than medium resolution AWiFS data to improve the spatial characterization of minor crops and their rotation distributed in small scattered patches.

Contrary to earlier studies, this study provided a comprehensive estimate of the area and spatial distribution of each principal and minor crop grown throughout the year (all three seasons) across the Indian Punjab. From the results, it was confirmed that inputs (water, fertiliser, pesticides and energy) intensive rice (in *kharif*) followed by wheat (in *rabi*) rotation is the dominant cropping system in the state. In the world literature, including Indian Punjab, it is well documented that rice is one of the highest guzzlers of water, fertilizers, pesticides and intensive energy in wet tillage operations, in particular transplanted puddled rice in Punjab. In the post-green phase of Punjab, the expansion of rice cultivation continues even in unsuitable areas such as coarse-textured soils, semi-arid south-western (annual rainfall below 500 mm) and central regions with declining water tables. The adverse effects of large-scale rice-wheat monoculture in the state have been clearly visible on the ecological front. Whether it is the erosion of genetic diversity, the fall of the water table (in >78% of Punjab) of over-exploitation and the south-west part is already in the process of desertification. Similarly, widespread contamination and degradation of soil and water resources, stagnating productivity of field crops (rice and wheat) and increasing production costs.

From the spatial distribution of crops revealed in this study, we suggest the following steps to address these gaps to the extent possible:

i. Diversification of input intensive rice by low water requiring crops (e.g. Desi cotton, rapeseed, mustard, millets, etc.), and soil enriching legumes and pulses (e.g. Green gram, black gram, Moong, groundnut, mint, etc.), specifically, in the semi-arid south-western regions, where annual rainfall is below 500 mm and coarse-textured soils predominate.

ii. In central Punjab, specific diversification of the rice growing area by low water demand and soil enrichment of legume crops. This could slow the pace of water table decline caused by excessive pumping of ground-water for irrigation, while minimizing the secondary impacts of water-logging in southwestern Punjab.

iii. The north-eastern parts of Punjab with high annual rainfall (>1000 mm) and good drainage should be preferred for growing maize and vegetables.

iv. In floodplains, fine-textured soils and areas with poor groundwater quality (salt affected), rice is expected to replace water-logging and salt sensitive crops such as maize, cotton, pulses and other minor crops.

v. Location specific diversification of wheat areas by *rabi* pulses, millets, and other low water requiring crops.

vi. Specific regenerative agriculture for improving soil health by enriching legumes and exploring the native microbial population, so that excessive dependence on input-based external agriculture can be gradually reduced.

This will reduce excess reliance on rice-wheat rotation while diversifying areas with more cotton-wheat, maize / cotton / pulses / vegetables based cropping systems. Therefore, the positive impact will be visible in the stressed available water resource, improving nutritional diversity and net profitability while minimizing ecosystem degradation, including soil, water and biodiversity.

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