Delineation of Cumin (*Cuminum Cyminum* L.) Production Zone Beyond Boundaries in India Based on Climate Analogues, Soil Suitability and Rainfall Analysis

Krishnamurthy KS (kskrishnamurthy@gmail.com)
Indian Institute of Spices Research https://orcid.org/0000-0003-2434-6199
Kandiannan K
ICAR-Indian Institute of Spices Research
Swetha Sudhakaran
ICAR-Indian Institute of Spices Research
Muhammed Bin Faras U P
ICAR-Indian Institute of Spices Research
Alagupalamuthirsolai M
ICAR-Indian Institute of Spices Research
Jayarajan K
ICAR-Indian Institute of Spices Research

Research Article

Keywords: climate change, CCAFS, efficient zones, relative yield index, relative spread index

Posted Date: June 16th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-466566/v1

Abstract

Here, we attempted to identify ideal ecological niche for cumin cultivation in India in the future climate scenario by adopting an integrated approach of climate analogues and soil suitability. This will help policy makers for area expansion to generate more revenue as cumin has huge export potential. Climate analogues tool, a web-based tool developed by the Research Programme on climate change, agriculture and food security (CCAFS) helps to identify, connect and map sites with statistically similar climates across space and time. Efficient cumin production zones in India were identified based on relative spread index and relative yield index which were used as the input/reference site for finding the analogues sites. Rainfall and temperature were the main climatic variables used in the study under SRES A1B emission scenario. The results showed a total of 453 analogues sites (districts) identified by 14 reference sites used in the study. The analogues sites identified by the tool were further corroborated with the soil suitability of the location and refined analogues sites which included soil suitability for cumin cultivation (337 analogues sites out of 453) were identified. Rainfall trend analysis from the rainfall data of past 110 years indicated that analogues sites are showing the rainfall trend suited for cumin cultivation. This is the first report on the use of climate analogues tool to identify analogues sites with soil suitability and rainfall trend analysis of the identified analogues sites.

1. Introduction

India has an old history of cultivation of spices and takes benefit of being the largest producer, exporter and consumer of spices in the world. There are about 63 spices which are grown in India out of which 20 have been classified as seed spices. The major seed spices grown in India are cumin, fenugreek, coriander and fennel. Cumin (*Cuminum cyminum* L.) is an important spice commodity cultivated in a large area in arid and semi-arid regions of Rajasthan and Gujarat which have favourable soil and climatic conditions for its cultivation (Dubey et al. 2016) and India contributes to 70% of world's cumin production (Sharma et al. 2019). Study by Aiswath et al. (2016) indicated that out of 3564000 ha total study area in Rajasthan, 4% was moderately suitable for cumin cultivation with little limitations of soil and water whereas 74% was marginally suitable with limitation of soil and water. Gujarat and Rajasthan together contribute more than 90% of total cumin production in the country.

Cumin is a drought-tolerant, tropical, or subtropical crop. It has a growth duration of 100 – 120 days. Optimum temperature requirement is 20–30°C and it can grow in an annual rainfall range of 30 to 270 cms. Cumin is vulnerable to frost damage, especially at flowering and early seed formation stages. The optimum growth temperature range is between 25 and 30° C. The crop can be grown well in soils having pH in the range of 6.5 to 8.5. However, for higher productivity of the crop and quality seed production, it is suggested that pH should be in the range of 6.5–7.5 with more than or equal to 0.6 per cent organic carbon and less than 10 per cent calcium carbonate content (Sharma et al. 2010). Cumin can tolerate even moderate salinity.

The Mediterranean climate is most suitable for its growth. Cultivation of cumin requires a long, hot summer of three to four months. At low temperatures, leaf colour changes from green to purple. High temperature might reduce growth period and induce early ripening. High humidity during flowering and fruiting period initiate the development of diseases like blight and powdery mildew causing damage to the crop. It is grown as an irrigated crop during winter in Indian condition. Planting date depends on climatic conditions of region, so that in temperate regions, it is an autumn crop and in cold areas, it is grown as spring crop and needs fertile, well-drained soil (Hajlaoui et al. 2010). In India, cumin is sown from October until the beginning of December, and harvesting starts in February. The proper time for sowing is from mid-November to first week of December. Various factors such as temperature, weather, irrigation facilities, clear sky etc. affect the development of crop. Productivity is mainly dependent on the climatic conditions prevailing during crop growth. As climate change has become a reality and reports suggest that climate change is likely to accelerate in future (IPCC 2007; Moss et al. 2010), it is likely to hit Indian agriculture as India is primarily an agricultural economy. This entails an urgent evaluation of risks for major food crops critical to food security (Brown,et al. 2008). Moreover, Kahrizi et al. (2011) reported that cumin yield and aroma are better under moderate climate compared to tropical climate, indicating that climate change in cumin growing regions of India is likely to decrease cumin yields and bring down aroma. Thus, it is essential to identify alternate sites for cumin production as the existing sites of cumin cultivation may become unsuitable due to climate change. A systematic and scientific appraisal of natural resources especially climate and soils and their database are important pre requisites for augmenting cumin production on a sustainable basis. It is important that impact of climate change are studied to get prepared for maintenance of food security. Climate analogues is one simple tool to assess crop suitability as analogues locations are expected to have the future climatic conditions of the reference site which is favourable for the crop cultivation (Haussmann et al. 2012). Thus, the main objectives of the present study were to identify efficient cumin producing zones in India; to identify climate analogues sites for cumin growing in future (2020–2049); to analyse rainfall trend in climate analogue sites and to integrate soil suitability to climate analogues sites to have better prediction of suitable sites.

2. Material And Methods

2.1 Collection of data

The official records on area and production of cumin in India were used to identify efficient producing zones as suggested by Kanwar (1972) and geo-referenced. The geographical co-ordinates of the selected reference sites were used for identifying the climate analogues against the search range of India. In this study, the analogues sites generated by the tool were based on the two climatic variables i.e. mean temperature and precipitation. We further selected the most suitable sites by incorporating soil information. The soil data available in the relevant sources like Central Ground Water Board and Central Research Institute for Dryland Agriculture (ICAR-CRIDA), Hyderabad were used to identify the soil type of analogues sites. Correlation and test of significance of correlation coefficient were conducted to analyse the rainfall trends using the past climate data (110 years) collected from Indian Meteorological Department, Pune, Maharashtra.

2.2 Identification of efficient production zones

The data on area, production and productivity of cumin in major cumin growing states of India viz. Gujarat and Rajasthan was collected from Spices Board, Govt of India and efficient cropping zones of cumin were identified based on relative yield index (RYI) and relative spread index (RSI) (Kanwar 1972) using the formula,

RYI = Mean yield of a particular crop in a district (kg/ha) / Mean yield of the crop in the State × 100

RSI = Area of particular crop expressed as % of total cultivable area in the district / Area of particular crop expressed as % of total cultivable area in the State × 100

Five years data (2011-12 to 2015-16) on area and production of cumin were collected and it was averaged to calculate RYI and RSI using the above formula. Criteria used for efficient cropping zone is presented in Table 1. RYI and RSI were used to categorize each district in selected states into different zones of production and the categories are represented in Table 2.

Table 1
Criteria for efficient cropping zone

Criteria for efficient cropping zone			
Relative Yield Index (RYI)		Relative Spread Index (RSI)	
> 125	High	> 100	High
75–125	Medium	75–100	Medium
< 75	Low	< 75	Low

Table 2
Categories for efficient cropping zones

Zone	*RYI*	*RSI*	Category
1	High	High	Most efficient zone
1a	High	Medium	Most efficient zone with variation
2	High	Low	Efficient zone
2a	Medium	High	Efficient zone with little year to year variation
2b	Medium	Medium	Efficient zone with medium year to year variation
2c	Medium	Low	Efficient zone with great year to year variation
3	Low	High	Not efficient zone with greater variation
3a	Low	Medium	Not efficient zone with medium year to year variation
4	Low	Low	Not efficient zone with little variation

2.3 Climate analogues tool

We used the climate analogues tool of Climate Change, Agriculture and Food Security (CCAFS) which allows to analyse data (identify analogue sites) in three temporal directions, i.e., (i) Future to Present, (backward direction), (ii) Present to Future, (forward direction), and (iii) Present to Present/Future to Future, (no temporal direction, i.e. none). In this study, we used forward direction to identify analogues sites based on the two climatic variables, monthly mean temperature and monthly precipitation.

The geographical co-ordinates of reference sites selected were input into the spatial analogues tool. For each site the inputs used were the ensemble of climate models for the Global Climate Model (GCM) and A1B, SRES for the emission scenario. In the analysis settings, Grid-analysis was selected to compare one single location with the whole geographic domain and output generated for any geographic region at any resolution will be equal to or above one km. Regarding similarity index, the CCAFS model calculates dissimilarity as a weighted Euclidean distance between the variables vectors for the reference (f). Based on this, target (p) scenarios were selected, and finally the optimum growing period of different regions were also input into the tool. The spatial analogues were determined on the basis of both, mean temperature and precipitation in case of climatic variables. Regions with high similarity were selected from the output grids produced by the tool and their geographical coordinates were derived. The analogues sites obtained using the tool were again classified on the basis of probability of matching i.e. highly likely (similarity value of 0.75–1) and moderately likely (similarity value of 0.5–0.75).

2.4 Mapping

ArcGIS (ESRI, India) was used for mapping. ArcMap allows exploring data within a data set, symbolizing features accordingly, and creating maps. This was used for giving boundaries to the climate analogues maps generated by the climate analogues tool and also for designing soil maps of the analogues sites.

3. Results

3.1 Efficient cropping zones of cumin in Gujarat

Cumin is cultivated in 21 districts of Gujarat in an area of 352657 ha with production of 307702 tons. The highest area of 95176 ha under cumin cultivation was observed in Surendranagar followed by 67710 ha in Banaskantha and 49082 ha in Patan. Similar trend was observed in production scenario of cumin in the state. Highest production was recorded in Surendranagar (98282 t) followed by Banaskantha (66793 t) and Patan (41411 t). Among the major producing districts, highest productivity of 1033 kg/ha was recorded in Surendranagar, well above the state productivity of 872 kg/ha. Banaskantha recorded 986 kg/ha and Patan 844 kg/ha.

Based on relative yield index and relative spread index, the different districts in the state are categorised as follows: efficient zone (Panchamahal); efficient zone with little year to year variation (Banaskantha, Jamnagar + Devbhumi, Porbandar, Patan, Rajkot + Morbi and Surendranagar); efficient zone with medium year to year variation (Kutch); efficient zone with great year to year variation (Bhavnagar, Junagadh, Kheda and Mehsana); not efficient zone with greater variation (Ahmedabad + Botad) and not efficient zone with little variation (Amreli, Anand, Gandhinagar and Sabarkantha + Aravalli) (Fig. 1).

3.2 Efficient cropping zones of cumin in Rajasthan

Cumin is cultivated in 28 districts of Rajasthan with a total area of 443582 ha and a production of 164751 tons. The major districts cultivating cumin in the state are Barmer (122751 ha), Jodhpur (104199 ha), Jalore (83647 ha), Nagaur (47196 ha), Jaisalmer (23281 ha) and Pali (13465 ha). The highest production of 45180 t was recorded in district of Jodhpur followed by Jalore (37180 t) and Barmer (34897 t). The state productivity of cumin was 371 kg/ha while the highest productivity of 565 kg/ha was observed in Karauli and the least in Churu (220 kg/ha).

Based on relative yield index and relative spread index, the different districts in the state are categorised as follows: most efficient zone (Nagaur); efficient zone (Dausa, Dholpur, Dungarpur Jhunjhumn, Karauli and S Madhopur); efficient zone with little year to year variation (Barmer, Jaisalmer, Jalore and Jodhpur); efficient zone with medium year to year variation (Ajmer, Pali and Sirohi); efficient zone with great year to year variation (Baran, Bhilwara, Bikaner, Bundi, Chittorgarh, Jaipur, Jhalawar, Kota, Pratapgarh, Rajsamand, Sikar, Tonk and Udaipur) and not efficient zone with little variation (Churu) (Fig. 1).

3.3 Identification of climate analogues sites for cumin cultivation in future using CCAFS climate analogues tool

3.3.1 Reference sites

For identifying the climate analogues, the most important aspect is the selection of reference sites. Efficient districts which contributed to 90 % of country's cumin production and among efficient districts, those which contribute more than 10000 t production were selected as reference sites. This comprised of 14 districts from the states of Gujarat and Rajasthan (Table 3).

Table 3
Reference sites used for climate analogues tool

District	Area (ha)	*Production (t)	Productivity (kg/ha)	RYI	RSI	RYI-RSI Average	Category
Surendranagar	90243	91738	1004	116	366	241	2a
Banaskantha	62758	61487	976	113	243	178	2a
Jodhpur	100789	45303	456	118	329	224	2a
Patan	44802	37200	809	94	492	293	2a
Jalore	81989	36025	599	155	530	343	1
Barmer	116306	31630	268	70	308	189	3
Nagaur	43094	21401	492	128	149	138	1
Jamnagar	25450	20232	827	96	118	107	2a
Morbi	19000	19570	1030	119	271	195	2a
Porbandar	17963	15615	899	104	405	255	2a
Rajkot	20206	14475	698	81	87	84	2b
Kutch	20103	13479	662	77	91	84	2b
Ahmedabad	25670	12796	513	59	142	101	3
Junagadh	13770	9830	753	87	73	80	2c

3.3.2 Analogues sites

Based on the reference sites listed Table 3, climate analogues sites were identified using CCAFS Climate Analogues tool. There are mainly 52 existing sites (districts) of cumin cultivation in India (Table 4). The Climate Analogues tool has identified 453 analogues sites for cumin cultivation in future. Besides Gujarat and Rajasthan, a few sites in the states of Uttar pradesh, Madhya Pradesh, Haryana, Punjab, Delhi, West Bengal, Karnataka, Jharkhand and Bihar also showed high similarity to the existing sites of cultivation (Table 4, Fig. 2).

Table 4
Climate analogues sites (pooled from all reference sites) as identified by CCFAS Climate Analogues tool and further refined using soil suitability

Existing sites of cumin cultivation		**New sites identified for cultivation during 2020–2049 using CCAFS Climate analogues tool**		
State	**No. of districts**	**State**	**Total no. of districts**	**No. of districts with soil suitability**
Gujarat	23	Andhra Pradesh	9	9
Rajasthan	29	Arunachal Pradesh	1	1
Total	**52**	Assam	2	1
		Bihar	38	38
		Chhattisgarh	27	1
		Delhi	11	11
		Goa	2	2
		Gujarat	10	10
		Haryana	22	22
		Karnataka	24	5
		Kerala	6	0
		Madhya Pradesh	51	51
		Maharashtra	36	34
		Meghalaya	2	0
		Mizoram	1	1
		Odisha	27	0
		Jharkhand	24	2
		Punjab	22	22
		Rajasthan	4	4
		Telangana	31	28
		Tripura	3	0
		Uttar Pradesh	75	75
		Uttarakhand	2	2

Existing sites of cumin cultivation	New sites identified for cultivation during 2020–2049 using CCAFS Climate analogues tool		
	West Bengal	23	18
	Total	**453**	**337**

3.4 Soil suitability

As the soil data is not included in the tool, soil suitability data was also incorporated to the identified analogues sites. The results showed that out of 453 analogues sites identified by the tool, 337 sites showed the soil suitability for cumin cultivation (Table 4, Fig. 3)

3.5 Rainfall trend of climate analogues

Past rainfall data from 1901 to 2010 (for 110 years) was collected from IMD, Pune to analyse the rainfall trend in climate analogues as well as existing sites of the crop. The results indicate that the climate analogues are showing the required rainfall trend for the crop. Among newly identified sites, 182 sites show positive trend (48 significant) and 271 (103 significant) sites show negative rainfall trend. This suggests that as opposed to the existing sites of cultivation, most of the analogues sites are moving towards dryer climate, thus making these sites suitable for cumin cultivation in future.

4. Discussion

4.1 Climate analogues sites

From all the 14 reference sites put together, 453 climate analogues sites were identified (Table 4) covering most parts of India except the places listed above. Except for a few studies (Adams et al. 1999; Ramirez Villegas et al. 2011), climate analogues approach is not much used to study climate change associated effects. Chaudhary et al. (2016) reported the use of climate analogues approach to identify analogues sites in rice. It is true that climate analogues approach predicts the future analogues based only on the climate of the reference site used whereas crop establishment depends on various other factors such as soil, photoperiod, light availability, elevation and interaction between various parameters. Data on production statistics of cumin over seven years shows that West Bengal, Uttar Pradesh and Madhya Pradesh are cultivating cumin in a few patches. A close look at the climate analogues maps (Fig. 2) reveals that the reference sites Jalore and Barmer have shown a wide spectrum of highly likely climate similarity sites. In the moderate range of climate similarity, same analogues sites are identified for all the reference sites covering the entire tracts of central and the northern plains of the country including Telangana. This is due to the fact that the climatic conditions of the places in these regions are not greatly altered. Southern and North Eastern parts fo India on the other hand were found unsuitable for extension of cumin cultivation except for some parts of central and northern Karnataka and Andhra Pradesh as precipitation and temperature of these places do not support cumin cultivation.

The uncertainty in climatic projections is mainly due to ‘the non-linear character of the climate system, future emissions of greenhouse gases, internal variability, model parameterization etc. (Gornall et al. 2010). However, climate analogues approach could still be used as it provides valuable information on the climate which is very useful for strategic planning (Grenier 2013). On the other hand crop simulation models such as CERES-Maize (Ritchie et al. 1989), SOYGRO for grains (Jones et al. 1988) etc. which simulate the effect of climate change on growth have been studied. Hence, in this study, we tried to combine soil suitability (Table 4, Fig. 3) also to make climate analogues sites identified by the tool little more realistic.

4.2 Climate analogues with soil suitability

All types of soils are suitable for cultivation of this crop. However, sandy loam to medium heavy soils having plenty of organic material with better fertility status is most suitable. The soil should have better drainage facility because stagnated water and excessive moisture are very harmful for successful cultivation of cumin and such soils should be avoided. Soil suitability including desert soil, alluvial soil and some parts of black soil are identified as suitable among analogue sites obtained. The crop can be grown well in soils having pH in the range of 6.5 to 8.5. However, for higher productivity of the crop and quality seed production, it is suggested that pH should be in the range of 6.5–7.5 with more than or equal to 0.6 per cent organic carbon and less than 10 per cent calcium carbonate content (Sharma et al. 2010). Loam, clay loam, silty clay loam are highly suitable while massive clay and coarse sand are not suitable for cumin cultivation (Sharma et al. 2019). Based on the soil requirement for cumin cultivation, the soil maps obtained for analogue sites were analysed and the distribution of soil types of most of the analogues sites were found complementing the required range of pH of 6–8 and well drained texture of sandy to loamy. However, some of the climate analogues sites were found to have unsuitable soils for cumin cultivation. Out of 453 analogues sites identified by the tool, 116 sites were found to have unsuitable soil for cumin cultivation (Table 4). Most of the analogues sites identified in the states of Chhattisgarh, Odisha, Jharkhand, Karnataka and Kerala have shown non-suitability of the soil as per the soil data of these states. By taking these unsuitable sites in to account, refined map depicting only the climate analogues sites with soil suitability was prepared (Fig. 3). It is clear from the map that the central part covering Madhya Pradesh, Maharashtra, Telangana, northern parts covering Delhi, Uttar Pradesh, Punjab, Haryana and eastern parts covering Bihar and West Bengal are mostly suitable for cumin cultivation in future climate (2020–2049). Analogues sites could be helpful to identify matching sites for germplasm exchange for future adaptation (Chaudhary et al. 2016). This will help in planning for exotic germplasm collections targeting the most suitable analogues sites so as to step up the production and to meet the demands of domestic as well as export market.

4.3 Rainfall trend

Correlation analysis of rainfall trend revealed that more than half the number of existing sites invariably follow a positive trend of rainfall for cumin cultivation with significant positive trends for four sites. Contrarily, 22 sites showed negative trend in existing sites of which, 2 were found significant. Cumin grows and yields well under dry weather conditions and more than half of the existing sites are showing positive trend indicate that many of the existing sites are slowly becoming non-suitable for cumin cultivation as these sites are receiving more rainfall. Cumin requires comparatively less irrigation water (218 mm) than other tropical plants. Seed quality is affected if there is rainfall during the harvesting period (Rao et al., 2010). Cumin can be cultivated in rainfall and temperature ranges of 30 to 270 mm and 9 to 26 ^{o}C respectively. However, rainfall of 250 mm and a mean temperature of 13–22 ^{o}C during growing cycle are highly suitable (Sharma et al. 2019). Nimisha Agarwal and Anindya Sinha (2019) identified the future climate analogues of current wheat production zones in India based on CCAFS climate analogues tool. They compared the present and future predicted yields in analogues sites. In this study, among climatic parameters, only temperature was considered in the climate analogues tool. They opined that for comprehensive understanding, other factors such as soil type, rainfall etc. are also important. Our study addresses soil characters as well as rainfall trend of the analogues sites. This is the first study as per our understanding which addressed the issue of soil character as well as rainfall trend of the analogues sites.

Thus, the present study employed CCAFS climate analogues tool to identify climate analogues of cumin. The analogues sites identified by the tool were further corroborated with the soil suitability of the location. Rainfall trend analysis of the existing and analogues sites indicated that existing sites are becoming less suitable while the analogues sites are showing the rainfall trend suited for cumin cultivation.

5. Declarations

Funding

This research work was funded by National Initiative on Climate Resilient Agriculture (NICRA), ICAR-Central Institute of Dryland Agriculture, Hyderabad, India.

Authors contribution

Krishnamurthy, Kandiannan and Alagupalamuthirsolai contributed to the study conception and design and supervision, data collection and analysis were performed by Faras Bin Muhammed, Swetha Sudhakaran and Jayarajan. The first draft of the manuscript was written by Swetha Sudhakaran, Krishnamurthy edited the draft and prepared the final version after receiving the comments from all the authors. All authors read and approved the final manuscript.

Acknowledgements

Authors are thankful to the Director, ICAR-Indian Institute of Spices Research, Kozhikode, Kerala for the encouragement and support.

6. References

1. Adams PJ, Seinfeld JH, Koch DM (1999) Global concentrations of tropospheric sulfate, nitrate and ammonium aerosol simulated in a general circulation model. J. Geophys. Res. 104: 13791-23; DOI:10.1029/1999JD900083
2. Aishwath OP, Singh HR, Velmurugan A, Anwer MM (2016) Analysis of soil suitability evaluation for major seed spices in semi-arid regions of Rajasthan using geographic information system. *Int. j. seed spices* 1: 29-37
3. Brown ME, Funk CC (2008) Climate. Food security under climate change. Science 319: 580–581
4. Chaudhary P, Joshi BK, Thapa K, Devkota R, Ghimire KH, Khadka K, Upadhya D, Vernooy R (2016) Interdependence on plant genetic resources in light of climate change. In: Implementing the International Treaty on Plant Genetic Resources for Food and Agriculture in Nepal: Achievements and Challenges (BK Joshi, P Chaudhary, D Upadhya and R Vernooy, eds). LIBIRD, Pokhara; NARC, MoAD, Kathmandu and Bioversity International, Rome; Nepal, pp.65-80
5. Dubey PN, Saxena SN, Mishra BK, Aishwath OP, Solanki RK, Singh B, Lal G (2016) Assessment of variability in physical and chemical composition of *Cuminum cyminum* seeds from arid and semiarid India. Indian J. Agric. Sci. 86(10):1366-70. (ISSN: 0019-5022)
6. Gornall J, Betts R, Burke E, Clark R, Camp J, Willett K, Wiltshire A (2010) Implications of climate change for agricultural productivity in the early twenty-first century. Philos. Trans. R. Soc. Lond., B, Biol. Sci, 365: 2973–2989.
7. Grenier P (2013) Spatial analogs: a decision support and communication tool. OURANOS newsletter. http:// www.ouranos.ca/ en/ newsletter/ documents/ Grenier_EN.pdf
8. Hajlaoui H, Mighri H, Noumi E, Snoussi M, Trabelsi N, Ksouri R, Bakhrouf A (2010) Chemical composition and biological activities of Tunisian *Cuminum cyminum* L. essential oil: A high effectiveness against *Vibrio* spp. strains. Food Chem. Toxicol. 48: 2186– 2192
9. Haussmann BIG, Fred Rattunde H, Weltzien-Rattunde E, Traoré PSC, Brocke V, Parzies HK (2012) Breeding strategies for adaptation of pearl millet and sorghum to climate variability and change in West Africa. J Agron Crop Sci, 198: 327–39: DOI: http://dx.doi.org/10.1111/j.1439 037X.2012.00526.x
10. IPCC (2007) IPCC Fourth Assessment Report (AR4): Climate Change 2007
11. Jones J, Boote K, Jagtap S, Hoogenboom G, Wilkerson G (1988) SOYGRO v5.41 Soybean Crop Growth Simulation Model, User's Guide, Florida Agricultural Experiment Station Journal No. 8304, IFAS, University of Florida, Gainesville, FL
12. Kahrizi D, Azizi K, Haghi Y (2011) Relationships among yield and yield components and essence in *cumin* (*Cuminum Cyminum* L.) under different *climate* conditions. Biharean Biol. 5: 63-68
13. Kanwar JS (1972) Cropping patterns, scope and concept. In Proceedings of Cropping Patterns in India, 11–38. New Delhi, India
14. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JF, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson

AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature, 463 (7282): 747–56

15. Nimisha Agarwal, Anindya Sinha (2019) Future climate analogues of current wheat production zones in India. Curr. Sci., 116 (2): 264-271
16. Ramírez-Villegas J, Lau C, Kohler AK, Signer J, Jarvis A, Arnell N, Osborne T, Hooker J (2011) Climate analogues: finding tomorrow's agriculture today. Cali, Colombia: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Working Paper-12
17. Rao SS, Singh YV, Regar PL, Khem Chand (2010) Effect of micro-irrigation on productivity and water use of cumin (*Cuminum cyminum*) at varying fertility levels. Indian J. Agric. Sci. 80(6): 507-11.
18. Rezvani Moghaddam P, Moradi R, Mansoori H (2014) Influence of planting date, intercropping and plant growth promoting rhizobacteria on cumin (*Cuminum cyminum* L.) with particular respect to disease infestation in Iran. J Appl Res Med Aroma 1: 134–143
19. Sharma RP, Rathore MS, Singh RS, Qureshi FM (2010) Mineralogical framework of alluvial Soils developed on the Aravalli sediments. J. Indian Soc. Soil Sci. 58: 70-75.
20. Sharma SS, Jajoria DK, Sharma RP, Rao SS (2019) Cumin (*Cuminum cyminum* L.) cultivation in Rajasthan as an opportunity - A soil and climatic suitability evaluation. Adv. Biores 10 (5): 5-11.
21. Shyampura RL, Sehgal J (1995) Soils of Rajasthan for Optimizing Land Use, NBSS Publication (Soils of India Series). National Bureau of Soil Survey and Land Use Planning, Nagpur, India, 76 + 6 sheet soil map (1:500,000 scale).

Figures

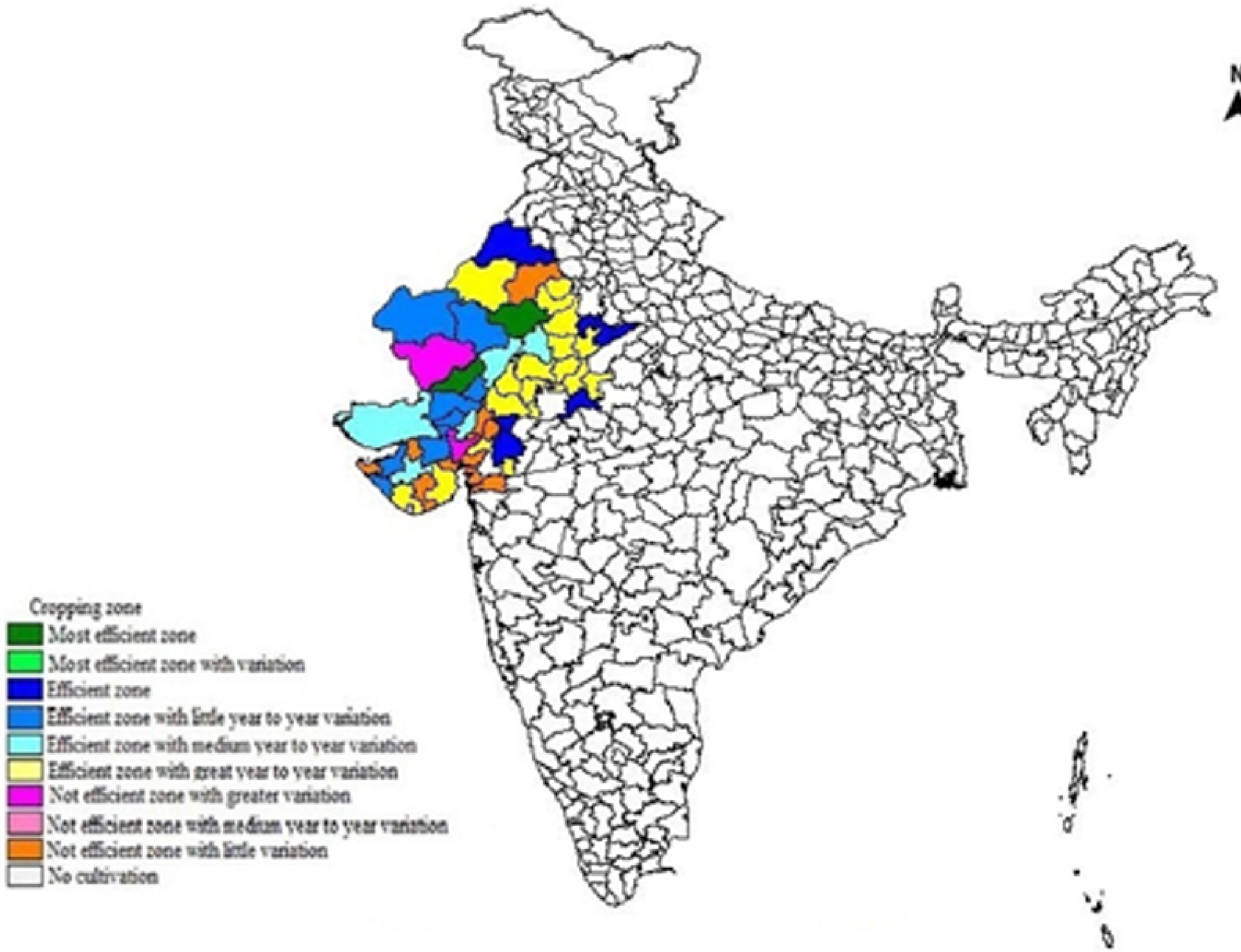

Figure 1

Efficient cropping zones of Cumin in India Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

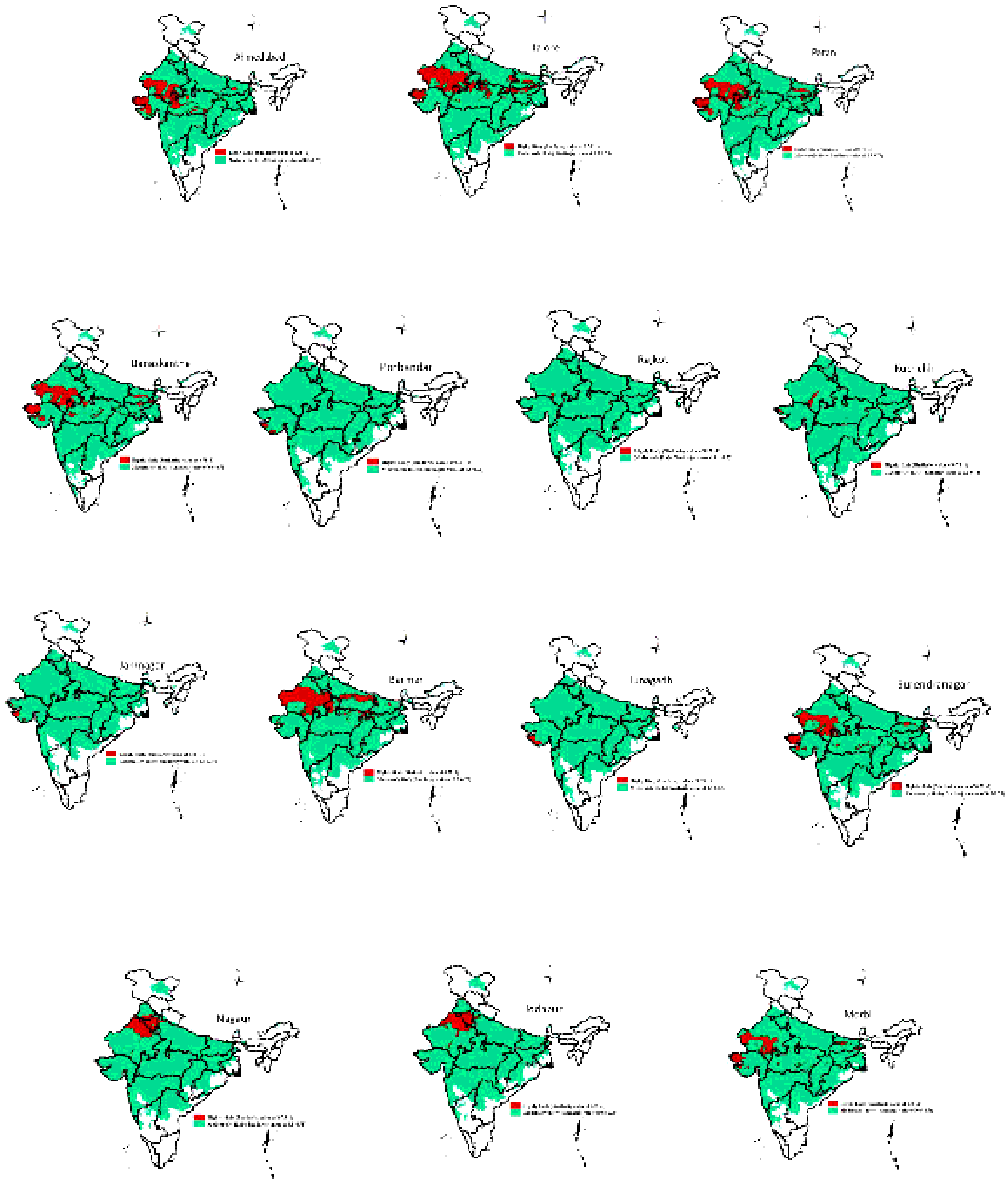

Figure 2

Climate analogues of selected reference sites using CCAFS Climate analogues tool for cumin production in 2020 – 2049 (Red indicates highly suitable and green moderately suitable) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

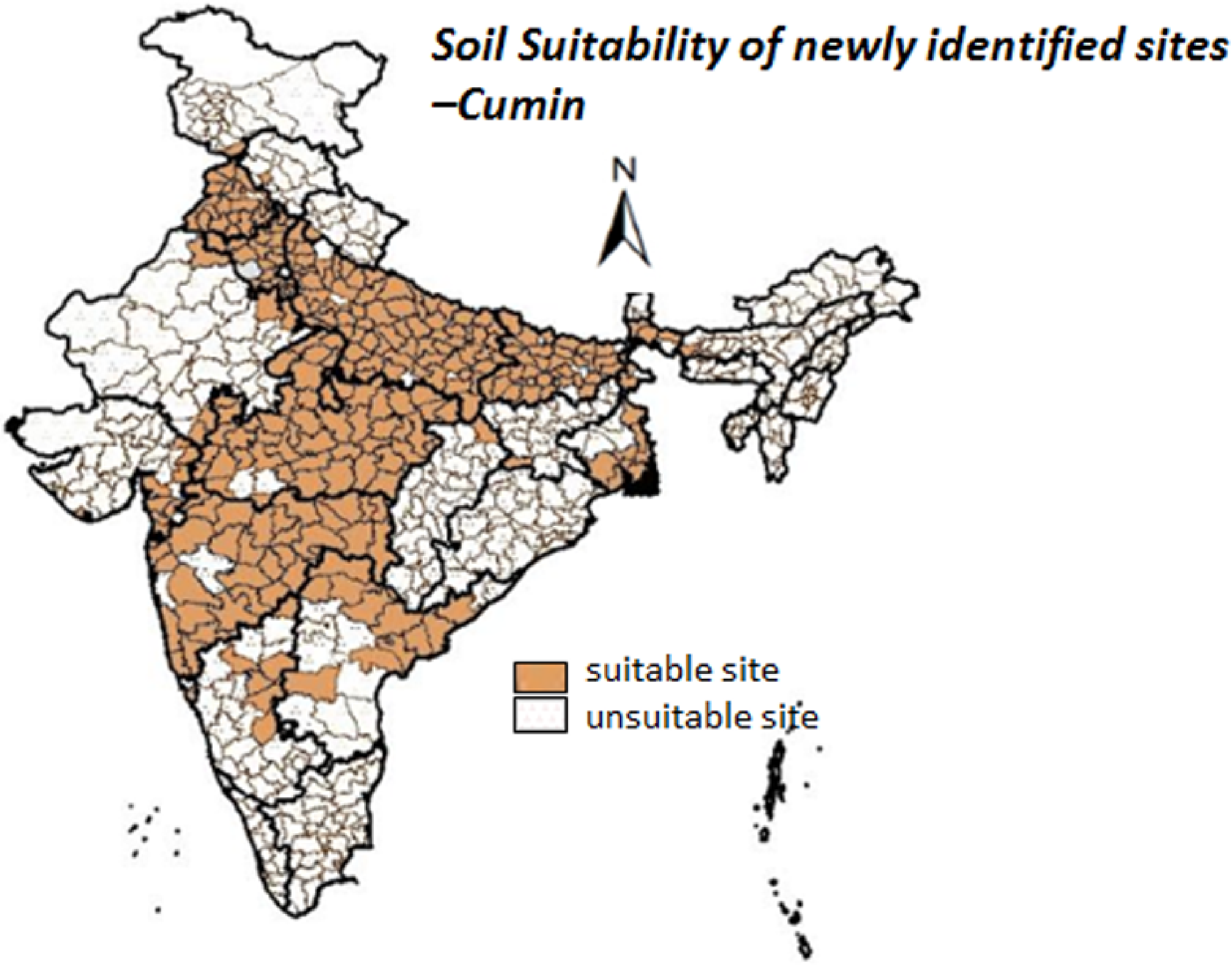

Figure 3

Climate analogues sites with suitable soils for cumin cultivation Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.