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Key Agri-Climatic and Socio-Economic Indicators for Cereal Production across the World

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Abstract— *This research focuses on the identification of key indicators of climate change impacting the cereal crop yields for fourteen countries across the world employing the principal component analysis (PCA) and the linear scoring technique using the World Bank Data for the period 1961 to 2013 for all indicators for all the countries. The Climate Change Crop Performance Indices (CCCPIs) are generated for each country for the first time using both the climatological and socio-economic indicators. These indices are used for comparing and monitoring the relative crop performance during the study period. The locations under study included Canada and Mexico from North America; Argentina, and Cuba from Latin America; France, and Portugal from Europe; Iran, and Israel from Middle East; Liberia and Somalia from Africa; and Mongolia, Nepal, Myanmar, and Philippines from Asia. Based on the PCA analysis and underlying assumptions, the following list of key indicators are identified for each country: Canada: temperature, CO_2e and LACP; Mexico, France and Israel: temperature, CO_2e and RF; Argentina and Cuba: CO_2e and RF; Portugal and Somalia: Temperature, CO_2e, LACP and RF; Iran: temperature, CO_2e, CY and RF; Liberia and Mongolia: CO_2e, CY and temperature; Nepal: CO_2e, CY and RF, and Myanmar and Philippines: temperature and CO_2e;. These indicators provide a signal of the desirable or undesirable changes in climatological or socioeconomic parameters that have occurred or may occur in future in the above-mentioned countries. These key indicators might help even the technology developers,* land managers and the policy makers to develop new strategies and formulate new policies.

Keywords—climate change, crop performance, principal component analysis, temperature, rainfall, CO_2 emissions.

I. INTRODUCTION

Agriculture is the key economic and sustainable development sector, sensitive [1] and vulnerable [2, 3] to climate change. It accounts to an average of 28% of the gross domestic product for many low-income countries[4] and its sustainability depends on many drivers acting at multiple scales from local to global [5].Majority of the crops are grown based on the role of climate change in agricultural productivity[6]. During the past years, due to climate change, most of the agricultural crops are reported to have a slower growth [7]. In places, where the agriculture is vulnerable to extreme climate variability like recurring droughts, floods, poor distribution of rainfall, temperature variations and carbon dioxide (CO_2) concentrations, the yields are directly affected especially during critical crop growth periods [3], which in turn has profound impact on the food security of a nation [8].Among the various factors, temperature, precipitation and CO_2 are the most influential ones affecting the crop yields directly and indirectly [7] causing a decline in the performance of most of the crops across the world by the end of the century. The broad agreement among the climate scientists is that due to an increase in CO_2 emissions under various scenarios, there will be an increase in temperatures by 1-5ºC to 5.8ºC by 2100.This will result in a shift in precipitation patterns that will cause the ecosystems to move poleward. This will also create a huge impact on the global economy and consequently decline in the quality of life [1]. For instance, it has been reported that there has been an approximately 40 million tonnes yield loss or $5 millions per year economic loss of the major crops such as wheat, maize, and barley, demonstrating the negative impacts of climate change [9].

To assess the effects of climate change on agriculture, literature provides an evidence of employing various impact assessment models like the climate, crop, and economic models, crop simulation models [8, 10], statistical models, process-based agro ecosystem models [11] and integrated ecological-economic modelling framework resulting in a wide range of projected climate outcomes [12]. Each of these models have their own advantages and shortcomings, presenting different levels of complexity and completeness in relation to the specific aspects considered in its analysis. In addition to the modelling approach, the impact of the climate change on agricultural sector can be assessed by selecting appropriate indicators and studying their changes in a long run. Indicators are any observations or measurable attributes that can be used to track changes or trends in any system. But the selection of appropriate indicators for climate change studies is very critical and depends on the consideration of environmental change and climate change from various perspectives. The indicators chosen should be continuous in time and space, easily measurable, monotonically increasing or decreasing, be a state variable, have a long record of observations with low natural variability [13]. In relation to agriculture, several indicators have been developed for climate smart agriculture [14] and environmental and socioeconomic indicators for measuring the outcomes of on-farm agricultural production [15]. For the Organisation for Economic Co-operation and Development (OECD) countries, which are the world's food suppliers, agri-environmental indicators have been identified related to soil water, air, and biodiversity [16]. Another study identified indicators for environmental sustainability of agriculture including waste, GHG emissions, land conversion, soil health, nutrients, and pesticides [17]. But studies involving the agri-climate change indicators are meagre and needs further research.

The current study has been aimed to identify the agro-climatological and socio-economic indicators which make an impact on agriculture, especially on the cereal yields at different geographical locations under different climatic conditions worldwide. The socio-economic indicators reflect the impacts on the current and future agricultural productivity in both developed and developing countries. However, in some of the developing countries, agriculture is purely based on the climatic conditions in addition to other factors like soil types, agricultural inputs, etc. Based on the key indicators identified, an index would be computed to show how any location would perform in terms of cereal production under the influence of the key indicators. This index would be termed as the Climate Change Crop Performance Index (CCCPI) and doesn't exist in the literature. This index might help in focussing on monitoring or keeping a watch on the qualified indicators and formulating suitable adaptation and mitigation strategies, develop suitable crop and land management technologies, frame relevant climate change policies to overcome or deal with the negative or positive consequences of climate change on the cereal crop production.

II. MATERIALS AND METHODS

2.1. Study Area

This study adopted fourteen heterogenous locations across the world representing various climatic regions. The criteria for selection of these countries include: locations having agriculture especially cereal production as one of the main livelihoods, their vulnerability to climate change variability and extremes, and their contribution towards GDP. The countries selected for the study were: Canada and Mexico from North America; Argentina and Cuba from Latin America and Caribbean; France, and Portugal from Europe; Iran, and Israel from Middle East; Liberia and Somalia from Africa; and Mongolia, Nepal, Myanmar, and Philippines from Asia.

2.2. Climatological and socio-economic Indicators

The variables used in the present study as indicators include the climatological indicators, which are, temperature and precipitation, and the socio-economic indicators, which are, Carbon dioxide emissions(CO_2e), cereal yield (CY), and land area under cereal crop production (LACP) (ha). The data for these indicators has been obtained from the World Bank data repository for a period from 1961 to 2013[18]. The observation records include the monthly temperature and precipitation for all the above-mentioned locations. CO_2emissions data, measured in kilo tons (kt), includes the emissions from burning of the fossil fuels and the manufacture of cement, consumption of solid and gas fuels and gas flaring. The cereal yield data, measured in kilograms per hectare (kg ha^{-1}), includes the dry grain yields for wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains and excludes the crops harvested for fodder, harvested for hay and food, feed, grazing, and silage purpose [18].

2.3. Methodology for identification of key indicators and computation of Climate Change Crop Performance Index (CCCPI)

The prime objective of this study is to identify the key agri-climatic indicators and compute the crop performance indices under varied climate conditions termed as "climate change crop performance index" (CCCPI). The methodology to calculate this index has been adopted with a few modifications from Andrews et al., Doran and Parkin [19], [20], followed by Sharma et al. [21, 22]. Although similar approach in computing the CCCPI has been employed in the present study, the current study will use the agriculture related climate change indicators for the first time to assess the impacts under climate change conditions. Principal component analysis and linear scoring techniques are used in calculating the index.

The initial step includes testing the indicators for their levels of significance using Mann-Kendall test and eliminate the non-significant indicators from the assessment process [23]. In the present study, as the number of indicators is low, all the indicators, irrespective of their levels of significance, have been included in the study. This is followed by identification of minimum data set (MDS) which is the smallest set of the indicators, that best represents the specific region and can be used to assess the impacts of climate change. All the indicators which have been retained in the minimum data set need not to be considered as the key indicators, but only the most appropriate ones selected based on further statistical analysis. It is only these key indicators which are included in computation of CCCPI. This is done by using principal component analysis (PCA) where the data is subjected to reducing the dimensionality (number) of the variables and retains only the original variability. Hence the principal components which received the Eigen values ≥ 1 and which explained at least 5 % of the variation in the data set [24] and which had high factor loadings are considered as the best representatives of the system attributes. Within each PC, only the highly weighted factors are retained for the MDS. In cases, where more than one variable was qualified, correlation analysis was performed to determine if any of the variables could be considered redundant and dropped from the MDS. Among the well correlated (r > 0.70) variables, only one variable with higher correlation sum is considered for the MDS. However, flexibility criteria were followed depending upon the importance of the variables for some of the locations. In cases, when the highly weighted variables are not well correlated, they were retained in the minimum data set. The variables thus qualified under these series of steps were termed as the key indicators. These key indicators were considered for computing the CCCPIs of various locations under the study.

Once the key indicators were identified, all the observations for these indicators were transformed using linear scoring technique [20]. To assign these scores, first the indicators were identified if a higher or the lower values were considered 'good' or 'bad'. In case of indicators with "higher values are better", each observation was divided with the highest value such that the observation with the highest value gets a score of one. In the case of "lower values are better" indicators, the lowest value was divided with each observation such that the lowest value gets a score of one. Once the observations are transformed using linear scoring, each observation of the MDS indicators were multiplied with the weighted factor using the PCA results. The weighted factor was obtained by dividing the % of variation explained by each PC with the total percentage of variation explained by all the PCs with only eigen value >1. Once these weighted scores were obtained for the MDS indicators, they are summed up for each observation to arrive at the CCCPIs using the following relation:

$$CCCPI = \sum_{i=1}^{n}(W_i S_i)$$

where, W_i is the weighted factor obtained from the PCA and S_i is the variable score. The underlying assumption is, higher the CCCPI value, greater is the crop performance under the prevailing climatic changes. Thus, the relative crop performance during various years of the study period under various locations has been assessed and the key climate change indicators which are responsible for causing any change in the crop performance can be monitored.

III. RESULTS

The results of identifying the minimum dataset, selection of key indicators and computation of the CCCPIs are presented here and the importance of the key indicators identified are also discussed briefly.

3.1. Identification of key agri-climate change indicators

To identify the key indicators of climate change which influence the cereal crop production, all the indicators i.e. temperature (Temp), rainfall (RF), CO_2 emissions (CO_2e), cereal yield (CY), and land area under cereal production (LACP) were considered. In the primary step, out of the five indicators selected for the study, rainfall showed statistical significance only for few countries out of all the locations (Table1). However, this climate variable has been retained in the data set for further processing since it is one of the most climatologically important indicators. The results of the PC analysis (Table 2) reveal that only two PCs i.e. PC1 and PC2 with eigen value >1 are qualified for all the locations except for Philippines and Myanmar. These PCs explained a cumulative variability ranging from 61.5 to 89.0% across the locations.

For both Canada and Mexico, PC1 included similar highly weighted variables i.e. temperature, CO_2e and the crop yields. But in PC2, Canada had LACP while Mexico had RF as the highly weighted variables. For PC1 of Canada, temperature did not show any correlation with other indicators while CO_2e and the CY showed a significant correlation (r = 0.78) due to which only CO_2e indicator has been retained for CCCPI calculation. While for Mexico, as all the three indicators were significantly correlated, correlation sums were calculated for all the three indicators. CO_2e and CY showed similar and higher correlation sum of (r = 2.70), and hence only CO_2e has been selected. Though temperature showed a lower correlation sum, it was also retained in the MDS based on its significant role in the climate change. Hence, for Canada, the indicators retained as the key indicators in the MDS included temperature, CO_2e and LACP while for Mexico, the key indicators retained were Temperature, CO_2e and RF.

Both Argentina and Cuba showed only two PCs with eigen values >1. Out of these in PC1, both the locations had same highly weighted variables i.e. CO_2e and CY while in PC2 both the locations showed RF as the highly weighted variable with a cumulative variance of 71.6 and 65.2% respectively. Significant correlation existed between CO_2e and CY of PC1 for Argentina ($r = 0.81$) and Cuba (r = 0.70) due to which only the CO_2e has been retained for the MDS. Hence, for both Argentina and Cuba, the highly weighted variables which were retained as key indicators in the MDS were CO_2e and RF.

Similarly, for France and Portugal, only two PCs were qualified. Under PC1, in case of France, three variables i.e. temperature, CO_2e and CY were highly weighted variables while for Portugal LACP is also qualified along with the above three variables. But in PC2, both the locations showed RF as the highly weighted variable in the data set. Among the variables in PC1 of France, CO_2e did not show any significant correlations with other variables while temperature was well correlated with the CY and CO_2e. Though, CY showed highest correlation sum, it has not been retained in the data set due to its correlation with temperature. Hence, temperature and CO_2e were retained as the variables for the MDS in PC1. In case of Portugal, among the variables of PC1, temperature did not show any significant correlation with other variables while CO_2e, CY and LACP were well correlated between each other. Between CO_2e and CY variables, CO_2e had the highest correlation sum (r = 3.33) compared to CY (r = 3.26) and has been retained. But compared to CO_2e, LACP had slightly higher correlation sum (r = 3.39) and is retained as an indicator in the MDS. Hence, for the European countries, the variables which are retained as key indicators in the MDS include: Temperature, CO_2e and RF for France; and Temperature, CO_2e, LACP, and RF for Portugal.

In the case of Iran and Israel, two PCs were qualified and explained a cumulative variability of 83.4% and 82.3% respectively. Under PC1, for Iran, temperature, CO_2e and CY were highly weighted and for Israel, temperature, CO_2e and LACP were found to be highly weighted variables. In PC2, for both the locations, RF was the only variable which was found to be highly weighted. In case of Iran, under PC1, though all the variables were found to be highly correlated, all the three variables were retained for the MDS irrespective of their correlation sums considering the importance of these indicators. In the case of Israel, among the three variables, both CO_2e with the highest correlation sum (r =2.64) and temperature with correlation sum of r =2.42 were retained in the MDS due to their primary role in these areas. However, the LACP with the lowest correlation sum was dropped out from the MDS. Hence, the variables which are retained as the key indicators in the MDS for Iran include: Temperature, CO_2e, CY and RF; while for Israel: temperature, CO_2e and RF.

For both Liberia and Somalia, the PCA analysis showed two qualified PCs explaining a less percent cumulative variability of 58.8% and 62.7% respectively. In PC1, for Liberia, CO_2e and CY were found to be the highly weighted variables while, for Somalia, temperature, and CO_2e were the highly weighted variables. In the case of PC2, for Liberia, only temperature has been found to be the highly weighted variable while for Somalia, both RF and LACP were qualified as highly weighted variables. It was quite interesting to note that none of the variables either in PC1 or in PC2 for both the locations showed any significant correlation and each were independent. Hence all these variables were inevitably retained in the MDS as indicators. Overall, the variables which are qualified and retained as the key indicators in the MDS were:CO_2e, CY and temperature for Liberia; and temperature, CO_2e, RF and LACP for Somalia.

Table.1: Tests of significance for the indicators used in the computation of climate change crop performance index

	Temperature (°C)	Rainfall (mm)	CO_2 emissions (kt)	Cereal Yield (kg ha^{-1})	Land area (ha)
North America					
Canada	**	**	**	**	**
Mexico	**	NS	**	**	**
South America					
Argentina	**	NS	**	**	**
Cuba	**	NS	**	**	**
Europe					
France	**	NS	**	**	NS
Portugal	**	NS	**	**	**
Middle East					
Iran	**	NS	**	**	**
Israel	**	NS	**	**	**
Africa					
Liberia	**	NS	**	**	NS
Somalia	**	NS	**	**	NS
Asia					
Mongolia	**	NS	**	*	*
Nepal	**	NS	**	**	**
Myanmar	**	**	**	**	**
Philippines	**	NS	**	**	**

*Note: * = $p<0.05$ and ** = $p<0.001$*

Among the Asian countries, Mongolia and Nepal showed two qualified PCs with eigen values greater than 1 and which explained a cumulative percent variability of 67.5 % and 86.4 % respectively. However, in PC1, for Mongolia, Temperature and CO_2e were found to be highly weighted variables while for Nepal, temperature, CO_2e and CY were found to be highly weighted variables. In the case of PC2, CY and RF were found to be highly weighted variables for Mongolia and Nepal respectively. However, the variables qualified under PC1 for Mongolia were not significantly correlated with each other and hence were retained in the MDS. But in the case of Nepal, all the three variables were found to be significantly correlated with each other and hence the correlations sums were worked out. Among the three variables of PC1 of Nepal, CO_2e and CY showed similar correlation sums of r=2.63 and r=2.62 respectively while temperature had the lowest (r=2.47). Hence, CO_2e and CY were retained to be qualified as indicators in the MDS. While in case of Myanmar and Philippines, only one PC with eigen value >1 was qualified for both the locations explaining 88.9 % and 84.3 % cumulative variation respectively. PC1 of Myanmar showed all the variables i.e. temperature, RF, CO_2e, CY and LACP to be highly weighted while Philippines also showed similar variables except RF. For both the locations, correlation analysis was performed which showed significant correlations between the variables. For Myanmar, temperature did not show much significant correlation with any of the parameters except CY while the rest of the indicators CO_2e, CY and LACP were found to be well correlated. Among these three variables, CO_2e had the highest correlation sum followed by CY, LACP and RF. Hence, among these variables, temperature has been retained due to its non-significant correlation with other variables except CY. But CO_2e was retained due to its high correlation sum. But in the case of Philippines, all the variables viz., temperature, CO_2e and CY were well correlated while LACP did not show any significant correlation with any of the variables and had the lowest correlation sum. Hence for Philippines, temperature and CO_2e were retained as indicators in the MDS.

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Table.2: Principal component analysis (PCA) – Factors, correlations sums, percent variance and variables selected for all the countries under study

	Components and variables qualified		Correlation sums
	PC1	PC2	
North America			
Canada	Temp, CO_2e, CY	LACP	2.08, 2.32, 2.32
Mexico	Temp, CO_2e, CY	RF	2.44, 2.70, 2.70
Latin America			
Argentina	CO_2e, CY	RF	1.81, 1.81
Cuba	CO_2e, CY	RF	1.70, 1.70
Europe			
France	Temp, CO_2e, CY	RF	1.76, 1.71, 2.01
Portugal	Temp, CO_2e, CY, LACP	RF	2.72, 3.33, 3.26, 3.39
Middle East			
Iran	Temp, CO_2e, CY	RF	2.40, 2.55, 2.57
Israel	Temp, CO_2e, LACP	RF	2.42, 2.64, 2.16
Africa			
Liberia	CO_2e, CY	Temp	1.39, 1.39
Somalia	Temp, CO_2e	RF, LACP	1.39, 1.39
Asia			
Mongolia	Temp, CO_2e	CY	1.26, 1.26
Nepal	Temp, CO_2e, CY	RF	2.47, 2.63, 2.62
Myanmar	Temp, RF, CO_2e, CY, LACP	-	3.51, 3.82, 4.18, 4.07, 4.08
Philippines	Temp, CO_2e, CY, LACP	-	2.97, 3.27, 3.31, 2.81

Note: PC = Principal component; Temp = temperature; RF = rainfall; CO_2e = CO_2 emissions; CY = Crop Yield; LACP = Land area under cereal production

In this case, LACP was also required to be included but as it was not found as a limiting factor in the study and hence, it was not considered. However, based on various assumptions and decisions, the variables chosen to be retained as key indicators in the MDS were: temperature, CO_2e and CY for Mongolia; CO_2e, CY and RF for Nepal; Temperature and CO_2e for Myanmar; and temperature and CO_2efor Philippines.

3.2. Climate Change Crop Performance Indices (CCCPI)

After identifying the key indicators, linear scoring was performed for all the selected variables in dataset. Temperature which was identified as the key indicator for most of the locations, was considered "more is better" for countries like Canada, Cuba, France, Portugal, and Mongolia while for rest of the countries, it was considered "less is better". Rainfall has been assigned "more is better" status for most of the locations where it has been qualified as an indicator except for Nepal. CO_2ewasconsidered "less is better" indicator for all the locations due to its deleterious role in climate change and its impact on agricultural sector. The CY and LACP were considered as "more is better" indicators for all the locations for which they were qualified. Each observation of the indicators was assigned the linear scores, multiplied by the weighted factors of the qualified PCs (Table 4) and the values were summed up to arrive at CCCPI values. These CCCPI values were computed for all the locations for all the years and would help to assess the relative performance of the cereal crops between the years as influenced by the climate change.

The graphical representations of the CCCPI indices against all the indicators (Fig 1 to 4) elucidates the relative trend in response to the indicators and correlations were worked out (Table 4) to make a comparative analysis.

Table.3: Weighted factors obtained from the qualified principal components of the PCA

	% variance		Cum. variance
	PC1	PC2	
North America			
Canada	54.51 (0.73)	20.19 (0.27)	74.69
Mexico	57.15 (0.69)	25.41 (0.31)	82.56
South America			
Argentina	45.40 (0.63)	26.20 (0.37)	71.60
Cuba	44.74 (0.69)	20.52 (0.31)	65.25
Europe			
France	46.25 (0.69)	20.68 (0.31)	66.92
Portugal	64.07 (0.76)	20.22 (0.24)	84.29
Middle East			
Iran	58.85 (0.71)	24.54 (0.29)	83.39
Israel	61.52 (0.75)	20.81 (0.25	82.33
Africa			
Liberia	32.14 (0.55)	26.80 (0.46)	58.84
Somalia	36.59 (0.58)	26.09 (0.42)	62.68
Asia			
Mongolia	36.07 (0.54)	31.38 (0.47)	67.45
Nepal	66.29 (0.77)	20.11 (0.23)	86.39
Myanmar	79.03 (0.89)	9.83 (0.11)	88.86
Philippines	64.55 (0.77)	19.73 (0.23)	84.28

Note: Figures in parenthesis are the weighted factors for each PC from the PCA

For the North and Latin American countries, CCCPI indices were slightly higher in the early years and thereafter tended to decline slowly up to 1970s and remained steady with some variabilities in between. Canada's CCCPI curve, declined slowly in the beginning and remained nearly constant thereafter throughout the years with rise in the climatic and socio-economic indicators. For Mexico and Argentina, the CCCPI showed a decline with rise in all the indicators expect the land area in case of Argentina. Cuba showed a lot of variability in the crop performance as influenced by climate change.

Of the European countries (Fig 2), the CCCPI indices for France tended to slightly rise over the years irrespective of the increase or decrease in the climate change variables. The CCCPIs for Portugal showed a slight decline during the years 1961 to 1975 and then remained steady until 2001 and thereafter showed an increase. In the case of the Middle East countries, Iran showed a slight decline in the CCCPI up to 1966 and thereafter remained constant. While for Israel, the CCCPI tended to decrease and was observed to decrease gradually over the years. In case of African countries, the CCCPI did not show any consistent rise or decline and displayed inconsistencies between the years. However, Liberia depicts an increase in the CCCPIs during the initial years. For Asian countries, a varied performance in the CCCPI has been observed across the study locations. Mongolia showed a lot of variations while in case of Nepal, Myanmar, and Philippines, the CCCPIs presented an initial steep decline and thereafter a gradual decline except for Nepal which showed a slight rise.

CCCPI showed a positive correlation with temperatures for Canada, Portugal, France, Iran, and Liberia while the rest of the countries showed a negative correlation. However, the correlations were significant and positive for France and significantly negative for Myanmar and Philippines. CCCPI showed a non-significant negative correlation with rainfall for Canada, Mexico, Liberia, and Philippines while the rest of the countries exhibited a positive correlation, of which

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Table.4: Correlations between CCCPI Indices and the climatological and socio-economic indicators

	Temperature (ºC)	Rainfall (mm)	Cereal Yield (kg ha^{-1})	CO_2 emissions (kt)	Land area under cereal production (ha)
Canada	0.12	-0.34	-0.52	-0.73	0.17
Argentina	-0.29	0.08	-0.81	-0.91	0.32
Mexico	-0.57	-0.02	-0.86	-0.90	-0.51
Cuba	-0.32	0.22	-0.69	-0.92	-0.32
Portugal	0.31	0.38	0.38	-0.01	-0.03
France	0.84	0.13	0.91	-0.59	-0.44
Iran	0.11	0.15	0.20	0.00	-0.37
Israel	-0.59	0.41	-0.63	-0.87	0.85
Liberia	0.21	-0.23	0.33	-0.51	-0.41
Somalia	-0.40	1.00	-0.05	-0.11	0.21
Mongolia	-0.20	0.18	0.14	-0.13	-0.14
Nepal	-0.15	0.002	0.12	-0.17	-0.50
Myanmar	-0.62	0.66	-0.87	-0.89	-0.76
Philippines	-0.72	-0.15	-0.75	-0.81	-0.78

only Somalia and Myanmar were significant. CCCPI exhibited a significant negative correlation with CO_2e for all the locations and the correlations were non-significant for Portugal, Iran, Somalia, Mongolia, and Nepal. Increase in the CO_2 emissions showed a decline in the CCCPI performance. France is the only country which showed a decrease in CO_2 emissions and hence the rise in CCCPIs while Liberia, Somalia, and Mongolia, did not show any conspicuous response irrespective of the huge variability. CCCPI revealed a positive correlation with cereal yields for Portugal, France, Iran, Liberia, Mongolia, Nepal. However, the correlation was significant only for France. For the rest of the locations, CCCPI had significant negative correlations except for Somalia. In the case of land area, the CCCPIs showed a positive correlation for Canada, Argentina, Israel, and Somalia of which Israel showed high positive significance. For rest of the locations, CCCPI showed a negative correlation of which Myanmar and Philippines showed a high significance while Portugal showed the lowest. However, it is beyond the scope of this study to discuss and present the underlying reasons for all the trends observed.

IV. DISCUSSION

The key agri-climate change indicators which have been identified for each country were most relevant to the climatic pattern of each location. For most of the locations, temperature and CO_2e were qualified to be the major indicators in PC1 except for Argentina, Cuba, and Nepal. Temperature affects the crop yields to a greater extent [27] by playing a significant role at all stages of plant development influencing the key physiological processes of flowering and grain filling in cereal crops [25, 26]. Additionally, the significant alterations in global climate due to rapid increases in CO_2 emissions is also an influential climate factor [28, 29] causing declines, stagnations, collapses and increased year to year variations in crop yields [7, 30, 31]. Thus, both temperature and CO_2 emissions have interconnected influence on agricultural production. Doubling of CO_2 might raise the temperature and absolute humidity indirectly influencing the soil and plant evaporation, soil and ground moisture storage, length of growing season, heating degree days, and crop heat units. High temperatures during growing season, might speed up crop maturity, but temperature induced water stress might contribute largely to yield decreases in crops such as barley, wheat, oats, sunflower, and canola. Conversely, the projected warm temperatures and the long growing seasons, might be beneficial to crops such as corns, soybeans, potatoes, beans, and sorghum and less affected by plant water stress. Indirect effects of temperature changes would be, the incidence of pests and pathogens and the dependence of existing varieties more on irrigation for sustenance [32].

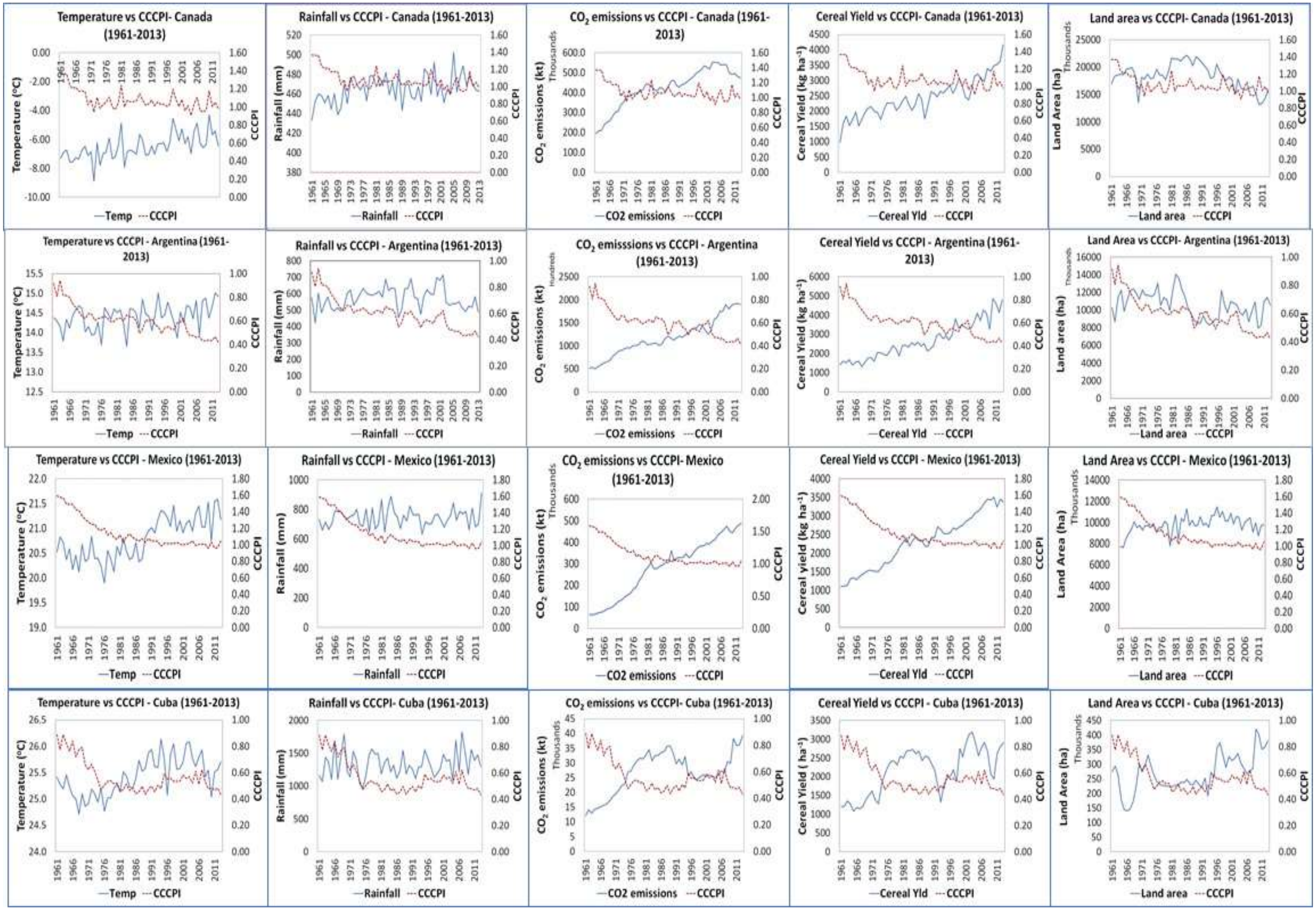

Fig.1: Climate Change Crop Production Indices (CCCPIs) plotted against each indicator for North and Latin American countries for the period 1961-2013

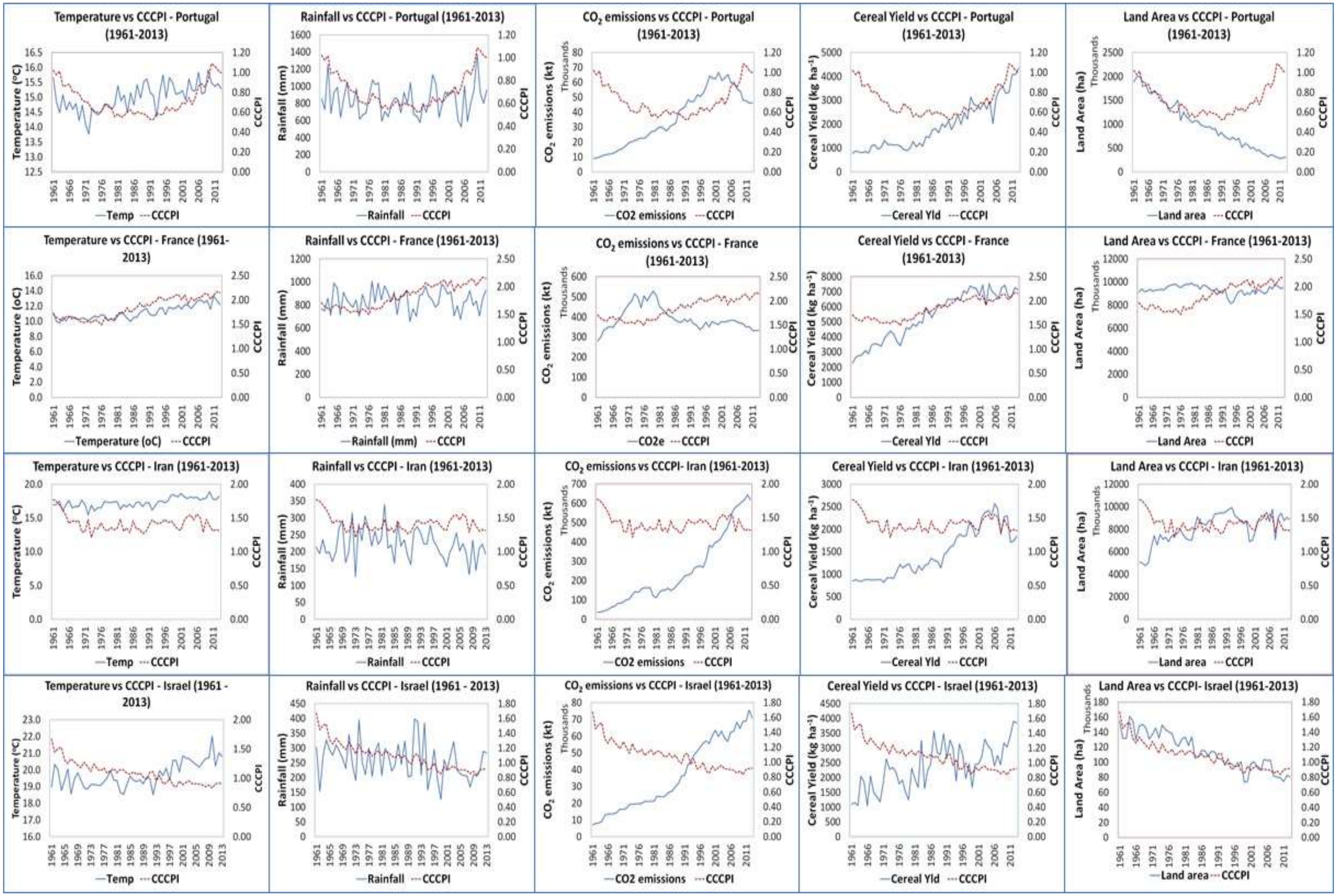

Fig.2: Climate Change Crop Production Indices (CCCPIs) plotted against each indicator for European and Middle East countries for the period 1961-2013

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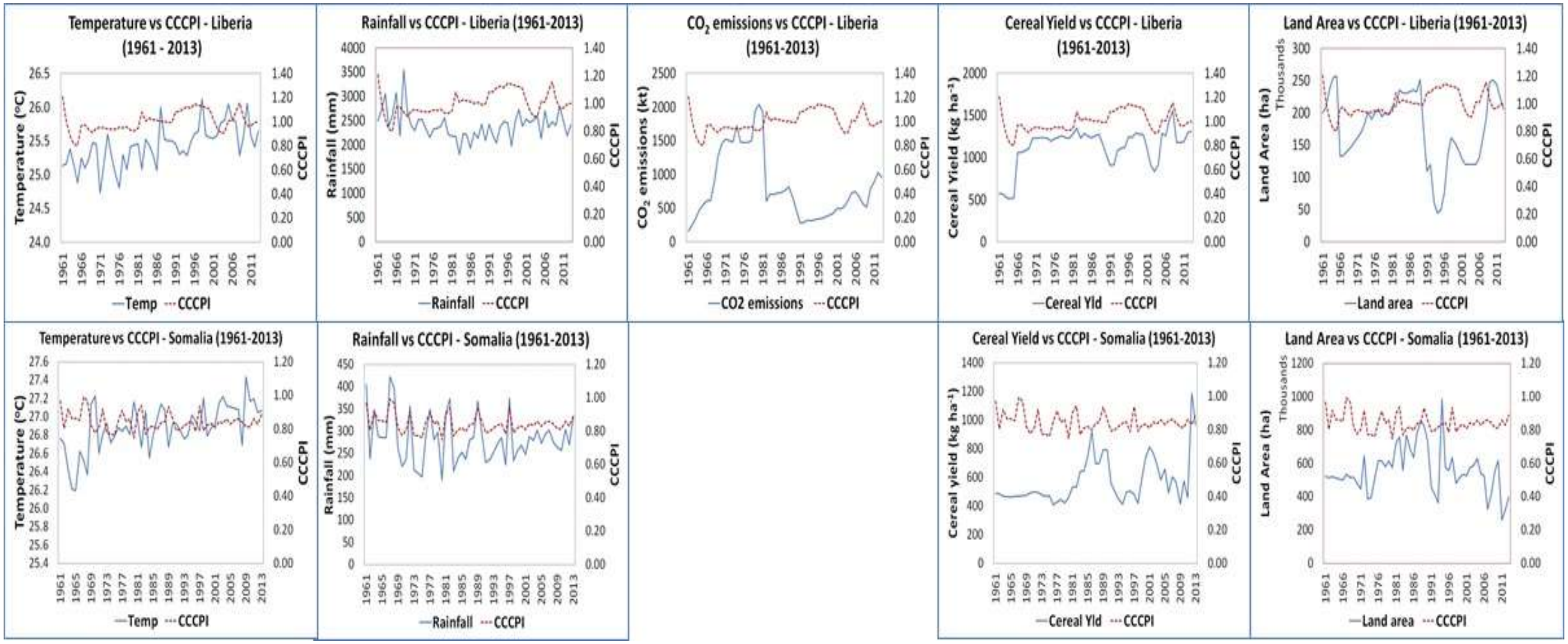

Fig.3: Climate Change Crop Production Indices (CCCPIs) plotted against each indicator for African countries for the period 1961-2013

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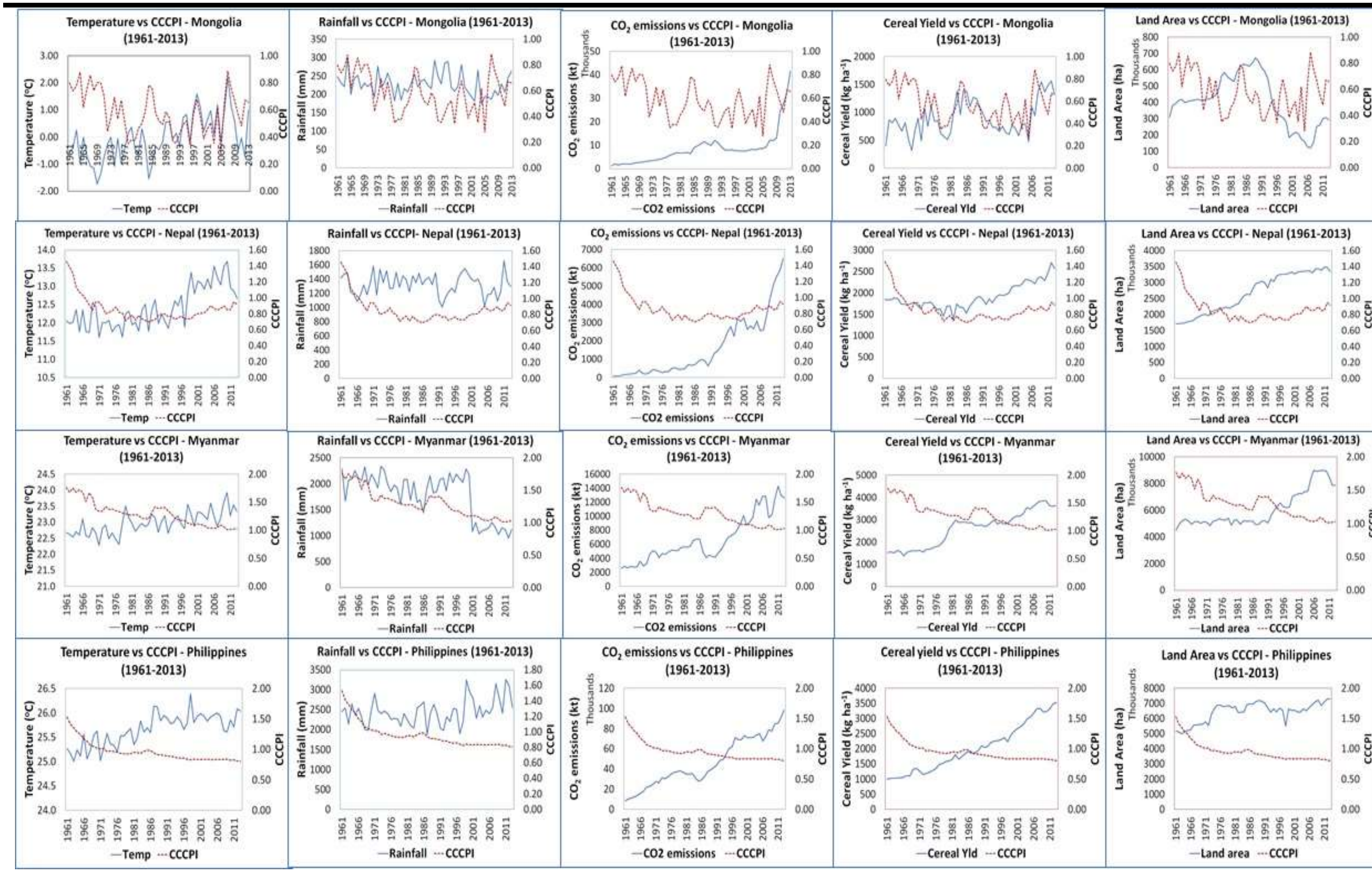

Fig.4: Climate Change Crop Production Indices (CCCPIs) plotted against each indicator for Asian countries for the period 1961-2013

Rainfall has emerged as one of the key indicators in PC2 for most of the countries, except Canada, Liberia, Mongolia, Myanmar, and Philippines. During the period of study, almost all the countries, with a few exceptions like Nepal and Portugal showed a decrease in rainfall over the successive decades with some variations in between (Fig 1 to 4). The African and the Asian countries with higher temperatures showed a decrease in rainfall, while the American and European countries showed very slight increase. Though rainfall might not be a limiting factor for countries receiving abundant rainfall per annum, but the change in its magnitude and timing is one of the most significant consequences of climate change [33].Increased rainfall events might reduce the pesticide efficacy requiring heavier and more frequent applications thus leading to increased costs and externalities [34]. For countries like Somalia, Israel, Iran, which receive very less amount of rainfall, it is an important indicator. In the case of Mongolia and Canada, though they receive less amount of rainfall, they also experience long and cold winter with precipitation as snow. Hence, rainfall has not emerged as an indicator for these countries. For high rainfall areas, rainfall distribution remains to be prime determinant of mitigation effects of adopting specific sustainable land management practices [35, 36]. In general, due to the uncertainties in the rainfall, shifts in seasonality, and the extent of rainfall, the concern and adaptation strategies for potential climate change are mostly focussed on agriculture sector [37].

Land area under cereal production (LACP) emerged as a key indicator only for some of the locations such as Canada, Portugal, Somalia, and Philippines and has been retained in the MDS. Canada, Portugal, Somalia, and Israel showed a strong decreasing trend in LACP over the decades. In Canada, the agricultural landscapes are impacted differently by temperature and precipitation by way of increase in spring precipitation and runoff, and high intensity storms, reduced sea ice cover, reduced summer rainfall, increasing drought frequency, and increasing demands for water. These factors challenge the water management causing decline in land suitability for some of the small grain crops [38]. The increase in droughts in Southern Prairies of Canada, thus shifting the production areas northward, could be one of the factors in reduction in land use [39]. In the case of Portugal, there is a drastic reduction in the land area under cereal production from 1961-2013 but the cereal yields showed an increase with high variability. This reduction might be due to the industries and service sectors increasing at a faster pace than agriculture [40] during 60s and 80s, urbanization and agricultural land abandonment in coastal areas during 1990 to 2000 [41], and permanent grassland and meadows gaining importance resulting in a decrease in the arable land during the 2000s [42]. There was agricultural intensification during this period thus improving the cereal yields [41].

Crop yield (CY) emerged as an indicator for most of the locations but has been retained only for Iran, Liberia, Mongolia, and Nepal. For Iran, the crop yields increased gradually up to the years 2005 and thereafter started declining which requires further insight. Liberia, and Mongolia showed huge fluctuations in cereal yields. Nepal showed increase in cereal yields over the years which might be due to increase in the land area under cereal production. It is necessary to understand the complex interactions of the effects of insects, weeds, and diseases on agricultural production thus necessitating the crop diversification as a measure to fight the climate change effects [34]. Despite the advancement in the crop production technologies including intensive research and breeding techniques, the climate and weather have a strong hold on the agricultural production in many ways [43]. Environmental stresses such as droughts and high temperatures will also become the key stress factors having a major impact on crop yields [44].

A clear perception of the possible impacts of climate change on crop production over time across the locations is needed to facilitate more informed climate change mitigation and adaptation strategies and policies [45] without which the long-term mean crop yields are likely to decline [25]. However, it would be difficult to isolate the compounding impacts of climate change, the technological advancements and the socioeconomic conditions on crop production. Hence, this indicator selection approach is an excellent option to investigate the effects of individual output by keeping all other factors constant [46]. These key indicators identified for each country can be centred to frame the adaptation and mitigation strategies.

The key indicators identified for Canada include temperature, CO_2e and LACP and the CCCPIs had significant negative correlation with the CO_2e. The temperatures of Canada are increasing gradually, CO_2e are already in rise while LACP is decreasing (Fig 1). These are the indicators which need to be given a careful consideration. Already a declining trend in CCCPI has been observed and future changes in any of these indicators might alter the CCCPI. Despite the predictable risks of extreme temperatures and droughts, the cereal yields have been managed and improved over the years with the adoption of processes like minimum tillage [38], conservation tillage, reduction in summer fallow, adoption of precision agriculture, enhanced crop rotation, improved cultivars, increased nitrogen use efficiency and improvements in technology. These processes also facilitated the increased removal of $CO_2$from the atmosphere and sequestration in the soil [47, 48, 49]. Although, there is expected possibility of increase in yields with increase in temperatures for some crops, the negative consequences from the introduction of new diseases and pests can negate the yield increases [50, 51]. Studies predict increased length of growing season, less cool periods, more hot periods, increase in crop heat units and growing degree days by 2040-2069 due to temperature rises; lower water stress for crops due to increased water use efficiency of crops under elevated CO_2 and increased crop yields [51]. However, predictions also exist for decreased snow accumulation, reducing spring runoff and increasing desertification thus calling for improved land and water management strategies [34].

The key agri-climatic indicators identified for Mexico were Temperature, CO_2e and RF and the CCCPI showed a negative correlation with all these indicators (Table 4 and Fig 1). The factors like low and intense rainfall, high CO_2 emissions and risk of frequent droughts and floods, hurricanes, climate change variability, long and hotter periods, and land use transformations constrain the food production in Mexico. But it can be observed that there is an increase in crop yields over the decades which might be due to the adaptation measures undertaken like formulating irrigation development policies, increased use of chemical inputs, land development and transformation, infrastructural and technological development, etc., to fight against the climatic change and the crop production risks [52, 53].

The key indicators qualified for Argentina and Cuba include CO_2e and RF. The CCCPI exhibited a positive correlation with rainfall and negative with CO_2 emissions (Table 4 and Fig 1). In Argentina, weather remains to be one of the most uncontrollable factors affecting agriculture mainly due to its inter-annual variability [46]. There was an increase in the temperature during the last decade and a slight decrease in the total annual rainfall and continuous increase in CO_2 emissions over the years of study period. Over the years, land area varied and increased crop yields during 1970s [54] while in the later years, it showed a decrease due to urban expansion [55]. Despite these variabilities, significant increases in productivity have been observed due to the agricultural transformation during the past 50 to 70 years owing to the adoption of no-till farming practices along with improved technologies, judicious fertilizer use, and less aggressive pesticides and use of improved varieties and hybrids [56, 57]. Though the cereal yields are increasing over the years, the declining trend in CCCPI from the present study, and the future predictions of increasing temperatures and decreasing crop yields calls for an attention to frame or strengthen the crop production strategies.

Similar to Argentina, Cuba also had RF and CO_2e as the key indicators which showed a positive and negative correlation respectively with CCCPI. Cuba is highly vulnerable in terms of water resources availability and water distribution. As the country lacks fresh water from rivers, and rainwater being the only available source for irrigation, makes RF as an important indicator. Cuban soils also exhibit poor soil structural and fertility properties. Added threats to agriculture from climate change in Cuba include seawater intrusions, rising median temperatures, shorter rainy seasons, suffocating summer temperatures, heavy rains, extended periods of drought and modifications in pest behaviour. Intense hurricane of 2008 resulted in decline in agricultural production [58]. Cuba has implemented sustainable organic farming as against the industrial farming like in Canada to mitigate the environmental impact on climate [59]. The use of most competent meteorological and extreme weather warning and response system, and the renewable energy sources has become a part of adaptation and mitigation programs [60].

For Portugal, the key indicators qualified were: temperature, CO_2e and LACP. The correlation effects of these indicators with CCCPIs were positive for temperature and negative for CO_2e and LACP but not significant. Agriculture mostly relies on wheat, corn, and rice. The overall agricultural performance in Portugal was unfavourable due to various factors. These include low level of agricultural investment, very low usage of machinery and fertilizer quantities, small and fragmented farms in the north not more than 5 ha maximum (mostly <1ha), incapability of modernizing the farms, poor productivity associated with low education levels of the farmers and finally, inadequate distribution channels and economic infrastructure [61]. In terms of climate change, Portugal has adapted conservation agriculture which reduced CO_2 emissions by decreasing number of farm machinery and by increasing soil carbon sequestration during the later years [62].

For France, temperature, and CO_2e were qualified as the key indicators and showed significant positive and negative correlation with CCCPIs respectively. However, the CCCPI indices for France has tended to slightly increase over the years irrespective of the increase or decrease in the climate change variables. The average temperature of France showed an increase of 0.5ºC per decade which might increase the warmer summers rather than cooler summers. The CO_2 emissions here, especially the industrial sources are substantial and are the most worrisome due to their long residency in the atmosphere as well as the societal reliance on energy and industrial processes emitting them. Hence, France has adapted the mitigation technology of deploying the CO_2 emissions only from the industrial sources by way of CO_2 capturing, transportation, and storage within the country, to address the CO_2 emissions across the sectors [63]. Mitigation measures are being taken to bring the CO_2 emission levels down. Negative responses were observed in wheat and barley yields due to spring and summer temperatures in France [64]. In terms of crop performance, France shows a positive trend and might continue if the temperatures do not increase further. With the prevailing temperatures, France was not exempted to experience the severe heat waves during 2003 and 2006 as well as severe flooding in 2010. Hence, there is every possibility that, increase in temperatures might cause an increase in the water stress for which adaptive measures need to be taken [65].

For the Middle East countries, i.e. Iran and Israel, the key indicators qualified for both the countries were temperature, CO_2e and RF and showed non-significant correlations with CCCPI. For Iran, the temperature changed by 0.2ºC per decade while rainfall showed less variations. The CO_2 emissions showed a continuous increase over the study period. The land area under cereal production and the crop yields were also increasing with a drop only during the last decade. The CCCPI also showed a slight decline up to the years 1966 and thereafter remained steady throughout the years. Under these prevailing circumstances, Iran is just planning to take some proactive steps to reduce its carbon foot prints [66]. However, it needs to develop adaptive and mitigation measures to reduce the water crisis and CO_2 emissions apart from other direct and indirect climate change effects before the situation gets to any worse. Switching to low water requirement and temperature tolerant varieties might be a good adaptation measure, but lack of technology and knowledge of the process and consumption are important factors to be considered [67].

For Israel, the key indicators qualified were temperature, CO_2e and RF. Despite being small, its climate shows remarkable variability and changes over minor distances [68]. During the study period, the temperatures showed a slight increase after 2000 and the rainfall remained to be similar with a very slight decrease during 2000-2010 due to the severe drought [69]. The CO_2 emission levels showed an increase of approximately 1.5 times per decade since 1961. It was quite interesting to note that the cereal yields increased over the decades while the land area under cereal production showed a continuous decrease. CCCPIs tended to decrease gradually over the years and showed a significant negative correlation with temperature and CO_2e and a significant positive correlation with RF. Specially in drylands, agricultural production mainly depends upon the temperature and rainfall and the crop performance becomes vulnerable with the vulnerability in these indicators mainly when associated with the accumulation of greenhouse gases like CO_2 [2]. Israelis agriculture depends more on water, and to cope up with the temperature and rainfall anomalies, the government already issues incentives to farmers to use the water efficiently. Another interesting aspect of Israel is to have a unique system of investing its capital to substitute water for land by adopting drip irrigation and cover technologies thus shaping their agriculture to take advantage of the heat rather than becoming a victim [70]. Hence, it can be observed in the present study, that according to the prevailing climate, the CCCPI is decreasing but, despite the decrease in land area under cereals, the crops yields tended to increase because of the adaptive measures taken. However, the observed changes from the study suggest that Israel's climate is entering a new period of uncertainty where it is likely to influence the water resources and agriculture [69].

The key indicators qualified for Liberia were CO_2e, CY, and temperature. Rainfall did not emerge as an indicator because Liberia is blessed with abundant rainfall [71]. Liberia showed a variability in temperatures and the CO_2 emissions were low showing a great variability especially up to 1980 and increased during the last decade. The cereal yields showed a drastic increase over the decade 1961-70 and continued to maintain the same yields [72]. Irrespective of the wide variability in the indicators, the CCCPIs showed a non-significant positive correlation with temperature and negative correlation with CO_2e and CY and was not affected much by the variability of the indicator patterns over the years. Agricultural production in Liberia is based on rainfed farming with rice as the staple crop. Heavy reliance on rainfall exposes these farmers to vagaries of weather and rice would be negatively affected by the higher temperatures even though the precipitation is adequate [72]. Liberia, however, is vulnerable to climate variability thus presenting challenges to socio-economic development of the country. The civil war of 1989-2003 has played a detrimental effect in making the country low in its adaptive capacity to respond to climate change. Agriculture itself supports 75 per cent of its population and contributes to approximately 76.9 per cent of GDP as of 2016. Given the dependency on agriculture and lower adaptive capacity, it might become sensitive to future rainfall shocks with extreme rainfall to become more common and the future is likely to experience more social conflicts due to climate change. Hence, the country should focus on improvements on water storage capacity and irrigation systems, improved crop varieties, measures to prevent flood damage and transparency in the government functions [73].

For Somalia, the variables qualified as indicators include temperature, CO_2e, RF and LACP. The climate is predominantly desert with a year-round hot climate, with a high average annual temperature of 26.9ºC and less total annual rainfall of 270.1 mm. Temperature and rainfall showed slight increases over the decades with high variability (Fig 3). The CO_2 emissions are very meagre and are similar over the decades from 1961. The cereal yields showed an increase over the decades and the land area under cereals increased up to 1980 and thereafter decreased. However, during 1991-92, the country experienced severe famine, thus decreasing the crop yields. The CCCPIs did not show any decline or rise throughout the years but remained at the same level with variability between the years. However, CCCPIs showed a significant positive correlation with RF and non-significant correlation with CO_2e and LCAP. Somalia has typically low and highly variable rainfall throughout the country with an annual rainfall ranging from 158 mm to 423 mm. The major cereal crops cultivated include sorghum and maize which are grown both under irrigated and rainfed conditions. At present, this country is worst hit by the drought, thus worsening the food security, escalating food prices, and increased malnutrition. Though early warnings for the 2011 droughts were issued, immediate action plans and risk management initiatives were not triggered due to major constraints of funding, access, and responsible mechanisms [74, 75, 76]. Water scarcity is a major problem as it is receiving less amounts of rainfall since the 1990s. Rehabilitation of malfunctioning boreholes, water trucking to exhausted areas would be a great asset [77]. Somalian agriculture contributes to 60.2 per cent towards GDP and remains to be an important economic sector. Though Somalia is a food deficit country, potential exists for the country to reduce its dependence on food imports and where irrigation is possible along the rivers of Shabelle and Juba [78]. It cannot rely upon the present agricultural production for its future food demands. Despite the 1.6 per cent land put to agricultural use, more amount of land can be brought under cultivation. Impudent strategies need to be evolved to engage in modern, intensive, and sustainable agriculture. Once grain sufficient in 1970s and 80s, can again be made grain sufficient with good farming system instead of remaining as food imports dependent [79]. The coping strategies available in other regions to cope with shocks and to mitigate long term stresses might be unavailable or inappropriate [80].

The indicators retained for Mongolia include temperature, CO_2e and CY. It is a land-locked developing country in the northern latitudes and is a place for the occurrence of highest global warming [81]. Due to its high altitude, it is generally colder than other countries at same latitude. It also has a harsh continental climate, with high annual and diurnal temperature fluctuations, and low rainfall. During the study period, from the year 1961, there is an increase in temperature each decade while during the last decade a decrease was observed. The CO_2 emissions increased each successive decade and was more pronounced during the last decade especially. The cereal yields also increased every successive decade and showed drastic changes recording high yields during 1981-90 and 2011-15. However, the land area under cereal production fluctuated with alternate increase and decrease. The CCCPIs also showed a great variability throughout the years and showed non-significant correlations with temperature, CO_2e and CY. Heavy rains, snowfall, strong winds, sandstorms, snowstorms hail and flooding are the major natural disasters affecting the socio-economic situations of the country. It is necessary to understand the complex interactions of the effects of insects, weeds, and diseases on agricultural production. Crop diversification is an essential measure to fight the climate change effects for a country like Mongolia [34].

For Nepal, the key indicators to determine the CCCPI include CO_2e, CY, and RF. During the study period, the CO_2 emissions drastically increased from the decade 1991-2000, while the cereal yields and rainfall did not show much variation between the decades except during the last decade, where it showed a sudden increase. The CCCPIs showed a decline during 1961-70 and remained at the same level for the rest of the period and then slightly increased at the end. CCCPIs showed a no significant positive correlation with rainfall and cereal yield and negative correlation with CO_2e. Precipitation is a major factor affecting the crop yields and the present study also reveals a decrease in rainfall. In 2006, the west Nepal experienced flash floods while the Eastern Nepal experienced extreme drought thus leading to a decrease in crop yields. Late or erratic monsoons might result in crop damages and subsequent food insecurity. A decline in agricultural productivity by 17.3% has been predicted if no adaptation or carbon fertilization strategies are to be implemented with the current technological growth [82]. Nepal, one of the least developed countries, categorises the climatic impacts to be severe due to its static adaptation capacity and high vulnerability. Hence, initiation of government supported large-scale planned strategies like controlling excess water flows arising from flash floods, and seasonal landslides are very important to protect the crops [82].

For Myanmar temperature and CO_2e were retained as the key indicators to determine the CCCPIs. Both these indicators showed a significant negative correlation with the CCCPIs. During the study period, temperature showed a variation of 0.1°C per decade while the CO_2 emissions showed a continuous and drastic increase from 1961 to 2015. Rainfall showed a greater variation and was observed to decrease. By 2100, there was a temperature prediction of 0.5ºC to 5.5ºC rise. Being a least developed nation, Myanmar is highly vulnerable to negative effect of changing climate. With its extensive coastline, it is inherently prone to extreme weather events like flooding, cyclones, tsunamis, droughts, heavy monsoon rains, and storm surges. The changing climate might increase the frequency of these extreme weather events posing new threats. Sea level rises might decrease the coastal rice producing shore level [83, 84]. Development of climate resilient cultivars by exploiting the genetic variability and yield potentials would be essential to sustain the crop productivity [85].

For Philippines, the key indicators retained to determine the CCCPI include temperature, CO_2e, and LACP. Temperatures and CO_2e showed a significant negative correlation with CCCPIs while LACP showed a significant positive correlation. Considering the temperatures, during the study period, Philippines had an average annual temperature of 25.5ºC with an increase of 0.1ºC over the years. The CO_2 emissions increased drastically over the past few decades and the land area also increased over the decades. According to a study, climate change is expected to impact agriculture by PHP145 billion dollars through 2050 [86]. Our study revealed a declining trend in the CCCPIs up to 1967 and thereafter remained steady for few years and then ultimately decreased slightly over the years, but the cereal yields showed an increasing trend which could be attributed to increase in land area. Philippines is usually highly vulnerable to adverse impacts of climate change especially the floods, droughts, heat waves, and typhoons which alter the agricultural output and productivity. Consequently, it has already experienced crop losses. Adaptation strategies like improved stress tolerant varieties and farm management techniques might have contributed to the improved yields added to the increase in land area [87]. In the recent past, measures like improving disaster risk management and reduced dependence on agriculture have been taken up to reduce its extreme vulnerability to climate change.

V. CONCLUSION

The climate change crop performance index calculated from this study gives an idea of the performance of the crops under varied climatic conditions over the years and comparison can be made to assess the impacts of range of climate variability. Just for the limitation of data availability, there would have been a broader scope of choosing additional indicators of agricultural related climatic and socio-economic variables, which are more relevant to the study location. Amidst the body of extensive literature of earths warming, crop production remains to be inherently sensitive to climate change and variability. Various adaptation and mitigation measures have already been adopted by some countries while some of the countries like Somalia are still at the initial stages of development of these measures.

In general, the study reveals a gradual increase in the temperatures, constant rise in CO_2 emissions (except for France), gradual or no change in rainfall, and rise or decline in land area under cereal crops. In most of these cases, the CCCPIs showed only a declining or no change trend. The negative correlations of the CCCPIs with most of the key indicators suggest every possibility of altering the cereal crop performance even with slight changes in any of the indicator. Contrary to the existing climatic situations, if future IPCC predictions of temperature increases, and rainfall reductions tend to set in, might result in direct or indirect influence on other indicators causing detrimental effects on cereal production. This demands a constant vigil and monitoring especially on the key indicators apart from other indicators. Suitable adaptation and mitigation strategies centered around these key indicators are very much essential for these countries. If appropriate adaptation and mitigation strategies have already been taken, a general appraisal of these strategies and policies should be made for developing new strategies. Despite the vast adaptation and mitigation practices, there still exist room for further adoption of climate proof and climate friendly practices.

The index could not be standardized as this is the first study of its kind. Detailed year-wise comparison in evaluating or assessing the crop performance for each location could not be taken up as it is beyond the scope of the paper. These indices can be further strengthened, and some critical points can be identified based on which the crop performance can be monitored regularly. The methods used to monitor these indicators should be fully defined to make easy comparisons. Thus, the findings of the present study might be found useful for the future researchers, land mangers, policy makers or any other stakeholder engaged in developing measures to sustain the cereal yields thus contributing to country’s economy and its food security.

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