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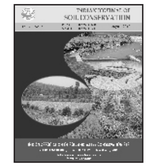

Geo-spatial analysis for assessment of agro-ecological suitability of alternate crops in Indian Punjab

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ABSTRACT

Crop intensification with the dominance of high energy input intensive rice–wheat mono-cropping system in Indian Punjab from early 1970's has led to over-exploitation of the agro-physical resources (soil and environmental health, ground water resources, ecosystem functioning and pollution etc.). It is now ecological compulsion to adopt suitable alternate land use practices including location specific crop area diversification. We made an attempt to delineate the state of Punjab into various agro-climatic and agro-ecological spatial zones (AEZ) using integrated approach of remote sensing (RS) derived agro-physical inputs (NDVI based biomass zones, existing cropping pattern and crop rotations), geospatial information (thermal zone, rainfall zone, length of growing period (LGP), soil texture, ground water etc.) and field observations. Based on standard criteria, integration and subsequent logical classification of these themes, the state of Punjab was divided into 7 major AEZ and 46 homogenous AEZ sub-zones. Considering the agro-ecological conditions of each zone, we suggested location specific suitable alternate crop/husbandry plan with due consideration to existing input resources like thermal and LGP requirements of different crops, biomass production potential, soil health problems (salt affected, water logging and water table status) etc. We also suggested potential areas for adoption of agro-forestry and horticulture based landuse systems in order to arrest the deterioration of forest cover and soil-environmental health of the state.

1. INTRODUCTION

The state of Indian Punjab and its farmers, once at the center stage of green revolution, are now facing serious problems of sustaining agricultural productivity (Aulakh, 2002 and Patel, 2013). The nature of problems faced by the farmers differs across the three regions (north-east foot hills, central plain and south-western zone) of the state (Hira and Kukal, 2014). In central plain, dominance of water intensive rice-wheat cropping system resulted in over-exploitation of ground water resources and thus, water table is declining at 0.3 m yr^{-1} (Sood *et al*., 2009a and Choudhury *et al*., 2013). In south-western zone, the cotton-wheat is the dominant system and ground water of this zone is brackish in nature, a factor limiting their exploitation for irrigation (Hira and Kukal, 2014). Extensive use of fertilizers and pesticides in cotton crop (Aktar *et al*., 2009) is increasing cost of cultivation while marginalizing the returns, besides creating serious environmental and health hazard problems. In the ecologically fragile north-eastern (*Kandi*) region, water erosion, occurrence of recurrent droughts in some parts, resource degradation and low level of overall socio-economic developments are the major impediments for sustaining the land productivity levels (Hira, 2002 and Hira and Kukal, 2014). Over the years, the state has witnessed a major shift in cropping pattern: from a diversified crop-husbandry practices of traditional low input requiring, soil enriching crops to input intensive rice-wheat/cotton-wheat mono-cropping (Sood *et al*., 2009a). As a result, pumping of ground water for irrigating rice areas has been over-exploited: water table depth below 10 m has increased from 3% in 1973 to more than 90% in the total geographical areas of the central plain region of the state (Hira, 2002; Sood *et al*., 2009b; Choudhury *et al*., 2013). Water logging and secondary salinity are the other consequences of indiscriminate use of good and marginal quality waters for irrigation (Hira and Kukal, 2014).

However, the enormous growth and expansion of irrigated agriculture (>99% of total cropped area) led significant changes in land use/land cover (removal of sand dunes and other natural vegetations) over the years. This led to change in agro-climatic conditions at various places in the last few decades (Bal *et al*., 2008 and 2012). This was evident from the gradual increase in minimum temperature (0.04-0.07^{o}C yr^{-1}), especially in the months of February and March over the past four decades, which is detrimental for productivity of stage sensitive crops like wheat (Kaur *et al.,* 2012). Thus, to sustain the productivity *vis-à-vis* food security and ecosystem health, current status of the state demands adoption of location specific diversified land use practices including crop / horticulture / agro-forestry considering suitability of various agro-physical input parameters (Lakkad *et al*., 2015; Vittorio *et al.,* 2016; Bandyopadhyay *et al.,* 2018). In this regard, allocation/ adoption of specific land use/husbandry practices should be based on agro-ecological condition. Location specific land use planning has direct bearing on land productivity enhancement as well as in assuring economic benefits to the adopter (Bandyopadhyay *et al.,* 2018). Therefore, delineation or redefining the state into different homogenous AEZ is the pre-requisite for sustaining the production system while conserving the natural resources.

In the past, agro-climatic zones for the state of Punjab were demarcated by manual integration of agro-climatic and other natural resources data (Mavi, 1984). As a result, large amount of agro-ecological spatial data could not be handled easily. This led to the loss of information on spatial variability. With the advent of modern tools such as satellite RS and GIS, new dimensions have been provided to periodic monitoring and managing effectively natural resources in spatial domain at regional or even larger scale (Lakkad *et al*., 2015 and Sudhishri *et al*., 2017). Thus, in the changing climatic and land use scenario, there is a need to analyze the existing agricultural land-use pattern and suggest the viable alternatives considering location specific condition to sustain the existing agricultural productivity and soil-environmental health.

2. MATERIALS AND METHODS

Study Area

The study was conducted during the years 2006 and 2007 at Punjab Agricultural University, Ludhiana in collaboration with Punjab Remote Sensing Centre, Ludhiana. The Punjab state, with a geographical area of 50362 sq.km, forms a part of the Indus plain and lies between the latitudes of 29^{o}33'N to 32^{o}31'N and longitudes of 73^{o}53'E to 76^{o}55'E (Hira and Kukal, 2014).

Collateral and Satellite (SPOT 10-day Composite NDVI Images) Data

Administrative boundaries (state and district) at 1:50000 scale from Survey of India (SoI) maps and soil map at 1:250000 scale prepared by National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) (Sehgal *et al.,* 1992), modified/simplified by Punjab Remote Sensing Centre was used. RS data of SPOT-vegetation sensor 10-day cumulative NDVI product of 1 km resolution was used (Bal *et al., 2012*). The data was available in the form of 10-day composites to escape the effect of cloud cover, satellite miss etc. All together, 36 composites per year (3 per month) were used starting from June 1, 2004 to May 21, 2005 and from June 1, 2005 to May 21, 2006. Spectral bands of Blue (0.45-0.52 μ), Green (0.52-0.59 μ), Red (0.62-0.69 μ) and Infra red (0.72-0.78 μ) were available in the images for analysis.

Crop Classification

Crop classification was carried out separately for each of the three seasons: May 21 to Oct 21 for *kharif* season, Nov 1 to April 1 for *rabi* season and March 21 to May 21 data was used for summer season crops (Panigrahi *et al*., 2010 and Choudhury *et al*., 2013).

Generation of Cropping Pattern and Crop Rotation Maps

Cropping pattern is defined as the yearly sequence and spatial arrangement of crops or crops-fallow, in a given area. For convenience, it was categorized on the basis of crop seasons as-*kharif*, *rabi* and summer season cropping patterns. RS based satellite data is one of the major sources for obtaining a detailed spatial (Lakkad *et al*., 2015) distribution of cropping sequence and crop rotations practiced in an area at different scales ranging from few sq. meters to regional level. One can distinguish the crop sequences from the rise and fall of NDVI values in its temporal profile. The pattern of rise and fall of NDVI values and the duration of the peaks can be distinctly linked to the life cycle of a particular crop, which after identification can be verified from field ground truth observations. The crop rotation map was generated by logical combination of the three seasonal cropping pattern maps (Bal *et al*., 2009). The class codes used to designate the crop rotations is: rice-wheat means rice in *kharif* while wheat in *rabi* season, cotton-wheat means cotton in *kharif*, wheat in *rabi* season.

Crop Diversification/Alternate Cropping Pattern Plan

An alternate sustainable crop diversification plan was generated at regional scale (Indian Punjab) using various agro-physical parameters in spatial domain such as LGP, soil texture, problem soils, ground water table condition etc. Thus, while suggesting the alternate crop plan for crop diversification, emphasis was given to the problems associated with the existing status of agricultural scenarios of Punjab like declining water table, water logging, soils with heavy salt concentration, mono culture, lesser forest cover etc. Different crops require different climatic condition and soil parameters for their optimum growth. Assessment of all these factors indicate that immediate measures for alternate sustainable agricultural practices with emphasis on crop diversification are needed to prevent irreparable damage of the natural resources of this granary state of India.

Assessment of Crop Suitability and Selection of Proper Crop Rotations

Assessment of crop suitability was carried out by a combination of matching constraints with crop requirements. Selection was done by taking consideration of the restrictions in space and time dimensions, and the fallow requirements of the annual cropping pattern options. Restrictions were imposed by agro-ecological conditions. For example, only mono-cropping is possible in the semi-arid areas. Crop rotation options were formulated for each agro-ecological cell for each cropping pattern options generated. Step-wise procedure followed for driving agro-ecological sub-zones have been depicted in Fig. 1 and the derived zones are presented in Fig. 2.

Matching Crops to Thermal, Growing Period and Problematic Soil Zones

The initial step in the matching process was the comparison of the temperature requirements of individual crop with the identified thermal zones of the climatic resource inventory. This step is essentially a screening exercise which excludes crops which are

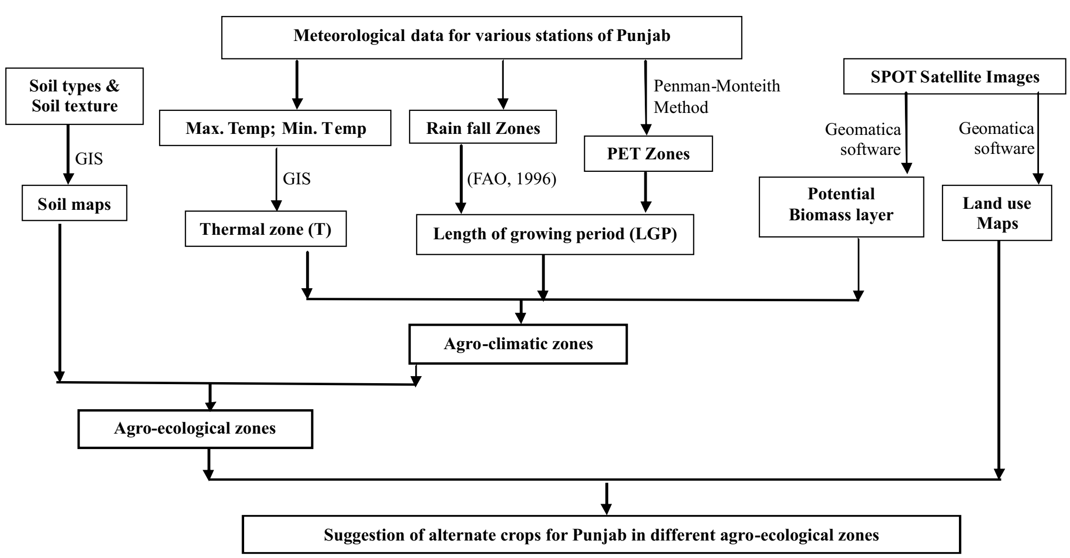

Fig. 1. Flow diagram depicting the step-wise procedures followed for Agro-ecological zoning of the study area

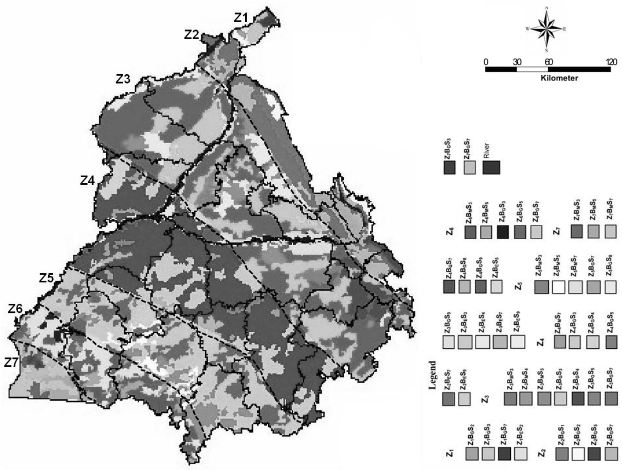

Fig. 2. Delineated agro-ecological zones of Punjab using remote sensing and GIS data

unsuitable in the specified temperature regimes from further analysis. On meeting all the requirements, the zone was rated TS1, while meeting partial requirements (sub-optimal), the zone was rated TS2. In the case of not meeting any requirements, the zone was rated as TN (not suitable). Since temperature across the state varied gradually (21-26°C), therefore, the concept of matching temperature requirements was less-significant. Rather, we gave more emphasis to variable LGP with wide variability across the state (< 60 to 180 days) and is also one of the major deciding factors for selecting crops in different parts of the state.

Under favourable climatic conditions, increased land productivity can be achieved through multiple cropping. Crops may be grown either sequentially or in mixtures. Sequential cropping is only possible when the available growing period (either single or multiple) extends beyond the duration of the growth cycle of a single crop. Keeping this in view, we suggested growing of crops throughout the year in areas with longer growing period (LGP >140 days) and lower ambient temperature (21-22°C). In areas with LGPs of 100-140 days and temperature of 22-24°C, we suggested growing of two crops, one in each season (*kharif* and *rabi*) while in areas with LGP < 100 days, single short duration annual crops were suggested. Soil texture plays a crucial role in crop suitability analysis. Heavy textured soils were favored for rice cultivation since rice is a high water demanding crop grown after heavy mechanized operation (*e.g.* puddling). Light textured soils were preferred for low water requiring crops (*e.g.* mustard, wheat, maize, cotton etc.) and deep rooted soil enriching crops like pulses including grams, ground nut and soybean. Various crops differ in their ability to grow differently in problematic soils like salt affected and water logged soils. These factors were also taken into consideration while suggesting crops for different agro-ecological zones. A generalized listing of crops sensitive and tolerant to salt affected and water logged soils are listed in Tables 1 and 2.

Selection of Alternate Crops Through Logical Approach

Seven agro-physical input parameters were finally selected for generating crop diversification plan. These were temperature, soil texture, physiography, LGP, problematic soil (saline/sodic), water logging and decline in water table depths. Based on logical classification of these themes (Table 3), the following crop suitability zones were derived and crops were suggested for different agro-ecological zones (Tables 4 and 5).

3. RESULTS AND DISCUSSION

Existing Agricultural Land-use Pattern Inventory

From the digital analysis of the SPOT 10-day composite NDVI images comprising 36 dates for the years 2004-05 and 2005-06, the present cropping pattern and crop rotation maps of Punjab state were generated. Season wise (*i.e. kharif*, *rabi* and summer) statistics on crop acreage from the cropping pattern and crop rotation maps were also estimated (Table 4). The same was validated with substantial representative

Table: 1
List of crops with relative tolerance to soil salinity

Tolerant	Semi-tolerant	Sensitive
Rice	Pomegranate	Maize
Date palm	Wheat	Citrus
Barley	Oat	Gram
Sugar beet	Sorghum	Peas
Rapeseed	Sunflower	Groundnut
Cotton	Potato	Green gram

(Choudhary, 2003)

Table: 2
List of crops with relative tolerance to water logging

Tolerant	Semi-tolerant	Sensitive
Rice	Barley, Soybean	Maize, Ground nut
Sugarcane	Wheat, Cotton	Peas
Broad bean	Sugar beet Oat, Sorghum citrus	Beans, Gram, Green gram Cowpea

(Hira, 2002)

Table: 3
Crop suitability plan derived for Punjab state based on agro-physical parameters

Physiography	Soil texture / Problem soil	Length of growing period (LGP)	Crop suitability
Piedmont plain	Finer than coarse loamy	> 120 days	Maize - Sugarcane
Piedmont plain	Finer than coarse loamy / soil salinity	> 120 days	Rice - Mustard
Piedmont plain	Coarser than fine loamy / soil salinity	< 120 days	Cotton - Mustard
Terraces	Finer than loamy skeletal	> 120 days	Rice - Wheat
Not equal to flood plains	Not equal to sandy	< 100 days	Cotton / Maize / Pulses - Wheat / Durum wheat
Not equal to Flood plains	Coarse loamy	> 100 days	Maize / Sugarcane
Flood plains, River bed	Coarse loamy	> 80 days	Agro-forestry
Piedmont plain with excellent biomass potential	Finer than coarse loamy,	> 120 days	Triple cropping
Piedmont plain	Sandy	> 80 days	Groundnut / Maize-Gram / Canola
Piedmont plain	Sandy	< 80 days	Pearl millet-Gram
Piedmont plain	Lighter than fine loamy	< 60 days	Pearl millet / Fodder - Mustard

Table: 4
Percent area under crop rotations of Punjab derived from remote sensing data (SPOT-VEGT NDVI, 2004-2005)

Type of crop rotation	% Area	Dominant zones
Rice - Wheat	54.0	Z_4
Cotton - Wheat	12.0	Z_5, Z_6 and Z_7
Potato - Vegetables	2.1	Central part of Z_3
Rice - Others	9.0	Scattered
Others - Wheat	19.6	Z_2 and Z_3
Others - Others	3.3	Scattered

points as ground truth. The farmer's survey showed that 25 out of 27 villages, the major cropping system was the same as generated from the composite NDVI product SPOT-VEGT data. This shows the contiguous areas, which were classified under different cropping systems, were true representatives of the ground situations. However, there might be under/over-estimation in the mapping of scattered minor patches of other cropping systems as individual classes using coarse resolution (spatial) SPOT-VGT data. Due to the scattered and small patchy distribution, coarse resolution (spatial) SPOT-VGT data is less effective in mapping them. 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 small, scattered distribution, finer spatial resolution multi-spectral images compared to SPOT-VGT data are needed (Panigrahi *et al.,* 2010). However, this study shows that the SPOT-VGT data product, despite coarse spatial resolution of 1 km, can be effectively used for mapping major cropping systems in homogenous patches, mostly due to their high revisiting frequencies. Panigrahi *et al.* (2010) also reported that 10-day composite SPOT-VGT data can be effectively used for identifying the major crops like rice, wheat, sugarcane, potato, and cotton of Indo-Gangetic plains (IGP) of India including Punjab. They also effectively classified and mapped major crop rotations of IGP like rice-wheat, sugarcane based cotton-wheat, rice-potato, rice-rice, maize / millet-wheat. Similarly, despite having coarse spatial resolution of SPOT-VGT satellite data, but by virtue of its high temporal resolution/revisiting frequencies had been effectively used by many researchers around the world (Begue *et al*., 2018) for monitoring crop phenology through time and over large areas (Alexandridis *et al.,* 2008; Dheeravath *et al*., 2010), characterization of sequential multiple cropping systems (Mingwei *et al*., 2008; Wardlow *et al*., 2007), discrimination between rainfed and irrigated rice (Kamthonkiat *et al.*, 2005), sugarcane area mapping with an accuracy of >97% (Lebourgeois *et al*., 2007).

Kharif cropping pattern

Kharif season cropping pattern showed that rice and cotton were the two major crops, occupied 76.9% of the total agricultural area (TAA) of the state. Spatial distribution pattern map derived from RS data shows that rice has encroached even in non-rice growing areas with light textured soils across the state, irrespective of their agro-ecological situations. As a result, rice covers about 63% of Punjab's total *kharif* cropped area (Table 4). The area under cotton was around 14% of the TAA of the state. Rice and cotton shared about 66 and 12% of TAA, respectively. Using coarse resolution (1 km by 1 km) multi-date SPOT satellite data, Bal *et al.* (2009) also reported that rice was the dominant *kharif* crop grown in 63% of *kharif* cropped area in Punjab. Similarly, Panigrahi *et al.* (2010) using 10 day composite NDVI product of SPOT-VEGT satellite data also reported that besides rice, cotton was the second most major crop grown in the south-western Punjab. Minor *kharif* crops like green gram, mash, groundnut, mentha, *susbania* spp. and fodder mixtures (Sood *et al.,* 2009a) grown in small, sporadic patches with low NDVI values could not be segregated into individual classes (Panigrahi *et al.,* 2010). Rice and cotton are very high water demanding crops and the state of Punjab receives an annual average rainfall of <600 mm with wide spatial variability from 400 (in major cotton growing south-western parts) to 1200 mm (in the foot hills of north-eastern *kandi* region), which is not sufficient enough to meet comparatively higher evapotranspiration demand of 1200-2000 mm. As a consequence, the state, particularly central parts has been experiencing fall in ground water table at an alarming rate due to over-pumping and over-exploitation of groundwater for irrigation (Hira, 2002; Choudhury *et al*., 2013). Therefore, a major challenge lies ahead to sustain its most precious natural resource *i.e.* water table depth especially in central and water quality in south-western parts of the state (Hira and Kukal, 2014; Sood *et al*., 2009b).

Rabi and summer cropping pattern

Wheat was the dominant crop during *rabi* season, covering 85.6% of the total *rabi* cropped area and spatially distributed in all parts of the state. Bal *et al.* (2009) using high frequency, coarser resolution SPOT data also reported that wheat was the dominant *rabi* crop grown in 85% of *rabi* cropped area in Punjab. Besides wheat, vegetables (mostly potato based) with large and continuous patches (2.1%) in the Jalandhar and Kapurthala districts could be identified and mapped separately. Using medium spatial resolution multi-date AWiFs data (56 m), Choudhury *et al.* (2013) also reported significant presence of potatoes in the Jalandhar district of Punjab. Other *rabi* crops identified from ground truth such as grams, massar, rapeseed, mustard, sunflower and fodders (Sood *et al.,* 2009a) could not be segregated into individual classes due to tiny and sporadic distribution coupled with coarser resolution satellite data with low NDVI values and had been clubbed into single class as others (12.3%) (Table 4). Similarly, using relatively finer resolution AWiFs data than the present SPOT-VGT data, Choudhury *et al.* (2013) also could not segregate *rabi* minor crops into individual classes.

In the summer season, marginal area (<5% of TAA) was under cultivation of summer pulse crops (Table 4) in the central and north-western parts of the state. The remaining (>95% of TAA) agricultural areas were under current fallow. Using different sensors with varying spatial resolutions (SPOT/IRS-1DLISS-III/AWiFs) for cropping system analysis of Punjab, other workers (Bal *et al.,* 2009; Sood *et al.,* 2009b; Choudhury *et al.,* 2013) also reported minor presence of summer crops.

Crop Rotation

Crop rotation indicates the dynamics of crop diversity in time and space. Crop rotation plays an important role in crop diversification as well as crop intensification, which directly influences total productivity and judicious use of resources. Information about crop rotations and rotation maps are so far indirectly deduced from the logical combination of seasonal cropping pattern maps (*kharif*, *rabi* and summer). At state level, rice-wheat (54% TAA) was the major crop rotation, followed by others-wheat (19.6% TAA) rotations (Fig. 2 and Table 4). Rice-wheat was in practice over all parts of the state while cotton-wheat was mostly restricted to the south-western parts of the state. In the Siwalik region, located in the north-eastern side (*kandi* belt), non rice-wheat (maize based) was the major crop rotation. Dominance of rice-wheat (all over the state) followed by cotton-wheat (especially in south-western part) in Punjab was also reported by many previous workers (Bal *et al*., 2009; Sood *et al.,* 2009a; Panigrahi *et al*., 2010; Choudhury *et al*., 2013).

Alternate Crops/Crop Diversification Plan

A large number of publications are available on crop diversification in Punjab and have suggested various crops for different regions of Punjab, without due consideration to spatial variability in agro-physical resource suitability characterization. These include maize, basmati rice, durum wheat, pulses, oilseeds, desi cotton, agro-forestry, fruit orchards etc. (Aulakh, 2002). We suggested crop diversification plan considering present agricultural scenarios of

Punjab *viz.*, declining water table, water logging, soil salinity, mono-culture, declining forest cover, agro-climatic condition etc. All these factors indicate that immediate measures need to be taken to prevent irreparable damage of the natural resources of the state to support agricultural productivity. In this regard, alternate crops have to be allocated to different zones based on their agro-ecological requirements. Keeping this in mind, a crop diversification plan was prepared based on thermal requirements, LGP, soil texture, problem soil (salt affected), ground water table status and forest cover (Fig. 2 and Tables 5a-5g).

Punjab should practice multiple cropping systems in different parts of the state, instead of simply going for input intensive mono cropping of rice-wheat system. Major expansion of irrigated rice-wheat cropping system in the IGP plain including Punjab occurred in the green revolution phase (1960s) and continued till 1990s and even today also. Introduction of short-duration and high-yielding

Table: 5a
Suggested alternate crops in agro-ecological zone I of Punjab

Zone	Annual Avg. Temp.: 21-22°C, LGP: 160-180 days	Existing Cropping System		Alternate cropping system
Z_1	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_1B_GS_2$	Loamy skeletal (*Typic Ustorthents / Fluvents*)	Maize	Non-wheat	Basmati-Celery-Bajra (fodder) / Litchi orchard
$Z_1B_GS_3$	Fine loamy (*Typic Haplustept*)	Maize	Non-wheat	Basmati-Celery-Fallow / Litchi / Agro-forestry
$Z_1B_GS_7$	Coarse loamy (*Typic Haplustept-I*)	Maize	Non-wheat	Agro-forestry (Poplar-Wheat)
$Z_1B_ES_2$	Loamy skeletal (*Typic Ustorthents / Fluvents*)	Maize	Non-wheat	Basmati Rice-Wheat-Fallow/Litchi orchard/Sugarcane

Table: 5b
Suggested alternate crops in agro-ecological zone II of Punjab

Zone	Annual Avg. Temp.: 22-23°C, LGP: 140-160 days	Existing Cropping System		Alternate cropping system
Z_2	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_2B_GS_1$	Sandy skeletal (*Typic Ustorthents*)	Rice / other crop	Mixture of wheat and non-wheat areas (maize, sugarcane etc.)	Agro-forestry (Poplar - Wheat)
$Z_2B_GS_2$	Loamy skeletal (*Typic Ustorthents / Fluvents*)	Rice / other crop		Maize (Fodder) - Maize / Basmati Rice - Celery - Bajra
$Z_2B_GS_5$	Sandy (*Entisols, Typic ustipsamments*)	Rice / other crop		Agro-forestry with vegetables
$Z_2B_GS_7$	Coarse loamy (*Typic Haplustepts*-I)	Rice		*Kharif* maize - Wheat - Summer Moong
$Z_2B_ES_7$	Coarse loamy (*Typic Haplustepts*-I)	Maize etc.		Basmati - Celery - Bajra / Sugarcane
$Z_2B_ES_9$	Coarse loamy (*Typic Ustfluvents*)	Rice / other crop		Basmati - Celery - Bajra / Sugarcane

Table: 5c
Suggested alternate crops in agro-ecological zone III of Punjab

Zone	Annual Avg. Temp.: 23-24°C, LGP: 120-140 days	Existing Cropping System		Alternate cropping system
Z_3	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_3B_MS_3$	Fine loamy (*Typic Haplustepts*)	Rice and others	Wheat and others	Rice-Berseem (fodder/seed)-Fallow
$Z_3B_MS_4$	Fine loamy (*Typic Haplustalfs*)	-do-	-do-	Rice-Berseem (fodder/seed)-Fallow
$Z_3B_MS_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Maize-Potato-Fallow
$Z_3B_MS_7$	Coarse loamy (*Typic haplustepts*-I)	-do-	-do-	Maize-Potato / Maize-Wheat
$Z_3B_GS_3$	Fine loamy (*Typic Haplustepts*)	-do-	-do-	Rice-Potato / Rice-Wheat
$Z_3B_GS_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Maize-Potato-Fallow
$Z_3B_GS_7$	Coarse loamy (*Typic Haplustepts*-I)	-do-	-do-	Maize-Potato-Fallow
$Z_3B_GS_9$	Coarse loamy (*Typic Ustfluvents*)	-do-	-do-	Maize-Wheat / Sugarcane
$Z_3B_ES_3$	Fine loamy (*Typic haplustepts*)	Rice and others	Potato and	Rice-Wheat-Fallow vegetables
$Z_3B_ES_4$				
$Z_3B_ES_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Rice-Potato/Pea-Green gram/Maize-fodder maize
$Z_3B_ES_9$	Coarse loamy (*Typic Ustfluvents*)	-do-	-do-	Maize-Potato/Onion-Fodder/Green gram

Table: 5d
Suggested alternate crops in agro-ecological zone IV of Punjab

Zone	Annual Avg. Temp.: 23-24°C, LGP: 100-120 days	Existing Cropping System		Alternate cropping system
Z_4	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_4B_MS_7$	Coarse loamy (*Typic Haplustepts-I*)	Rice / others	wheat / others	Cotton-Wheat-Fallow
$Z_4B_GS_3$	Fine loamy (*Typic Haplustepts*)	-do-	-do-	Rice-Wheat-Fallow
$Z_4B_GS_4$	Fine loamy (*Typic Haplustalfs*)	-do-	-do-	Rice-Wheat-Fallow
$Z_4B_GS_5$	Sandy (*Ustic Torripsamments*)	-do-	-do-	Groundnut-Gram/Mustard/Canola-Fallow
$Z_4B_GS_7$	Coarse loamy (*Typic Haplustepts-I*)	-do-	-do-	Cotton/ Maize/Groundnut-Wheat-Fallow
$Z_4B_GS_8$	Coarse loamy (*Typic Haplustepts*)	-do-	-do-	Rice/Maize-Wheat-Fallow
$Z_4B_GS_9$	Coarse loamy (*Typic Ustfluvents*)	-do-	-do-	Rice/Maize-Wheat-Fallow
$Z_4B_ES_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Agroforestry (Poplar-Ginger)

Table: 5e
Suggested alternate crops in agro-ecological zone V of Punjab

Zone	Annual Avg. Temp.: 24-25°C, LGP: 80-100 days	Existing Cropping System		Alternate cropping system
Z_5	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_5B_MS_3$	Fine loamy (*Typic Haplustepts*)	Rice/cotton/others	wheat / others	Rice-Wheat-Fallow
$Z_5B_MS_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Ground nut/Maize-Wheat/Mustard-Bajra
$Z_5B_MS_7$	Coarse loamy (*Typic Haplustepts-I*)	-do-	-do-	Cotton-Wheat/Mustard-Fallow
$Z_5B_GS_7$	Coarse loamy (*Typic Haplustepts-I*)	-do-	-do-	Cotton-Wheat/Mustard-Fallow
$Z_5B_GS_8$	Coarse loamy (*Typic Haplustepts-II*)	-do-	-do-	Cotton-Wheat/Mustard-Fallow

Table: 5f
Suggested alternate crops in agro-ecological zone VI of Punjab

Zone	Annual Avg. Temp.: 24-25°C, LGP: 60-80 days	Present Cropping System		Alternate cropping system
Z_6	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_6B_MS_3$	Fine loamy (*Typic Haplustepts*)	Cotton, rice/others	Wheat / others	Cotton-Wheat-Fallow
$Z_6B_MS_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Groundnut-Gram-Fallow or Ber/Kinnow orchard
$Z_6B_GS_3$	Fine loamy (*Typic Haplustepts*)	-do-	-do-	Cotton-Mustard/Canola-Fallow
$Z_6B_GS_5$	Sandy (*Typic Ustipsamments*)	-do-	-do-	Cotton-Gram-Fallow or Ber/Kinnow orchard
$Z_6B_GS_7$	Coarse loamy (*Typic Haplustepts-I*)	-do-	-do-	Cotton/Arhar-Chickpea-Fallow

Table: 5g
Suggested alternate crops in agro-ecological zone VII of Punjab

Zone	Annual Avg. Temp.: 25-26°C, LGP: <60 days	Present Cropping System		Alternate cropping system
Z_7	Soil type	*Kharif*	*Rabi*	*Kharif*-*Rabi*-Summer / Orchard / Plantation
$Z_7B_MS_3$	Fine loamy (*Typic Haplustepts*)	-do-	-do-	Urd-Chickpea or Ber/Kinnow orchard
$Z_7B_MS_5$	Sandy (*Typic ustipsamments*)	-do-	-do-	Pearl millet-Gram/Mustard/Canola-Fallow
$Z_7B_MS_7$	Coarse loamy (*Typic Haplustepts-I*)	-do-	-do-	Gram/Mustard-Fallow or Ber/Kinnow orchards
$Z_7B_GS_3$	Fine loamy (*Typic Haplustepts*)	-do-	-do-	Urd-Mustard/canola-Fallow
$Z_7B_GS_7$	Coarse loamy (*Typic Haplustepts-I*)	-do-	-do-	Chickpea/Canola or Ber/Kinnow orchard

modern varieties of rice and wheat, free electricity for ground water pumping for irrigation, supported by subsidies for inputs while better minimum support prices for outputs from respective Governments etc. collectively promoted in expansion and pre-dominance of rice-wheat rotation in the state of Punjab (Choudhury *et al*., 2007; Sood *et al*., 2009a,b; Choudhury *et al*., 2013). This has led excessive use of high-energy agricultural chemicals, soil health deterioration, erosion, salt hazards, decline and pollution of ground water table, poor irrigation water quality, erosion of biodiversity and crop area diversification, and increase in cost of production etc. Therefore, it is high time to go for crop area diversification with intensification including soil enriching pulses / legumes / oilseeds besides less input intensive maize and other cereal based systems. Thus, by using all possible combination of crops using the logical approach (Wart *et al*., 2013), different crops were assigned to suitable agro-ecological zones of the Punjab (Fig. 2 and Tables 5a-5g).

4. CONCLUSIONS

In the post-green revolution phase, the state of Punjab is facing threats from various degradative forces pertaining to sustain its natural resources (soil health, water resources, biodiversity, environment etc.) and land productivity. However, due to location specific variation in nature of problems persist; there is a possibility to address them with a suitable alternate land use/crop area diversification plan, specific to agro-ecological situations in the state. Using integration of RS, GIS, ancillary information and field observations, we demarcated the state into seven agro-ecological regions with 46 homogenous sub-zones, considering many primary input factors (agro-physical parameters) of production in spatial domain. Our plan suggested that the northeastern *kandi* region (zones 1-3) with good resources can afford high remuneration input intensive basmati rice and other cash crops, the central part (zone 4-5) can afford selective rice, maize and other cash/pulse crop combinations while the semi-arid to arid south-western part (zone 6-7) with poor quality water needs cotton and low water requiring crops such as pearl millet, sorghum, groundnut and soil enriching pulses/oil seeds. The erosion prone hilly and flood prone alluvial plains need agro-forestry and horticulture based system interventions. However, the adoptability of the suggested plan will depend on the availability of surface/ground water, socio-economical aspects and an active support from various stakeholders including policy implementers.

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