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Agroecology for Crop Diversification: A Case Study from Anantapur District, Andhra Pradesh

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Abstract

The article delves into the Agroecology concepts aimed at providing alternatives for low-input dryland farming with a history of low groundnut yield in the semiarid regions of Andhra Pradesh. It examines evidence-based agroecology concepts for rainfed groundnut farming, particularly focusing on the high instability of the yield index in Anantapur district. This is achieved through a detailed analysis of rainfall patterns and soil characteristics to determine the suitability of the region for groundnut cultivation. The study spans a period of 45 years (1966 to 2010) and reveals that the rainfall distribution is highly irregular, with pronounced seasonality and extended dry periods, as indicated by a seasonality index ranging from 0.8 to 0.99. By conducting a thorough analysis of rainfall data, three distinct clusters and two principal components were identified, highlighting the variability in both inter and intra seasonal rains. Furthermore, the evaluation of the soil map, which consists of 36 soil mapping units, indicates that only 29.7% of the total area is moderately suitable for groundnut cultivation, while 43% is considered marginally suitable. The unsuitability of the remaining area is attributed to factors such as moisture stress, prolonged dry spells, shallow soils, gravelly and stony surfaces, as well as severely eroded granite landscapes. Considering these findings, the analysis underscores the importance of exploring agroecological alternatives to mitigate these challenges, conserve land resources, and ultimately enhance groundnut yield in the region.

Keywords: Agroecology; Agro Environment; Groundnut; Precipitation concentration index; Seasonality index; Principal component analysis; K mean clustering.

INTRODUCTION

Modern agriculture has transformed natural agroecological systems to increase crop productivity in an exponential way and to ensure food security in proportion to demographic growth (Shattuck, 2021). The transformation of modern agriculture has brought in changes of installation of monoculture, deep plowing and genetically modified crops (Wu *et al.*, 2021). Monocultures rely on chemical fertilizers primarily due to the specific nutritional requirements of the single crop being cultivated over large areas resulting in nutritional imbalances and decline in soil fertility (Altieri, 2009, Bhattacharya, 2019, Shukla *et al.*, 2019). The interconnected issues related to rainfed agriculture like rising temperatures, altered precipitation patterns, and extreme weather events have disrupted traditional growing seasons and heightened the incidence of crop failures due to pests and diseases and seasonal droughts specially in semiarid regions of southern India (Mukhopadhyay

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et al., 2021). There is an urgent need in revival of rainfed agriculture in semiarid regions by adopting agro ecological concepts consisting of three strands: (i) systematic integration of agricultural practices as per context-specific regional methods for sustainable productivity with biodiversity conservation, Participatory approach involving farmers in land use programs for upgrading skills and promoting inclusive food production (Altieri, 2018; Wezel *et al.*, 2014, Elouattassi, *et al.*, 2023).

Arid and semi-arid tropical areas face increased risks and vulnerabilities due to climate change. These climates are characterized by infrequent adiabatic rise of air and distance from an oceanic moisture source (McDonald, 1958). Agroecology is a comprehensive approach that combines ecological principles with agricultural systems to enhance productivity, resilience, and sustainability. It emphasizes biodiversity, ecological processes, and local knowledge (Kesselman, Ngcoya and Casale, 2021). By integrating ecological principles into farming practices, agroecology promotes sustainable techniques that improve soil health, biodiversity, and ecosystem services while reducing external inputs (Glassman, 2014). Strategies include using indigenous crops, conservation agriculture, intercropping, agroforestry, and water management. These methods aim to boost crop resilience, soil fertility, water efficiency, and overall farm productivity, benefiting smallholder farmers' livelihoods and ensuring food security (Akanmu *et al.*, 2023; Tittonell, 2014). Agriculture in these regions is challenged by declining productivity and natural resource degradation. As a result, many of these areas struggle with food insecurity due to various natural and human-induced factors affecting agricultural production. The scarcity of water critically limits the production of food, fodder, and firewood in these regions, leading to low crop yields and occasional crop failure due to limited and unpredictable precipitation. The small and marginal land holding in India is less than 2ha, accounting 87% (126 million operational holdings of total 146 million (DoAC&FW, 2019). The decline in the average size of landholdings from 2.28 ha. in 1970–71 to 1.08 ha. in 2015–16 is a major concern for adoption of new technologies and looking for better opportunities elsewhere (NITI Aayog, 2016). The shift towards sustainable agriculture and food systems often proves to be challenging due to the failure to address the issue in a comprehensive manner and to acknowledge the critical significance of pervasive interactions among various biological, socio-economic, cultural, and political factors over time (Tamburino *et al.*, 2020). It is not solely a matter of poor selection of germplasm and cropping system design, but also of constraints in soil nutrient availability, often associated with the prevalence of pests and diseases; the connection between land degradation and poverty; unfavorable national and global policies in terms of incentives; and institutional shortcomings (Tittonell *et al.*, 2016). Nevertheless, the restructuring of agricultural systems towards sustainability necessitates a comprehensive yet widely applicable monitoring and evaluation framework. Ongoing evaluation is crucial to the restructuring (Tittonell, 2019), and in the context of social-ecological transitions guided by the 10 Elements of Agroecology, hereafter referred to as 'agroecological transitions' for brevity, monitoring and evaluation should entail integrative frameworks that consider the ecological as well as the socio-economic, cultural, and political dimensions of agroecology. Agricultural productivity, conservation of the environment, and agroecological systems rely on accessible and effective farming technologies to minimize land degradation through soil erosion while increasing production (Hong *et al.*, 2018). The land suitable for agriculture may also be suitable for conservation to support other ecological creatures, thus raising conflicting interests in land use (Mkonda, 2021). Protection of environmentally sensitive areas, such as riverbeds or riverbanks, is affected by farmers who consider such areas fertile and supportive of farming activities without taking precautionary measures of conserving the environment (Msuya and Kideghesho, 2012). In the long run, unregulated farming activities cause soil erosion. The farming activities that degrade the environment or deplete microbial activities in the soil may include the use of synthetic fertilizers. In most rural areas in Tanzania, traditional farming systems such as shifting cultivation and monoculture partly contribute to agricultural productivity, however, they are not environmentally friendly (Mbeyale and Mcharo, 2022).

Anantapur is the only arid district of Andhra Pradesh with about 536 mm annual rainfall. This district lies in the rain shadow area of the state and suffers from frequent droughts. It has only 11% of the area under irrigation with groundnut occupying maximum area under rainfed condition accounting for over 75% of the cropped area. Other important crops are gram (6.3%), rice (4.2%), sunflower (3.7%), pigeon pea (3.0%) and sorghum (1.2%). The productivity of the major crops is less than 0.5 t ha^{-1} reflecting the harsh production environment in the district. However, Anantapur is unlike the district of Jaisalmer, most of the rural population (70%)

depends on agriculture. For example, the district has about 4.13 lakhs cultivators, 8.79 lakhs agricultural laborers, whereas the district Jaisalmer's cultivator population and agricultural laborers are about 1.32 lakhs and 0.43 lakhs respectively (Census of India, 2011), thus, making the district most vulnerable to climate change. Among the farming systems of marginal farmers, integrated farming system involving crop production (groundnut + pigeon pea intercropping) and rearing of small ruminants (90 sheep and 30 goats) was found better with a net return of 1,57,855 year^{-1} compared to other farming systems. Similarly, among the three farming systems of small farmers, integrated farming systems involving crop production (groundnut + pigeon pea intercropping) and livestock rearing (2 desi cows and 100 sheep) gave higher net return rupees 1,09,650 year^{1}) compared to other farming systems. Sahadeva Reddy, *et al.* (2010) also reported that farming systems involving livestock component and groundnut production were profitable in the rainfed area of Anantapur. The study focused on adoption trends and benefits of agroecology practices, particularly in semi-arid environments where vulnerable communities rely on rain-fed agriculture. The findings provide insights for future ecological and agricultural policies to support small farmers in adopting agro-ecology production systems in semi-arid and drought hit areas of ground nut growers Ananthapur district over years. It was, of course, not possible to thoroughly assess all the biophysical parameters predominate in dryland regions.

MATERIALS AND METHODS

Study area

Ananthapur district is situated in Rayalaseema region of Andhra Pradesh state and lies between 13°-40′N to 15°-15′N Latitude and 76°-50′E to 78°-30′E Longitude with a population of 40,83,315 (2011 census). The bordering districts are Bellary and Kurnool in the North, Kadapa to the southeast, and Kolar to the North. Agriculture is the main livelihood of farmers in arid districts with a mean annual rainfall of 598 mm (1980–2010) and a coefficient of variation (CV) of 28%. The higher CV of rainfall relative to the threshold level of 25% for annual rainfall suggests high risky dependability of rainfed agriculture. The major soil types are Alfisols covering 78% of the area. Next to that Vertic Inceptisols (20%), and other soils are (2%). The texture of soils is sandy loam (31%), clay (24%) loamy sands (14%), sandy clay loams (13%) and rocky lands (12%). This district is known for groundnut (A. hypogaea L.) and mostly grown by small and marginal farmers with low yields due to low and erratic distribution of monsoon rainfall. The mean pod yield was 516 kg/ha but varies from 200 kg/ha to 1200 kg/ha from year to year. The studies on seasonal rainfall on yield reported that if there is Evidence from 10% less of normal seasonal rainfall, there is 42% of reduction in pod yield (Bapuji Rao *et al.*, 2011). The simulation studies in recent times using CROPGRO-Peanut model showed that there is a scope to increase pod yields on average by 1.0%, 5.0%, 14.4%, and 20.2%, following the adoption of heat tolerance, drought tolerant cultivars and supplemental irrigation respectively. The benefits of adaptation of options differ spatially but benefits are more by growing drought tolerant new varieties and one supplementary irrigation at 60 days after sowing (Kadiyala *et al.*, 2015).

DATA COLLECTION

Forty five years of rainfall data (1966 to 2010) of monthly data from the website of Ministry of earth sciences was downloaded (India Meteorological Department O/O Additional Director General of Meteorology Research) from climate application group (2015) and open repository data of year wise groundnut area and yield from ICRISAT data (2020). These data sets were used in the present studies to put up a viewpoint on agroecological strategies for crop diversification in arid district like Ananthapur. The soil data was taken from NBSS&LUP (2008) report on Soil resources of Anantapur district, Andhra Pradesh. A detailed soil survey was carried out using Survey of India Toposheets on 1:63360 scale as per the procedures described (Soil Survey Division Staff, 2017) and identified 36 soil series. Derived soil map with 36 mapping units as series association. The soils were classified up to subgroup level as per Soil Survey Staff (2014). The suitability for groundnut was worked out based on Sys *et al.* (1993). The limitations of agroecological strategies were explored in Anantapur district where groundnut was grown under modern monoculture systems and incurred heavy crop loss during drought years. This study made on rainfall characteristics and biophysical limitations from land resource inventory as discussed under:

Rainfall variability analysis

Rainfall variability was worked out using Coefficient of Variation (CV), Precipitation Concentration Index (PCI) and Seasonality index

(SI).

Coefficient of variation (CV)

The CV value was calculated as: CV = σ/μ × 100 (10) where, CV is coefficient of variation; σ is standard deviation and μ is mean of rainfall. The degree of variability based on CV was classified as low <20, 20 to 30 moderate and >30% as high (Kokag *et al.*, 2022). ***Precipitation concentration index (PCI)***.

The PCI value was calculated both for annual and seasonal as per the formulae of Gao *et al.* (2022) as given under:

PCI annual = $\frac{\sum_{i=1}^{12} Pi^2}{\sum_{i=1}^{12} P^2}$ X100

PCI winter $\frac{\sum_{i=1}^{12} Pi^2}{\sum_{i=1}^{12} P^2}$ X24.7

PCI monsoon $\frac{\sum_{i=1}^{12} Pi^2}{\sum_{i=1}^{12} P^2}$ X33.42

PCI premonsoon $\frac{\sum_{i=1}^{12} Pi^2}{\sum_{i=1}^{12} P^2}$ X25.1

PCI post monsoon = $\frac{\sum_{i=1}^{12} Pi^2}{\sum_{i=1}^{12} P^2}$ X16.71

where, pi is the rainfall amount of i^{th} month. P is Annual rainfall (mm), Winter (December, January, February), Premonsoon (March, April, May), Monsoon (June, July, August, September) and Post monsoon (October, November) for study area as per Indian Meteorological Department. PCI values are categorized as PCI=<10 as uniform precipitation, 10 to 15 as moderate precipitation, 15-20 as irregular distribution and>20 as strongly irregular precipitation.

Seasonality index (SI)

A seasonality index allows for the quantification of precipitation variability throughout the year using a single figure. This index does not offer a detailed month-by-month view of seasonal variation but should be supplemented by a detailed analysis of monthly precipitation across a specific area, as demonstrated in the current study. One commonly used seasonality index is the one developed by Walsh and Lawler (1981): SI = 1 / R * ∑ |Xn - R̄| 12 Where R represents the total annual precipitation for the year under study and Xn is the actual monthly precipitation for month n. In this study of spatial and temporal variation in seasonality, Xnis the mean rainfall of month n and R is the mean annual rainfall. Theoretically, the SI can vary from zero (if all the months have equal rainfall) to 1.83 (if all the rainfall occurs in one month).

Seasonality index (SI) classes: Very equable ≤ 0.19, Equable but with a definite wetter season 0.20–0.39, Rather seasonal with a short drier season 0.40–0.59, Seasonal 0.60–0.79, Markedly seasonal with a long drier season 0.80–0.99, Most rain in 3 months or less 1.00–1.19 and Extreme, almost all rain in 1–2 months ≥ 1.20.

Statistical analysis

The software application such as Microsoft Excel, Stat Blue, and Statistics Kingdom Online were utilized for the computation of PCI and SI as well as for conducting descriptive statistics on rainfall data, correlation and regressions, principal component analysis, scatter plots, and histograms as outlined in the study. PCA was used for climate zoning method (Richman, 2010). The forecasting of rainfall trends and of PCI was calculated using AAA version of Exponential smoothing technique for handling a time series that displays a slowly changing linear trend (Microsoft 365, Gardener, 1985, Deckker *et al.*, 2004.). The relative variability in the area, yield and precipitation in Groundnut was assessed using the Cuddy-Della Valle Index (1978). The formula for the instability index was given by IX = CV√(1 − R^2), where IX represents the instability index, CV denotes the coefficient of variation (expressed as a percentage), and R^2 represents the coefficient of determination obtained from a time trend regression adjusted by the number of degrees of freedom.

RESULTS AND DISCUSSION

Descriptive statistics of Rainfall characteristics (1966 to 2010)

Mean monthly and seasonal variation and trends in rainfall

The average annual rainfall in Anantapur is 544.60 ± 124.51 mm, with a coefficient of variation of 22.6%. The range of rainfall varied from 300.8 mm in 1985 to 825.8 mm in 1988, showing a high degree of variability. The standard deviation and coefficient of variation (CV) were higher, indicating a high variability in the annual rainfall series. Monthly rainfall variability is also high, with values less than 50% of CV in September and October but exceeding 100% in other months. The seasonal rainfall is 14.19mm for winter, 75.54mm for pre-monsoon, 313.10mm for monsoon, and 141.68mm for post-rainy season. Monsoon rainfall contributes to 57.49% of the total, while 26.02% comes from post-monsoon and 13.87% from pre-monsoon. The winter rainfall is 14.29mm/year, with high standard deviation and CV, indicating unreliable rainfall for rabi crops. The confidence intervals have a lower limit of 494.01 mm and an upper limit of 595.19 mm but show drastic changes in forecasting from 2011 to 2022 (Table 1). The seasonal rainfall is highly skewed for winter, pre-monsoon, and monsoon months, except moderately skewed for May, August, September, and October. The kurtosis with values >3 indicates positive kurtosis for February, March, June, July, and December, but negative for the rest of the months. The SKp is used to measure the direction of variation, with values of 4.5 for February but minimum for October (0.25), indicating positively skewed data. The yellow trendline illustrates a gradual decline in rainfall, with a chance of reaching a maximum of 1000mm and a minimum of 350mm (refer to Fig. 1).

Table 1. Descriptive statistical summary of rainfall from 1966 to 2010

Statistical parameters	January	February	March	April	May	June	July	August	September	October	November	December	Total
Mean	3.00	3.59	7.88	15.26	52.40	53.10	57.37	72.13	130.50	105.24	36.43	7.70	544.60
SD	5.61	8.74	14.68	11.50	33.92	32.65	47.20	49.15	65.12	52.46	34.14	10.27	124.51
CV	186.79	243.82	186.27	75.33	64.73	61.50	82.28	68.14	49.90	49.84	93.70	133.46	22.86
Mini	0.00	0.00	0.00	0.10	1.80	8.60	7.50	6.80	23.30	20.30	1.60	0.00	300.80
Max	20.30	53.00	85.00	54.70	129.00	166.20	265.10	210.60	272.90	231.00	150.43	54.40	825.80
CF	2.28	3.55	5.96	4.67	13.78	13.27	19.18	19.97	26.46	21.31	13.87	4.17	50.59
Upper	5.28	7.14	13.84	19.93	66.18	66.36	76.55	92.11	156.96	126.56	50.30	11.87	595.19
Lower	0.72	0.03	1.92	10.59	38.62	39.83	38.19	52.16	104.04	83.93	22.56	3.52	494.01
Skewness	1.86	4.76	2.25	1.28	0.75	1.69	2.36	0.92	0.46	0.26	1.16	2.49	0.44
Kurtosos	2.38	26.15	5.55	2.36	-0.46	4.49	7.52	0.58	-0.48	-0.95	0.84	8.20	0.11
Sk.p	1.80	4.59	2.17	1.23	0.73	1.63	2.27	0.89	0.44	0.25	1.11	2.39	0.43

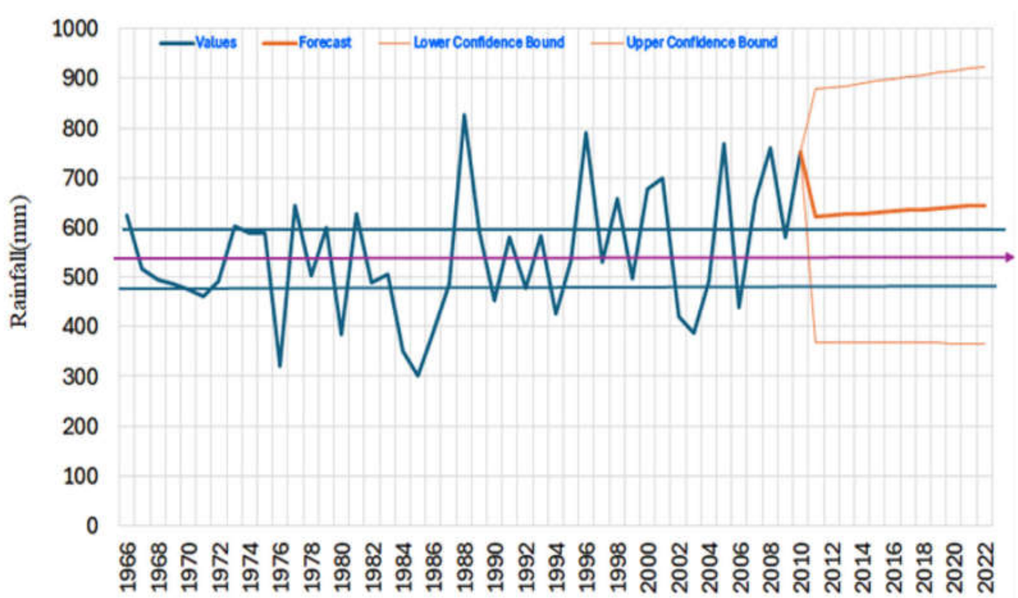

Fig. 1: Trends and forecasting of rainfall from historical data of 1966 to 2010

2. *Precipitation concentration index (PCI)*

The mean annual PCI is 19.08 with SD of 3.90 and moderate variability (CV -20.44%). The rainfall is irregular but frequency data shows that out of 45 years, the region has 20 irregular and 17 strongly irregular distribution of rainfall (Table 2). The four distinct seasonal data of PCI shows distinct variations in occurrence of rainfall distribution.

Among four seasons, The monsoon and post monsoon period, has 24 to 25 moderate intensity of rainfall and 15 events of uniform distribution whereas winter has 21 strongly irregular distribution of rainfall events. The pre monsoon period has 22 moderate and 11 irregular rainfall events.

The 45 years of both seasonal and annual PCI values were used for deriving two Principal components having Eigen value more than 1 (Fig. 2). Based on the PCA analysis, three main components (PC1–PC2) were obtained from these indicators, while the varimax rotation was employed to improve the significance of the influencing variables. According to the matrices of the two principal components after rotation, PC1 explains 39.01% of total variation (1.95 eigen value) while PC2 accounts for 21.72% (1.09 eigen value) of total variance of 60.72% (Table 3). The correlation coefficient (r) of the principal components after rotation exhibits an identical confidence level of 95%. According to the data presented in Table 4 and displayed in strong relation of monsoon (r=0.57*) and post monsoon PCI (0.50*) with annual PCI. The Seasonality index has a strong correlation with annual PCI (r=0.81**), monsoon (r=0.42*) and post monsoon PCI (r=0.68*). The bivariate plot between PC1 and PC2 shows positive scores for both intra and inter annual precipitation indices but well expresses the proximity of both monsoon and post monsoon PCI with Annual PCI.

Table 2: Year wise Annual and seasonal PCI in Anantapur district (1966 to 2010)

Year	PCI					
	Annual	**Winter**	**Pre-monsoon**	**Monsoon**	**Post-monsoon**	**SI**
1966	13.83	13.14	15.08	9.02	8.26	0.73
1967	17.93	20.44	14.61	11.32	13.56	0.92
1968	20.20	12.67	9.57	17.04	10.33	0.81
1969	22.12	25.00	22.82	15.06	14.77	1.08
1970	20.96	13.89	20.62	13.31	15.92	1.08
1971	22.05	8.80	15.12	12.77	15.06	1.07
1972	21.37	25.00	20.43	17.76	11.07	0.89
1973	22.98	25.00	19.75	11.62	12.91	1.08
1974	23.11	0.00	21.27	15.16	15.74	1.07
1975	23.11	0.00	21.27	15.16	15.74	1.07
1976	19.79	0.00	13.63	12.04	8.51	0.78
1977	14.10	0.00	17.58	8.62	8.81	0.75
1978	16.70	17.82	13.63	12.38	8.31	0.73
1979	22.79	25.00	18.09	14.69	9.65	0.89
1980	14.70	25.00	14.79	10.25	8.26	0.72
1981	23.99	13.61	12.69	14.42	10.18	0.94
1982	18.94	0.00	15.46	12.59	8.75	0.83
1983	21.45	25.00	24.91	11.23	14.95	0.99
1984	19.71	14.33	10.95	14.15	14.18	1.00
1985	15.88	14.50	12.23	9.51	11.88	0.79
1986	18.20	9.62	14.42	12.02	8.25	0.85
1987	21.84	25.00	22.02	10.74	12.11	1.02
1988	22.15	23.47	13.29	11.36	13.85	1.09
1989	32.59	25.00	8.54	13.25	11.86	1.24
1990	16.19	24.24	22.30	8.57	8.81	0.81
1991	17.74	20.73	11.62	12.02	10.26	0.85
1992	13.83	0.00	14.92	8.64	8.21	0.75
1993	14.70	25.00	10.28	8.96	11.13	0.69
1994	21.11	15.75	13.19	8.87	12.60	0.72

Table Cont...

1995	17.01	12.51	15.39	9.63	12.74	0.91
1996	18.13	25.00	12.59	9.82	14.64	0.97
1997	16.90	13.94	8.48	12.65	8.22	0.71
1998	17.25	21.83	12.03	10.14	10.67	0.93
1999	16.67	21.54	17.34	10.70	11.30	0.87
2000	16.49	19.74	15.91	10.41	14.84	0.84
2001	24.88	13.00	12.21	17.32	14.45	1.05
2002	15.20	10.88	14.62	9.54	13.00	0.72
2003	25.30	18.31	10.72	9.19	15.01	0.99
2004	18.37	25.00	13.86	12.83	14.05	0.81
2005	15.91	10.17	15.34	9.43	10.93	0.83
2006	14.51	25.00	10.80	11.77	8.78	0.77
2007	20.79	25.00	22.51	9.47	13.60	1.08
2008	13.89	23.66	12.88	9.68	9.34	0.68
2009	19.09	20.95	18.97	13.01	8.24	0.91
2010	14.16	10.76	14.32	9.23	9.20	0.71
mean	19.08	16.56	15.40	11.72	11.62	0.68
sd	3.90	8.46	4.17	2.48	2.61	0.89
cv	20.44	51.10	27.06	21.12	22.44	1.24

Table 3: Results of PCA analysis

Parameter	PC_1	PC_2	PC_3	PC_4	PC_1
Eigenvalue	1.95	1.09	0.96	0.67	0.33
% of Variance	39.01	21.72	19.24	13.47	6.57
Cumulative (%)			79.96	93.43	100

Table 4: Correlation matrix

PCI Group	Annual	Winter	Premonsoon	Monsoon	Post monsoon
Annual	1	0.11	0.11	0.57	0.5
Winter	0.11	1	0.046	-0.054	0.099
Premonsoon	0.11	0.046	1	0.071	0.27
Monsoon	0.57	-0.054	0.071	1	0.22
Post monsoon	0.5	0.099	0.27	0.22	1

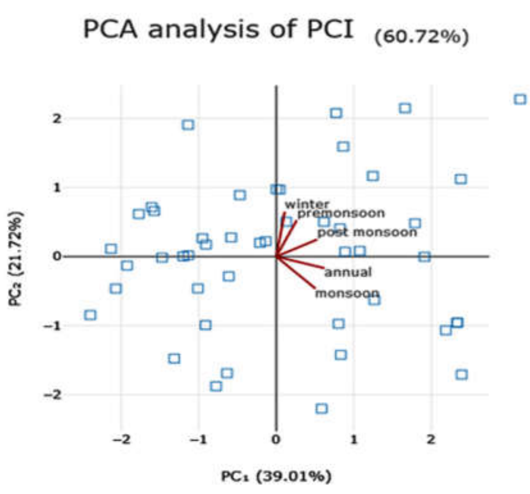

Fig. 2: Scatter plot of PCI with PC2

K mean clustering

Three groupings were established (Fig. 3). The first group (red dot line) consists of eight years, the second group (blue dot line) consists of 10 years, and the third group (green dot line) consists of 27 years, encompassing both seasonal and annual PCI/SI data sets spanning 45 years (1966-2010). The data sets for each group are discussed individually.

Cluster 0: The average annual PCI is 22.32±2.67, suggesting a highly erratic distribution of rainfall over an eight-year period. Annual PCI values ranged from 18.13 (1996) to 32.59 (1989) with a low level of variability (CV of 11.95%). The average seasonal PCI values indicate moderate rainfall, with values of 12.51±1.48 for pre-monsoon and

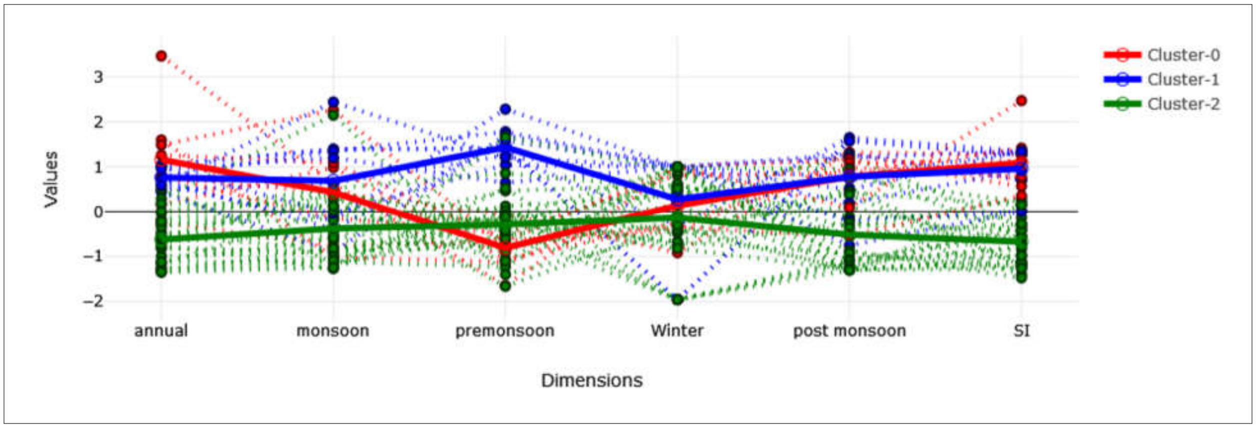

Fig. 3: Clustering of PCI and SI data sets of Anantapur district

13.91±1.70 for post-monsoon, showing low variability (CV <15%). The cluster mean for SI is 1.02±0.06, with a CV of 5.45%, suggesting that most of the rainfall occurs in 1 or 3 months. In 1989, the SI is >1.2, indicating extreme rainfall, with almost all the rain falling in 1–2 months (Table 5).

Table 5: Descriptive statistical summary for cluster wise PCI and seasonality index

*ID/Name	Annual	Monsoon	Pre-monsoon	Winter	Post-monsoon	SI
			Cluster-0			
Mean	22.32	12.72	12.51	16.65	13.91	1.02
SD	2.67	2.85	1.48	5.90	1.70	0.06
CV	11.95	22.43	11.85	35.42	12.22	5.45
			Cluster-1			
Mean	22.05	13.42	21.37	18.89	13.65	1.03
SD	0.90	2.58	1.86	10.54	2.17	0.08
CV	4.09	19.24	8.71	55.80	15.91	7.55
			Cluster-2			
Mean	16.64	10.77	14.19	15.37	10.27	0.79
SD	2.10	1.95	2.90	8.27	2.08	0.07
CV	12.59	18.07	20.44	53.83	20.25	9.45

Cluster-1 presents a 10-year dataset show casing the mean annual PCI of 22.05±0.9 with a CV of 4.09%. The PCI values exhibit a strong irregular distribution, ranging from 20.79 PCI annual (2007) to 23.11 for 1974/1975. The mean PCI during winter (18.89±10.54) and pre-monsoon (21.37±1.86) periods are irregular, while post-monsoon (mean 13.65±2.17) and monsoon period (mean 13.42±2.58) show a more moderate pattern. The highest CV is recorded for winter PCI at 55.8%. The mean seasonality is 1.03±0.08 with a CV of 7.55%. Two out of the 10 years (1972/1979) experienced marked seasonal rains with extended dry periods, while the remaining eight years had rains occurring in 3 or fewer months. Cluster-2, on the other hand, spans 27 years and displays a moderate mean annual and seasonal PCI with CVs below 20%, except for winter PCI which has a CV of 53.84%. The mean seasonality index is 0.79±0.07 with a CV of 9.45%. The seasonality index indicates 14 years as seasonal (<0.79) and 13 years as markedly seasonal with prolonged dry spells (0.8 to 0.99). The PCI trendline suggests a moderate distribution, forecasting moderate precipitation levels up to 2042. However, from 2030 to 2042, the upper limit shows irregular to strongly irregular patterns, while the lower boundary indicates a uniform distribution with a declining trend (Fig. 4).

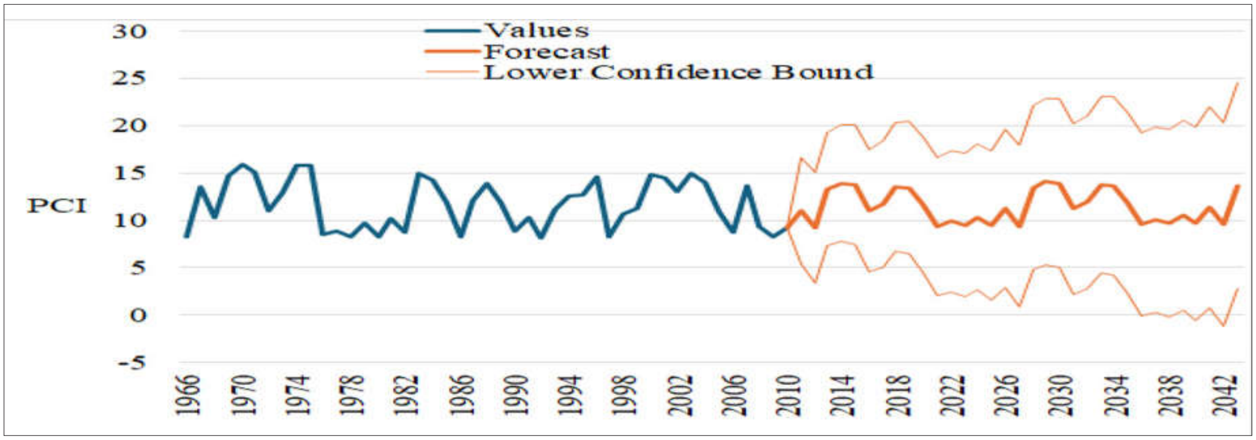

Fig.4: Trend line of PCI and its forecasting upto 2042

Trends of Area (000, ha) and yield (kg/ha) of Groundnut over 45 years in Anantapur district (1966 -2010)

The average area is 548.216 ± 231.856 thousand hectares with a high degree of variability (CV of 42%). Similarly, the average pod yield of groundnut is 692.26 ± 288.14 kg/ha with a high degree of variability (CV of 41.62%). The average southwest monsoon rainfall is 313.09 ± 112.39 with a CV of 35.89 per cent. The relationships between yearly rainfall, yield, and area are depicted in Fig. 5, and regressions have been calculated. There is a significant positive linear relationship of area with time, resulting in an R^2 (coefficient of determination) of 0.8394. The results of the instability index with time regression show medium instability for area (16.94%), whereas there is a high instability index for yield (38.78%) and rainfall (35.86%) according to Dudhat (2017). The regression equation, which represents how much y changes with any given change of x, can be used to construct a regression line on a scatter diagram, and in the simplest case, this is assumed to be a straight line. The area has a linear relationship with time to predict y from x and provides a better summary of the relationship between the two variables. This linear equation explains 83.9% of the variability in area with time. The 4th order polynomial equation of yield with time has resulted in a poor correlation with an R^2 of 0.1645, while rainfall has a linear relationship with time and a poor R^2 of 0.0371.

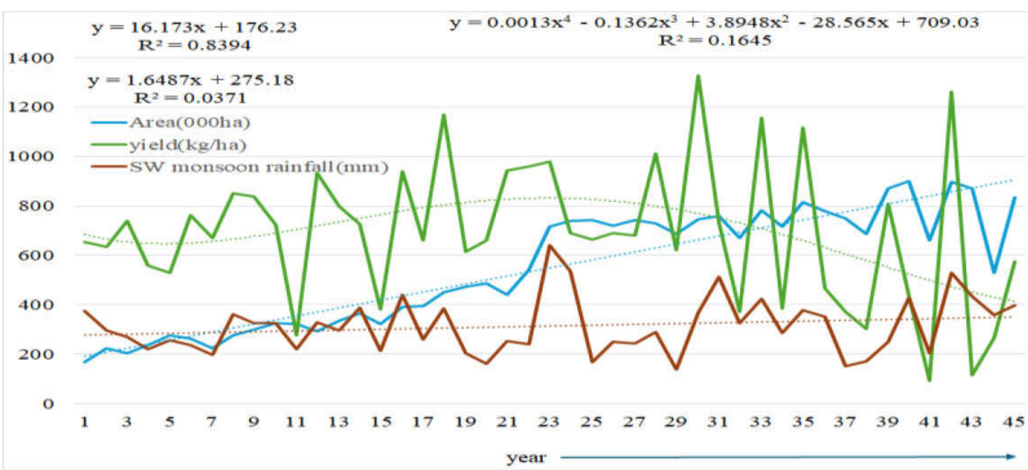

Fig. 5: Yearly changes in area, yield and rainfall in groundnut growing Anantapur district

The correlation between yield and rainfall is statistically significant at the 5% level, as indicated by the equation: yield (kg/ha) = 394.5 + 1 monsoon rainfall (mm) (F - 1, 43) = 6.86, p = .012, R^2 = 0.14, R^2adj = 0.12. The R square (R^2) value of 0.1 suggests that the predictors (Xi) account for 13.8% of the variance in Y. The coefficient of multiple correlation (R) of 0.4 indicates a weak correlation between the predicted data (ŷ) and the observed data (y), with a lower limit of 151.2 kg/ha and an upper limit of 637.8 kg/ha. The forecasting line diagram illustrates that starting from a base level yield in 1983, yield trends can be predicted to range from 1000 kg/ha to 1500 kg/ha, with a lower limit of 500 kg/ha and an upper limit of 2000 kg/ha (Fig. 6).

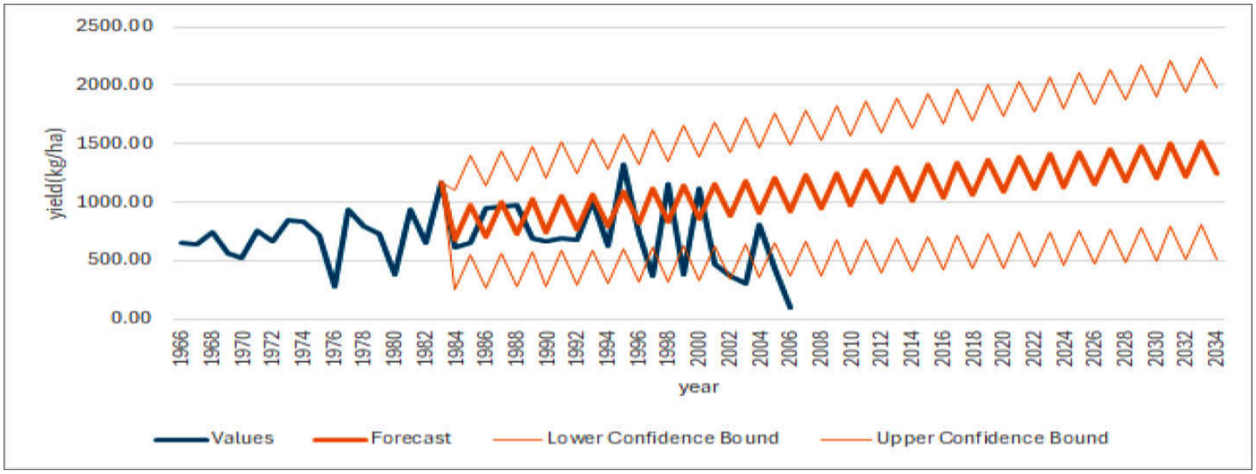

Fig. 6: Trends and forecasting of yield (kg/ha) up to 2034 with Confidence intervals

Soil resources and their characteristics

Anantapur district is characterized by a variety of soil types, with 73% of the soils occurring on granite-gneisic and sedimentary landforms, 10% on schist, limestone, and sandstone landscapes, and the remaining 17% on fluvial landforms. The dominant soil series in the hilly and rocky granitic terrain are the shallow and well-drained Kondapuram series, characterized by a reddish-yellow matrix. On rolling lands, the Madakasira, Batrepalle, Gooty, and Rampuram series are prevalent, with deep to moderately deep and well-drained soils featuring yellowish-red, reddish-brown, and reddish-yellow subsoil with more than 35% gravels. Undulating pediments are dominated by the Mallereddipalle, Vayalpad, and Wajrakarur series, while gently sloping pediments have the Brahmanapalle, Kottacheruvu, Sataralapalle, Teligi, Uravakonda, Gollapalle, and Itigi series. These soils are characterized by yellowish red to very dark gray matrix and clayey subsoils, occurring on slopes ranging from 2 to 5%. Valley floors are home to very deep, brown to grayish brown Anantapur, Garudapuram, and Manesamudram series, while poorly drained loamy Peruru and Penner soils are found on 1 to 3% sloppy lands.

The Peddampalle series, consisting of shallow and well-drained gravelly clay, can be found on ridges of the schist belt. Meanwhile, undulating pediment surfaces are home to the moderately deep reddish-brown Mincheri series, and gently sloping pediments host the moderately deep and reddish-brown Velidandla series. On gently sloping pediments, the Bogalkata, Hugaluru, Velamakuru, and Kamalapadu series are deep with dark grayish-brown clay soils. Valley soils like Sazzaldinne and Utakallu, on the other hand, have dark gray, poorly drained soils with subsoil mottles. In the northeastern/eastern parts of the district, ridges on sedimentary landscapes feature the shallow and well-drained Kadavakallu series alongside the Lakshmipalle series. Pediment surfaces are characterized by the very deep and dark grayish Mussukota and Tambalapalle series, which exhibit calcareous and visible sheet erosion features. These soil series fall under the subgroups of Entisols, Inceptisols, Aridisols, Alfisols, and Vertisols (Table 6).

Table 6: Soil series and their classification

Soil taxonomy	Soil series
Aridic Haplusterts	Teligi, Valamakuru, Mussukota, Boglakatta
Lithic Haplocambids	Itigi, Gollapalle, Kondapuram, Mincheri, Kadavakallu, Madakasira, Lakshmupalle
Typic Ustifluvents	Uttakallu, Anantapur, Chitravathi
Typic Haplocambids	Wajrakarur, Gooty, Batrwpalle
Typic Torriorthents	Garudapuram
Typic Paleargids	Ramapuram

Table Cont...

Typic Haplargids	Kottacheruvu, Satralapalle, Brahmanapalle
Typic Rhodustalfs	Vayalpad
Lithic Haplustepts	Kondapuram, Velidandla
Fluventic Haplocambids	Mallereddipalle,
Typic Haplustert	Velamakuru
Aquic Torriorthents	Peruru
Aquic Ustifluvents	Penner
Lithic Torriorthents	Peddamallepalle

Soil mapping

The soil map of Anantapur district displays 36 soil mapping units as series associations, as shown in Fig. 7 and Table 7. Among these units, only four are highlighted, covering more than 5% of the total area. Soil mapping unit 7, which encompasses 14.1% of the total geographical area (270475.87ha), consists of two soil series associations - Madakasira and Kondapuram (Lithic Haplocambids) with reddish brown subsoils. These soils range from slightly acid to neutral, with clay content increasing from 13.4 to 52.4% in Kondapuram and 20.3 to 48.8% in Madakasira soil. The CEC of these soils ranges from 8.9cmol/kg to 22.3cmol/kg, with exchangeable Ca and Mg being dominant. Soil mapping unit-3 features the Kondapuram series associated with rock outcrops, covering 194117.61 ha (10.1% of the total geographical area). This series is classified as Lithic Haplocambids, with shallow reddish yellow gravelly loamy sand horizons over yellowish red gravelly clay subsoils. The soil is neutral to slightly acid, with a CEC of 8.9cmol/kg on the A horizon. Soil mapping unit-19 comprises the Vayalpad (Typic Rhodustalfs) and Kondapuram series association, covering 10.3% of the area (197344.49ha). This association includes Vayalpad series (moderately deep with dark reddish brown clayey subsoil) and Kondapuram series (shallow reddish yellow gravelly loamy sand surface layer and yellowish red gravelly clay subsoils). Lastly, mapping unit-11 consists of Batrepalle (Typic Haplocambids) and Ramapuram (Typic Paleargids), covering 6.5% of the total area (125229ha). These soils are moderately deep, with Batrepalle having a light brown sandy loam subsoil and Ramapuram featuring dark reddish brown to dark red gravelly clay subsoils. The soils are slightly acid to neutral, with a slight increase in clay content. The CEC ranges between 11.0 and 15.2 cmol/kg. The soil map vividly displays the spatial arrangement of aridic subgroups of Inceptisols linked with argillic subsoils of Aridisols in the southern regions, Vertisols, and vertic soil subgroups in the northeastern areas. The presence of highly alkaline sodic soils is widespread in the valley floors of Pennar/Chitravathi basins (Bhaskar and Nagaraju, 1998).

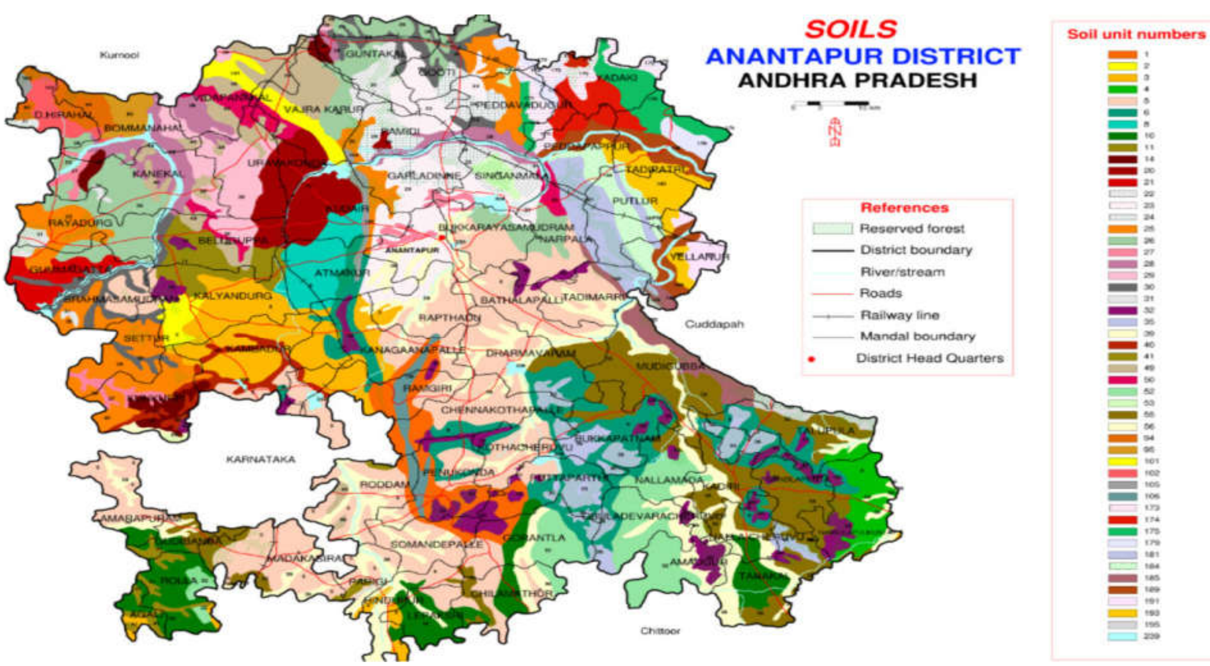

Fig. 7: Soil map of Anantapur

Table 7: Extent and per cent area under each soil mapping units in the soil map

Mapping unit number	Soil series association	Area	
		(ha)	(%)
1	Peddampalle	9404.41	0.5
2	Kadavakallu-Rockoutcrops	9424.99	0.5
3	Kondapuram-Rockoutcrops	194117.61	10.1
4	Lashmupalle-Rockoutcrops	14036.19	0.7
5	Gollapalle-Satarlapalle	17802.41	0.9
6	Itigi-Teligi	24880.29	1.3
7	Madakasira-Kondapuram	2704750.87	14.1
8	Mincheri-Rockoutcrops	5082.00	0.3
9	Velidandla	27963.98	1.5
10	Brahmanapalle-Kottacheruvu	40765.14	2.4
11	Batrepalle-Ramapuram	125229.41	6.5
12	Gooty	34652.89	1.8
13	Kottacheruvu-Madakasira-Brahmanapalle	20259.32	1.1
14	Mallereddipalle-Ramapuram	8473.27	0.4
15	Mussukota-Velamakuru	34028.50	1.8
16	Peruru-Penner	8915.54	0.5
17	Ramapuram-Kottacheruvu	64054.68	3.3
18	Sararlapalle-Brahmanapalle	3978.35	0.2
19	Vayalpad-Kondapuram	197344.49	10.3
20	Wajrakarur-Gooty	20828.41	1.1
21	Ananthapur	11676.9	0.6
22	Boglakatta-Velamakuru	5221.24	0.3
23	Chiravathi	6654.52	0.3
24	Garudapuram	20787.32	1.1
25	Hagari-Chitravathi	10950.41	0.6
26	Hugaluru	70478.33	3.7
27	Kamalapadu-Lakshmupalle	8189.14	0.4
28	Manesamudram	11493.44	0.6
29	Penner-Peruru	28076.52	1.5
30	Sazzaldinne-Satarlapalle	59703.9	3.3
31	Tadipatri-Sazzaladinne	14891.1	0.8
32	Tamballapalle	3089.18	0.2
33	Teligi-Itigi	58787.6	3.1
34	Uravakonda-Gooty	11905.85	0.6
35	Uttakallu	12800.4	0.7
36	Valamakuru-Mussukota	4358.73	2.3
	tank	16740.0	0.87
	river	25862	1.35
	marshy	5148	0.27
	total	1921599	100

Suitability for Rainfed groundnut

Anantapur district is characterized by 40% class-IV lands (764477ha) with soil moisture and depth limitations, predominantly found in Dharmavaram, Kadiri, Anantapur, and Tadipatri. On the other hand, class-III lands cover 27% of the area, particularly in parts of Gooty, Hindupur, Rayadurg and Madakasira Tehsil. Approximately 60% of the land features moderately deep to shallow soils, often associated with rock outcrops, especially in Gooty, Madakasira, and Rayadurg tehsils. Reports indicate that 50% of the area is deficient in DTPA extractable Zn, while 61% lacks available nitrogen. However, the district shows a medium status in Olsen's P and high availability of K. Groundnut is the principal crop, covering more than 75% of the net sown area, and serves as a vital source of livelihood for small and marginal farmers in the region. The evaluation of rainfed Groundnut suitability considered soil constraints following FAO guidelines in ARC info Version 10.8.1 (Fig. 8). The map indicates that only 1% of the total area is highly suitable, while moderately suitable lands cover 28%. Additionally, 45% of areas are marginally suitable due to severe limitations in rooting depth, gravelliness, and texture in areas such as Kadiri, Madakasira, Hindupur, Kalyanadurg, and Tadipatri tehsils. Overall, suitable to moderately suitable lands for groundnut cultivation are estimated at 569419ha (29.77% of the total area), while marginally suitable lands cover 43% of the total area (830731ha). The main constraints include rock outcrops and severely eroded granitic landscapes with shallow soils.

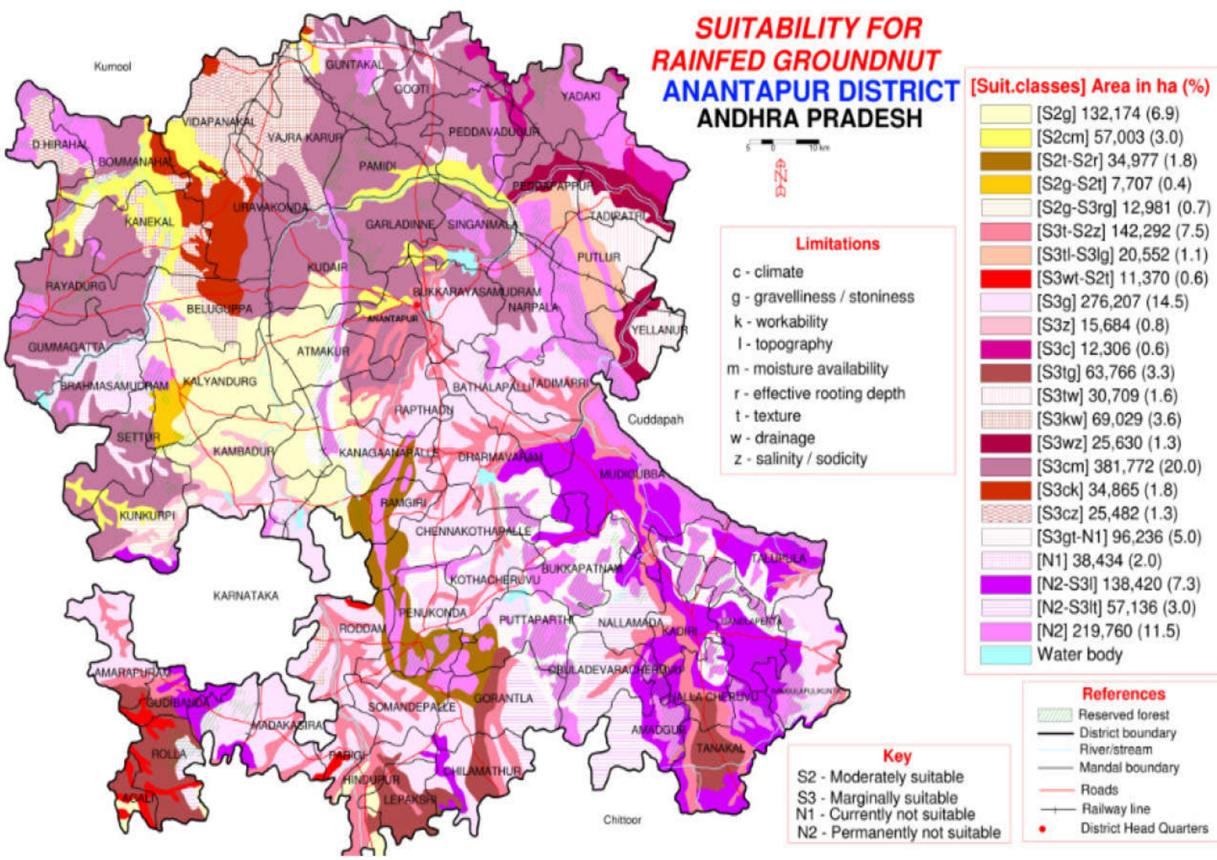

Fig. 8: Suitability map for Groundnut

Agroecology for alternatives

The Anantapur district heavily relies on rainfed groundnut cultivation, which has led to low productivity in the area. Groundnut haulms are a crucial source of fodder for cattle production in the semi-arid zones of Andhra Pradesh, particularly in the south-western region including the Anantapur district (ISAP, 197). Despite being a significant food-feed crop in developing countries, the conventional methods of groundnut cultivation in Anantapur district have been failing under rainfed conditions, resulting in a steady decline in yield over the years. Efforts are being made to explore agroecological alternatives for crop diversification due to the consecutive failure of conventional methods. Anantapur district leads in groundnut production and area in Andhra Pradesh, but despite having the largest area under cultivation, the productivity remains low. The area's agri-environmental conditions are characterized by granitic landscapes supporting deep and bright red soils in uplands, with argillic dark red to reddish brown subsoils in lower topographic positions. Monocultures heavily depend on chemical fertilizers due to the specific nutritional requirements of the single crop being grown across vast expanses. Monocultures rely heavily on chemical fertilizers due to the specific nutritional needs of the single crop being cultivated across large areas (Clapp, 2023). When one crop dominates the land, it depletes the soil of essential nutrients necessary for its growth, leading to nutrient imbalances and reduced soil fertility over time (Bhattacharya, 2019). To maintain high yields and meet the crop's nutritional requirements, farmers turn to chemical fertilizers to compensate for the lacking nutrients (Kloppenburg, 2005). This practice disrupts ecological processes, services, and has negative effects on human health (Cornu, 2021; Shukla *et al.*, 2019). As a result, the overall productivity of Andhra Pradesh in 2020-2 was reported at 891 kg/ha (apagrisnet.gov.in). The area and yield of Groundnut in Ananthapur over 45 years from 1966 to 2020 are considered, and estimated predictions indicate a possible mean area of 548.216 ±231.856 thousand hectares with high variability (CV of 42%).

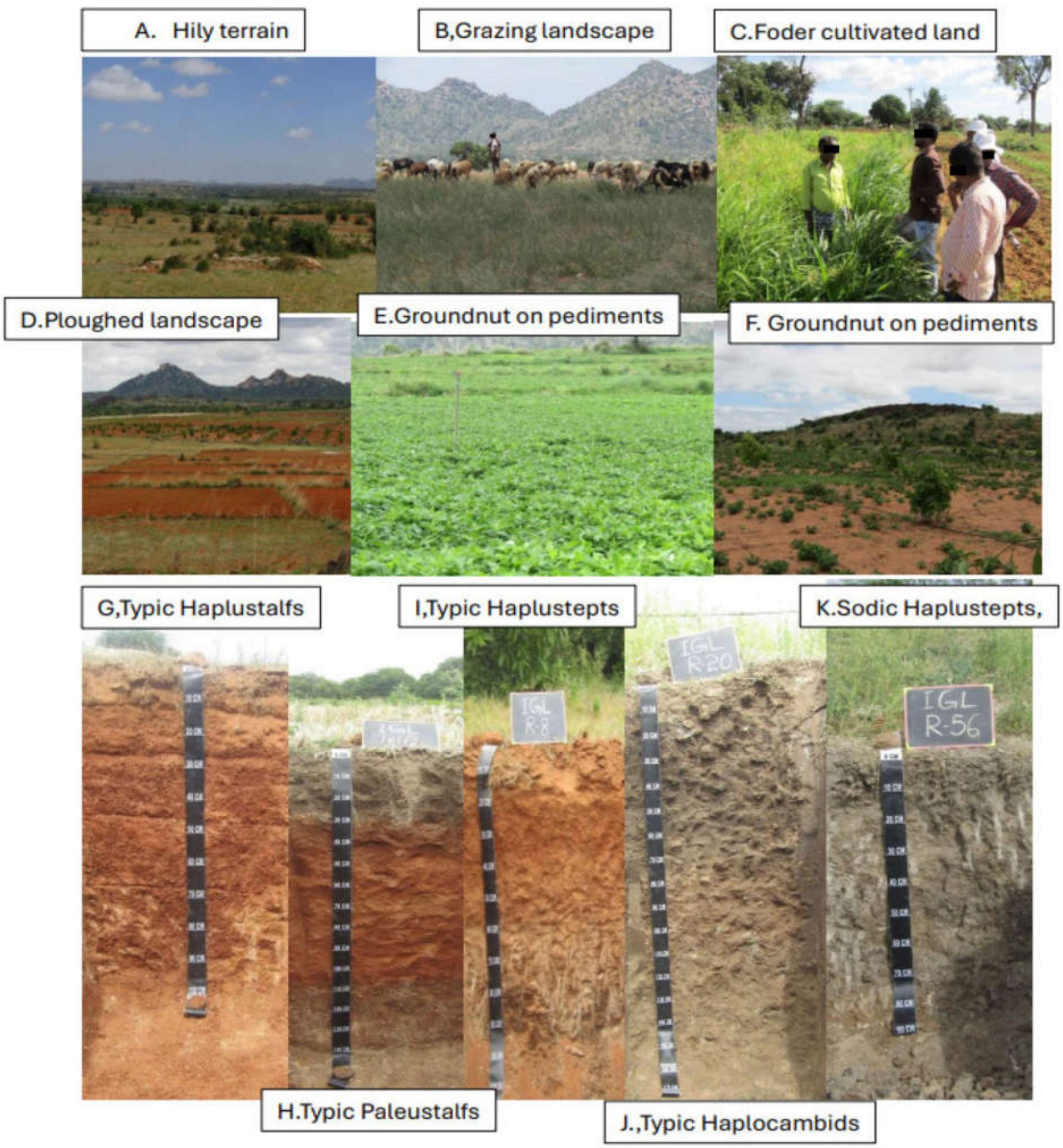

Fig. 9: Agri-environment of groundnut systems in eastern part of Anantapur district

The southwest monsoon precipitation exhibits significant variability, showing a yield trend of 692.26 ± 288.14 kg/ha and a coefficient of variation (CV) of 41.62%. Similar findings have been documented, prompting the need to explore alternative high-yielding crops for rainfed groundnut cultivation in Alfisols (Radha kumara *et al.*, 2016). In areas where rainfall is evenly spread throughout the growing period, crops typically yield about 5 to 10 kg/ha of pods per millimeter of rainfall. For rainfed peanuts, a minimum average rainfall of 400 mm between June and September is necessary to ensure a successful harvest. Long-term rainfall data indicates a 60 mm deficit, but more than 135 mm of rainfall is received during the pod development stage in September. Natarajan and Willey (1986) conducted a study on the effects of drought on enhanced yields by implementing multi-cropping techniques with varying levels of water stress on intercrops of sorghum and peanut, millet and peanut, and sorghum and millet. All intercrops consistently showed increased yields across five different moisture availability levels, ranging from 297 to 584 mm of water applied throughout the growing season. The impact of drought on yield is influenced by environmental factors, including agricultural practices (Sun *et al.*, 2021), pre-drought conditions, and soil characteristics, particularly soil moisture retention properties (Hofer *et al.*, 2016). Notably, an average annual rainfall of 250 mm at the time of sowing, with a deviation of -100 to +100 mm, can enhance water utilization and boost yields in heavy clay soils (O' Leary and Connor, 1997). It was observed that 72% of soils have high (48%) to very high Cation Exchange Capacity (CEC) (24%), while the remaining 28% have low (12%) to moderate CEC (16%). It is worth mentioning that low CEC levels can be attributed to the high sand content and low organic matter in the soils. This evaluation of the correlation between pedological systems and climatic variations in the region is based on two key assumptions. The distribution of seasonal rains plays a crucial role in determining crop yields. Evenly distributed rains tend to result in good yields, while poorly distributed rainfall, such as mid-season droughts and prolonged dry spells, often leads to poor productivity. These assumptions are based on socio-economic surveys and district-level crop statistics. Additionally, consecutive crop loss and prolonged poor yields of groundnut in drought-hit Anantapur district highlight the need for a thorough appraisal of land resources for groundnut suitability (Taghizadeh *et al.*, 2020). Evaluating the climate, soil, and topographical components is essential in determining the suitability of agricultural land and promoting sustainable agricultural systems. This, in turn, has a direct impact on farmer income and supports the decision to engage in sustainable agriculture (Pineiro *et al.*, 2020). Identifying suitable lands for local crops can help mitigate unsustainable agriculture and environmental degradation (Mesgaran *et al.*, 2017). The semiarid regions of Andhra Pradesh are at a higher risk of environmental deterioration, emphasizing the need to assess their climatic and biophysical aspects to prevent further degradation and enhance resilience (Mathur and Sundaramoorthy, 2018). An example of this is the Anantapur district in Andhra Pradesh, which is currently grappling with severe drought conditions leading to environmental degradation, reduced groundnut productivity, and a threat to food security.

Considering the vulnerability of agroecosystems in the region, it is crucial to conduct a comprehensive analysis of rainfall patterns along with biophysical factors to evaluate the potential of implementing a groundnut system for agricultural diversification. The incorporation of rainfall characteristics into agroecological measures is vital for sustaining the economic system of agroecosystems. Harvey *et al.* (2014) have proposed various strategies, such as climate-smart agriculture and agroecological practices, to address climate change impacts. These approaches are highly recommended for their ability to reduce costs, enhance soil health, and strengthen community resilience against climate change, environmental, and economic adversities (Lin, 2011). The recommended methods include agroforestry, crop diversification, ground cover, incorporation of legumes into agricultural systems, and utilization of organic production techniques (Bezner Kerr *et al.*, 2021; Mbow *et al.*, 2014). Blessing *et al.* (2022) conducted a thorough examination of four intercropping models. These models consist of relay intercropping, row intercropping, strip intercropping, and mixed intercropping. Relay intercropping involves planting one or more crops within an already established crop, ensuring that the second crop's initial growth stage aligns with the first crop's maturity stage. Row intercropping entails growing two or more crops in the same field, while strip intercropping involves cultivating multiple crops in wide strips to facilitate modern agricultural machinery and promote interaction between associated species. Mixed intercropping, on the other hand, involves completely mixing cultures in the available space without a defined line arrangement. Each model offers unique benefits, such as mechanical cultivation, crop harvesting, income increase, ecosystem diversity improvement, soil quality modification, and response to forage preferences and cultural requests (Iqbal *et al*., 2019; Bi *et al*., 2019).

CONCLUSIONS

The Anantapur district in Andhra Pradesh has the potential to become a leading groundnut producer, despite historical low yields. With a unique climate characterized by 3 months of rains and high yield instability over 45 years, this district offers a challenging yet promising environment for crop diversification. By analyzing the agro environmental conditions and integrating soil maps with pedological data sets, it was oberved that nearly 30% of the area is suitable for groundnut cultivation. Despite limitations such as rock outcrops and nutrient deficiencies, there is a clear opportunity to enhance groundnut yield up to 2000 kg/ha by implementing innovative agroecological technologies. It is crucial to adopt conservation strategies to combat droughts and ensure a stable yield for groundnut production. Let's seize this opportunity to transform Anantapur into a thriving groundnut hub for years to come!

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