Potential Change of Soil Microbial Diversity in Anticipated Atmospheric-CO2 Elevation Triggers Rhizosphere Activation: A Meta-analysis.

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Abstract

One of the key challenges in present time to meet out growing global food demand without damaging environment under constant threats of climate-extremes. Enhancement of nutrient use efficiency and build up intrinsic system tolerance through soil microbial manipulation has gained significant international support to address this challenge. Impact of elevated carbon dioxide (CO_2) on soil microbial diversities both at present and future climatic scenario in spatial and temporal scale is highly debated with respect to its effects on soil functioning, nutrients dynamics and crop productivity and its practical consequences on resource conservation and food security. We conducted a meta-analysis on global database using 572 observations from 202 studies to investigate the effects of elevated CO_2 on soil microbial biomass carbon (MBC), yield and structural (soil microbial populations) and functional (soil enzymatic activities) diversities across 22 countries and 108 crop species. Overall, our results revealed that MBC and functional diversity increases with elevated atmospheric-CO_2 irrespective of temperature zone and crop type. However, data trends showed structural diversity has been gradually adapted under elevated CO_2 across the region over decadal scale. Anticipated elevation of atmospheric CO_2 increase rhizospheric activities and could make soil more input demanding and more so in temperate region. Therefore, to fetch the benefits of CO_2 fertilization and to meet out the higher demand both plant and soil (microbes), real time judicious nutrient supply is necessary; otherwise, soil priming, loss of fixed soil carbon reserve and land degradation might threat the future food security.

Introduction

To address the issues of yield sustainability and food security under climate change risks, build-up of system resilience with higher resource use efficiency through microbial manipulation is a sustainable approach that harm the environment least. Elevation of atmospheric CO_2 level from 273 to 412 ppm (from 1750 to 2020) and mean annual surface temperature from 14 to 14.89°C (from 1750 to 2020) are evident due to climate change in last two centuries [1]. Further, atmospheric CO_2 concentration is going to be increased @ 1.5 ppm year^{-1} up to 2050 [2, 3] which will affect the crop yield, soil nutrient and water balance and microbial diversities in near future. Soil microbes plays a crucial role in nutrient dynamics [4, 5, 6, 7], soil aggregation [7, 8] and yield [9, 10]. More so, it has higher adaptability under stress [11, 12, 13] and ability to build up intrinsic system resilience (to drought, salinity, flood, nutrient scarcity) [14, 15] and enhance nutrient use efficiency (e.g., N, P, K, Mn etc.) [16, 17].

We know that elevation of atmospheric CO_2 influences the above ground and belowground biomass production and carbon (C) allocations. The below ground C allocation primarily due to higher root exudation, higher availability of labile C as substrates for microbial enrichment and greater microbial activities [18]. The microbial biomass C and soil-enzymatic activities enhances due to elevated CO_2 which lead to higher nutrient mobilization, GHGs emissions and soil priming [19]. However, there are contrasting reporting about change in soil microbial diversities due to elevation of CO_2 and temperature, particularly population dynamics of bacteria and fungus and their functionality. Manny research group emphasized that there would be no change in microbial diversity as microbes are highly adaptable. Other groups provided evidence regarding shifting of structural as well as functional diversities both in negative and positive directions [19, 20, 21, 22]. The debate is on, but the question is not on the change in the directions of diversities, it is the matter of functioning of crop rhizosphere in anticipated climate change scenarios. Whether the change in microbial functioning in rhizosphere would affect the crop yield, soil health and food security? Whether the nutrient demand would be more for getting the desired yield? Whether our soil would be going to loss for its reserve C due soil-priming in elevated CO_2 condition?

To answer these questions, we analysed scientific evidence at global scale to assess the impacts of elevated CO_2 on soil microbial biomass carbon, microbial diversities (both structural and functional) and yield on spatial and temporal scale.

Materials And Methods

Data inventories and data base

A compressive meta-analysis was done on published data in peer reviewed journals and books, representing a significant assessment on this key issue. Because most of the studies on the effect of elevated CO_2 on plants were focused on yield, biomass production and photosynthetic efficiencies, not on soil microbial diversities and functionalities; both field and laboratory studies containing tropical and temperate regions, on cereals, horticulture, grassland, and forest crops over last five decades (1970-2020) were included in metadata base. Since, impact of climate change, specifically the effect of elevated CO_2 on soil microbial diversities are distinctly depends on temperature, tropical and temperate zones were analysed separately irrespective of types of crops and CO_2-elevation range. To assess, how the effect of elevated CO_2 varied across the two temperature zones on temporal scale on plants (agriculture/forest), yield, microbial biomass carbon (MBC) and microbial diversities (structural and functional) including bacterial and fungal population and soil enzymatic activities were grouped based on original data. For comparison, two temperature zones (tropical and temperate), three decadal time scales (1970-1990; 1990-2010; 2010-2020) and eight CO_2- elevated ranges (0-10%; 10-20%; 20-30%; 30-40%; 40-50%; 50-60%; 60-70%; 70-80%) were considered. In total, there were 202 studies covering 22 countries and 108 plants /crops species in the data base.

We exhaustively search the literatures including research articles, books, book chapters that were peer-reviewed for studying the effects of elevated CO_2 on crop yields, microbial biomass carbon and structural (bacterial and fungal population) and functional (soil enzymatic activities) soil microbial diversities from 1970 to 2020. Search keywords included elevated CO_2, open top chamber, free air CO_2 enrichment (FACE), climate change, crop yield, microbial biomass carbon, bacterial population, fungal population and soil enzymatic activities in the article, title, abstract and keywords. Not reviewed and non-English language publications were discarded. These searches produce around 2000 publications. Then the publications were screened based on following criteria; a) field and laboratory experiments of elevated CO_2 on either yield or MBC or enzymatic activities or bacterial and fungal population or any of the two must be compared with ambient (reference/ control) condition; b) cereals (particularly grain) and forestry crops were both from temperate and tropical region were considered; c) in field experiment yield was stated; d) location/ latitude-longitude of the experiment reported; e) management options and replications mentioned; f) different experiments even at same location at different times were also included. As this type of futuristic study are not quite common and there are limitations of crop phenology (height, duration), we tried to gather relevant published data for meta-analysis. We also rejected confusing and unclear results and methods according to our knowledge and more emphasis were goes to C_3 crops (cereals) as those are directly related to food security of resource poor countries. Specific attention was given to reject and avoid the duplicate data (e.g., different experiment reported similar kind of data in different perspective). A portion of our researched publication on climate change/ elevated CO_2 experiments were avoided due to absence of control treatment that did not satisfy our criteria.

Contain cases where specific latitude-longitude were not provided, we extracted those from google earth-apps with the help of location name/ experimental station name. Vector map in the form of point shape file of 86 locations of the climate change/elevated CO_2 experiments are prepared and shown as bubble plot over the world map using ArcGIS (Figure 1). Greater the size of bubble in the plot indicates higher number of experiments conducted on that location. Percent change of different parameter due to elevation of CO_2 (over ambient/ control) in different research finding were estimated/ analysed where directly not given in publication. In certain places where data were only given in figures or graphs, values were extracted through plot digitizer (http://plotdigitizer.source.net/). Tropical and temperate zone were classified based on generalized climate classification scheme.

Nutrient and water management practices followed were recorded in each study and presented in basic data base (Supplementary Table 1) as binary values (i.e., year category (3): 1970-1990; 1990-2010; 2010-2020); spatial scale (2) (region category: tropical; temperate) and CO_2 elevation range on percentage basis (8) (0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%).

Metadata analysis

The classified data were subjected to one way analysis of variance (ANOVA) and correlation analysis using PROC GLM and PROC CORR of SAS (SAS institute, Cary, NC, USA), respectively to assess significance of change in yield, MBC, MDC, BP, FP, and enzymatic activities with respect to spatial changes, temporal changes and with changes in CO_2 levels. The summary statistic (mean, quartiles, minimum, maximum, and extreme observations/probable outliers) was presented using the box-and-whiskers plots of measurements along with the F-value and Prob >F. Significance among the mean values were assessed at $p<0.05$.

Result

Impact CO_2-elevation range on microbial diversities

The yield increase was found maximum with 40-50% CO_2-elevation; however, magnitudes of increase were higher at 60-70 and 70-80% CO_2-elevation over ambient. The highest MBC was reported for the CO_2-elevation range of 50-60% over ambient (Figure 2). However, highest increase of MDC was noticed at 30-40% CO_2 elevation. Soil enzymatic activities were affected both positively and negatively. Negative effects were found maximum at 40-50% CO_2 elevation over ambient (Table 1, Figure 2). Correlation study revealed that percent increase of microbial biomass carbon and MDC were positively correlated with elevated CO_2. Minimum correlation was found in case of increase of fungal population to CO_2 elevation (Table 1).

Table 1
Correlation study of percentage increase CO_2 with percentage increase of yield, and microbial diversities.

Dependent variable	Independent variable	% Increase Yield	% Increase MBC	% Increase MDC	% Increase BP	% Increase FP	% Increase Enzyme
% Increase CO2	Pearson Correlation Coefficient	0.092	0.584	0.145	-0.095	0.007	-0.134
	Prob > |r| under H0: Rho=0	0.392	0.561	0.518	0.604	0.969	0.389
	Number of Observation	87	101	22	32	29	43

[Note: microbial biomass carbon (MBC), microbial diversity community (MDC), bacterial population (BP), fungal population (FP) and soil enzymatic activity].

Temporal variation of impact elevated CO_2 on microbial diversities

Critical analysis revealed that percentage increase of yield and variation during 1970-90 was higher followed by 1990-2010 and 2010-2020. Correlation analysis revealed that the percentage increase in CO_2 have a significant positive correlation with percentage increase in MBC during 1990-2010 (Figure 3). Our result revealed that the impact of elevated CO_2 on percentage of total microbial structural diversity (MDC) (including bacteria, fungi, actinomycetes, archaea) change in decadal time frame. Less variability and relatively lower increase of percent MDC in last decades compared to previous one indicates gradual increase of adaptability of microbial communities towards climate change (Table 2). The increase was higher during 1990-2010 compared to 2010-2020. The temporal change was not significant except for soil enzymatic activities with maximum in temperate region (Figure 3).

Table 2
Correlation study of percentage increase CO_2 with percentage increase of yield, and microbial diversities in respect to temporal scale (1970-1989; 1990-1999; 2010-2020).

Dependent variable	Year	Independent variable	% Increase Yield	% Increase MBC	% Increase MDC	% Increase BP	% Increase FP	% Increase Enzyme
Percentage Increase CO_2	1970-1989	Pearson Correlation Coefficient	0.090	-	-	-	-	-
		Prob > |r| under H0: Rho=0	0.802	-	-	-	-	-
		Number of Observation	10	0	0	0	0	0
	1990-1999	Pearson Correlation Coefficient	0.026	0.269	-0.385	0.135	-0.112	-0.035
		Prob > |r| under H0: Rho=0	0.854	0.026	0.271	0.618	0.668	0.879
		Number of Observation	54	68	10	16	17	21
	2010-2020	Pearson Correlation Coefficient	-0.266	-0.058	0.418	-0.208	0.196	0.113
		Prob > |r| under H0: Rho=0	0.219	0.747	0.175	0.439	0.539	0.615
		Number of Observation	23	33	12	16	12	22

[Note: microbial biomass carbon (MBC), microbial diversity community (MDC), bacterial population (BP), fungal population (FP) and soil enzymatic activity].

Spatial variation of impact elevated CO_2 on microbial diversities

We analysed data from hundreds field (198 numbers), and laboratory (4 numbers) trials across 22 countries and 108 crop species (Extended data, supplementary S 1), showed elevated CO_2 significantly increased the yield by 26-35% under temperate and tropical region. Yet average effect of elevated CO_2 on yield in respect to region (tropical and temperate) were not found significant although more variation noticed in temperate region. Spatial variability was significantly evident ($p<0.05$) for MBC, bacterial population (BP) and soil enzymatic activities with highest in tropical region due to elevation of CO_2 (10 to 80% over ambient) (Table 3, Figure 4).

Table 3
Correlation study of percentage increase CO_2 with percentage increase of yield, and microbial diversities in respect to tropical and temperate region.

Dependent variable	Region	Independent variable	% Increase Yield	% Increase MBC	% Increase MDC	% Increase BP	% Increase FP	% Increase Enzyme
% Increase CO_2	Tropical	Pearson Correlation Coefficient	-0.382	0.213	-	0.052	.	0.273
		Prob > |r| under H0: Rho=0	0.398	0.466	-	0.948	.	0.326
		Number of Observation	7	14	1	4	0	15
	Temperate	Pearson Correlation Coefficient	0.079	0.187	0.138	0.137	0.007	-0.098
		Prob > |r| under H0: Rho=0	0.483	0.082	0.551	0.488	0.969	0.621
		Number of Observation	80	87	21	28	29	28

[Note: microbial biomass carbon (MBC), microbial diversity community (MDC), bacterial population (BP), fungal population (FP) and soil enzymatic activity].

Discussions

Overall, elevated CO_2 significantly affects the yield irrespective of region and decadal slabs. Those higher yields corresponded to higher photosynthetic efficiency [10, 19, 23] of C_3 crop led to higher biomass production and carbon (C) accumulation [19, 24]. Further, the magnitude of percentage yield-increase and variation over decades reduces gradually, indicated greater adaptation of plant communities to elevated CO_2 [10, 11] and or also due to technological advancement (i.e., introduction of climate resilient varieties and improved soil-water-plant management practices [15, 25, 26]. However, the crop specific (cereals, forest, grass land, etc.) impacts on yield in our study were masked the temperature zone-effect under elevated CO_2 [27, 28, 29, 30]. These finding are consistent with smaller data set (572 observations) in which considered both the crop types (both C_3 and C_4) together. In general, we found that cereals (mostly C_3) were positively affected (83 nos. crops; note presented separately), providing support to our conclusion [31, 32]. However, detrimental consequence due to temperature rise associated with elevation of atmospheric CO_2 level is well established particularly in dry season crop in tropics [33, 34].

To sustain global agricultural productivity and limit soil degradation in future climate change scenario (higher atmospheric CO_2 concentration), MBC and functional microbial diversities need to be regulated/managed judiciously [35, 36, 37]. Microbial biomass C found to be most sensitive indicator to rhizospheric functioning under elevated CO_2 irrespective of temperature zones and crop types [38, 39, 40, 41]. In temperate region, a significant change in the MBC was reported with respect to percentage increase of atmospheric CO_2 [39, 42]. However, in our study, the overall non-significant effects of elevated CO_2 on bacterial and fungal population indicated higher structural adaptability of microbial communities (bacterial and fungi) to climate change consequences (elevated atmospheric CO_2).

In our study, the impact of elevated CO_2 on microbial diversities was found more in temperate region than tropical due to relatively higher temperature build up in cooler region (due to CO_2-elevation) which triggered microbial activities, soil enzymatic activities and respiration [14, 43, 44, 45, 46]. That means, we have been getting and going to get more functionally active rhizosphere in temperate zone compared to tropics in coming century [36, 47, 48].

It is often noticed that crop could not response to best management practices as expected due to unprecedented climate related stresses. So, their always exist risk for short to medium-term reduction in crop production possess a barrier for farmers [49, 50]. Nutrient-water use efficiency causally related to microbial functionality at rhizosphere level. Our results confirm that there would be a change in functional diversity of microbes due to elevation of CO_2 (predicted in high certainty of climate change consequences) in root zone of cereals, grass, and forest crops both in tropical and temperate region. So, we are going to get a more active rhizosphere in temperate zone which could increase the availability of nitrogen (N), phosphorus (P), potassium (K), and micro-micronutrients. Obviously, the crops demand of those nutrients would be more to maintain proper C: N/P/S ratios in plant and to produce sustainable yield [16, 17, 51, 52]. Therefore, real-time judicious nutrient management (both fertilizer and manure) is necessary in coming future; otherwise, we could loss the CO_2-fertilization benefit in one hand and may emit more GHGs to atmosphere causing positive feedback to climate change [2, 34, 35]. As we found significant increase (6-59%) in MBC irrespective of crops and temperature zones, we can say that our soil would be hungry to meet the higher demand of microbes. So, if we are not able to supply the demand of nutrients in available form there could be soil-priming [53, 54, 55]. Soil priming could exhaust the reserve of fix-C and in long run could cause soil health deterioration and land degradation [53, 56, 57, 58]. Non-significant structural changes of microorganisms due to CO_2 elevation indicated greater adoptability of them. So, there are ample possibility that those changes in microbial diversity could provide intrinsic stress (drought, flood, salinity) tolerance to crop. Therefore, intelligent water as well as nutrient management for harnessing the climate change-benefits and saving the resources are in the card. There are positives of CO_2-elevation (climate change consequences) both in plant, soil, and microbial context. But the mechanism and interrelationship need to understand properly. As per example, we must give more C, N, P, K and micronutrient input to soil considering both plant and microbes demands in future; otherwise, there would be soil-degradation and crop- productivity deterioration [59, 60].

It could not be determined from our study, whether typical biophysical conditions (e.g., soil texture/structure, soil-surface feature, residue-decomposition history etc.) or sub-optimal management practices are the reason for change in yield, MBC, and microbial diversity. Our hypothesis was that the dataset represents a holistic change in MBC, yield, microbial diversity and soil enzymatic activities across the regions and crops. Further, global scale study is needed to identify the combine effect of elevated CO_2 and temperature on microbial diversity in specific water regimes.

However, climate change is a global phenomenon but the impacts on soil microbial diversity is typically site specific [44, 46]. Nevertheless, disproportionate number of world's poor farmers resides in Africa, South-Asia, Saharan-Africa, still struggling with food security are more vulnerable to climate change vagaries, land degradation and yield reduction. Microbial health of soil is the key indicator of soil-health and land degradation. Therefore, efforts need to be done for intelligent nutrient and water management through microbial mediated rhizosphere manipulation to make the soil-plant systems more climate smart.

Therefore, our result suggested the integrated microbe-nutrient-water management practices in stressed region to meet current and future production challenges and to fetch beneficial effect of higher rhizosphere activities (higher microbial functioning) in terms of better nutrient availability and C-build up (Figure 5). This is a key finding in respect to the prediction (>90% certainty) that millions of hectares in temperate -Asia, America and Europe are going to fetch benefits from climate change induced-CO_2 fertilization [9, 49, 61, 62], still, if microbial mediated crop management is to be successful to cope up climate change vagaries and utilize the beneficial effect of CO_2 fertilization for sustaining crop productivity, it should be adjusted to local situations through an innovative coordinated approach that is sensitive to farmers preference, market-choice, and facilities available [30, 46]. Therefore, we should give more focus to utilize and manipulate the functional aspect of microbes related to nutrient dynamics, water availability, C-sequestration for farming as short to mid-term strategies to climate change adaptation. Projected climate changes in respect to temperature and precipitation causing frequent drought/ flood, pest virulence, water scarcity is expected in critical agricultural hub of the world [14, 15]. Depending on the type, intensity and severity of those climate change-vagaries, critical adaptation measures would be necessary to sustain global agricultural production at a desired level; the microbial mediated rhizosphere-manipulation could provide sustainable solution for improving water-nutrient use efficiencies, greenhouse gasses (GHGs) emission-mitigation and to impart intrinsic tolerance to the system (soil-plant-atmosphere continuum) to climate change threats [63, 64, 65].

Conclusion

Clearly, there are enhanced functional diversity and biomass carbon of microbes under elevated CO_2 which have both economic and environmental consequences. Future (coming 2-4 decades) crop-soil systems would require more nutrients, water, and carbon to produce sustainable yield; failed to provide that soil-priming and land degradation would be the risk. Climate change-land degradation-soil microbial health is in a vicious cycle. Unless we break the cycles, starting from microbial manipulation, positive feedback to climate change would continue. Hence, conscious efforts to improve real-time nutrient-water management in crops in response to change in microbial functional diversity in near future could “backfire” and promote negative feedback to climate change.

Declarations

Conflict of Interest: The authors declare no competing interest.

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Consent for Publication All authors agreed with the publication of this manuscript.

Availability of Data and Material All data during this study are included in this published article and its supplementary information files.

Code availability The PROC GLM and PROC CORR of SAS (SAS institute, Cary, NC, USA) were used for data analysis.

Author Contribution P.B. and T.M. were involved in conceptualizing, editing and language correction of the manuscript. E.V. and P.S. conducted the meta-analysis constructed the spatial distribution map. P.B. and S.R.P. were collected the review paper, prepared the manuscript and analysed the data.

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Figures

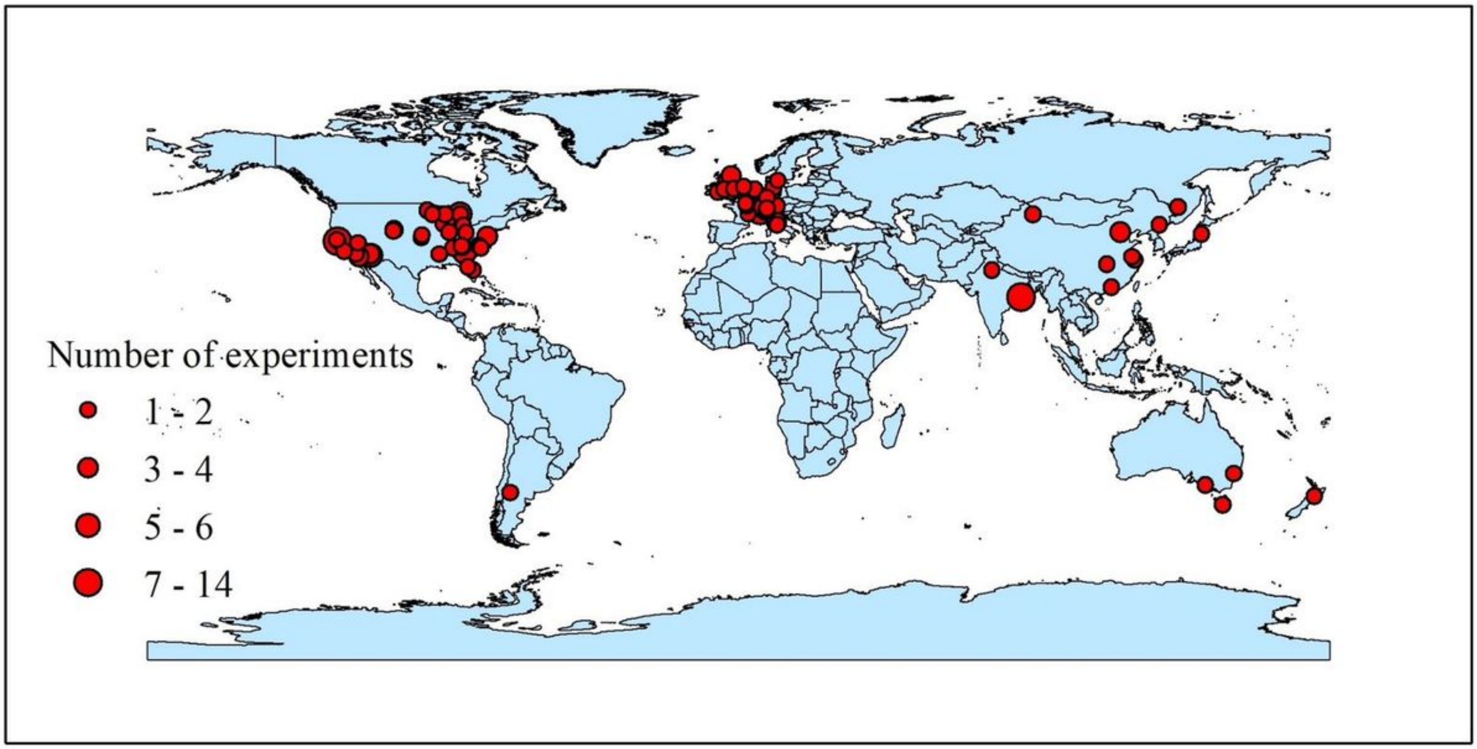

Figure 1

Spatial distribution of experimental sites considered for meta-analysis in the study.

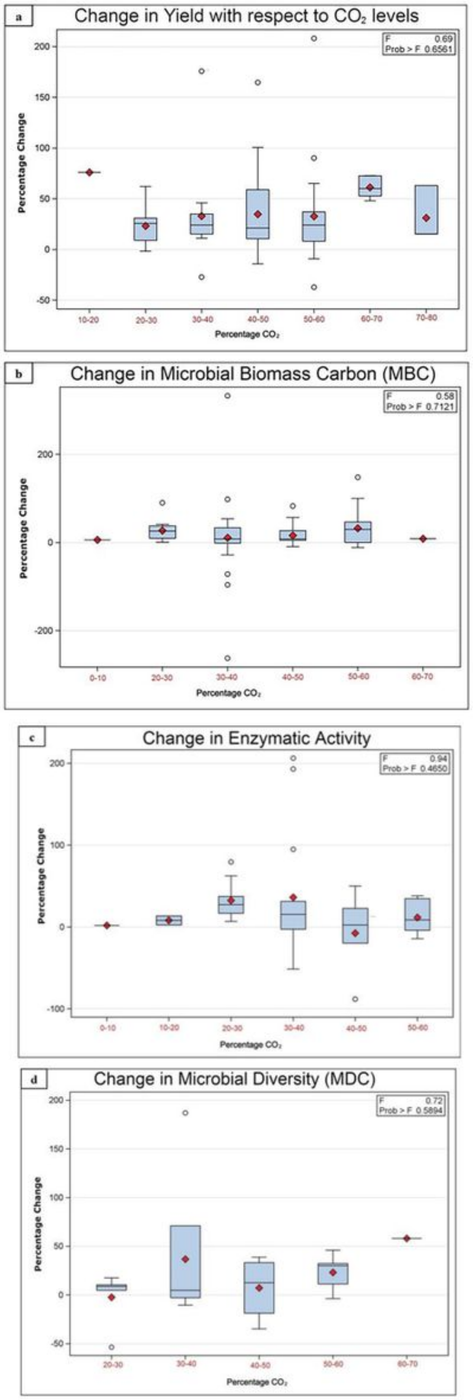

Figure 2

Changes of (a) Yield, (b) Microbial biomass carbon (MBC), (c) Soil enzymatic activities (d) Microbial diversity (MDC) at different CO2- elevation range. [Note: The summary statistic (mean, quartiles, minimum, maximum, and extreme observations/probable outliers) of measurements along with the F-value and Prob >F.]

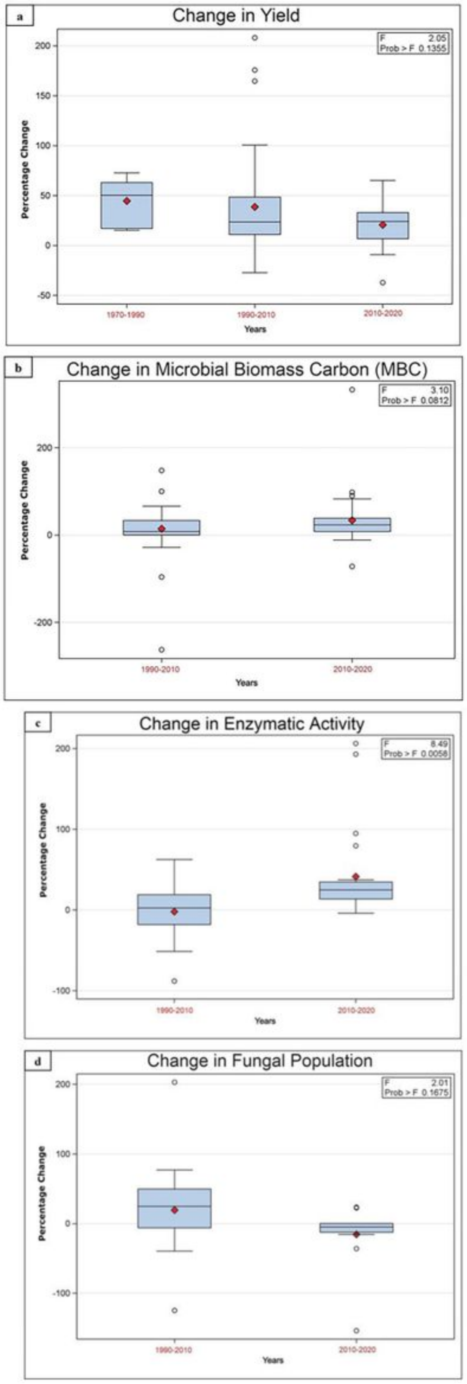

Figure 3

Changes of (a) yield, (b) Microbial biomass carbon (MBC), (c) Soil enzymatic activities and (d) Fungal population (FP) at temporal scale (1970-1989; 1990-1999; 2010-2020). [Note: The summary statistic (mean, quartiles, minimum, maximum, and extreme observations/probable outliers) of measurements along with the F-value and Prob >F.]

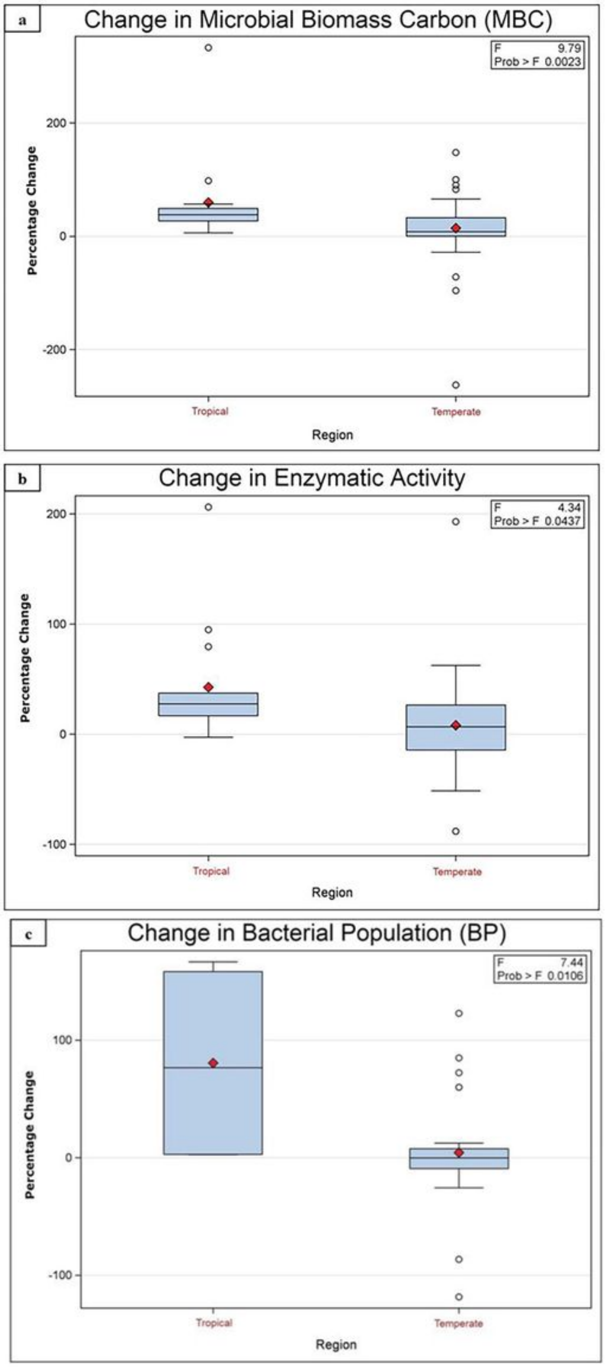

Figure 4

Changes of (a) Microbial biomass carbon (MBC), (b) Soil enzymatic activities and (c) Bacterial population (BP) in tropical and temperate region. [Note: The summary statistic (mean, quartiles, minimum, maximum, and extreme observations/probable outliers) of measurements along with the F-value and Prob >F.]

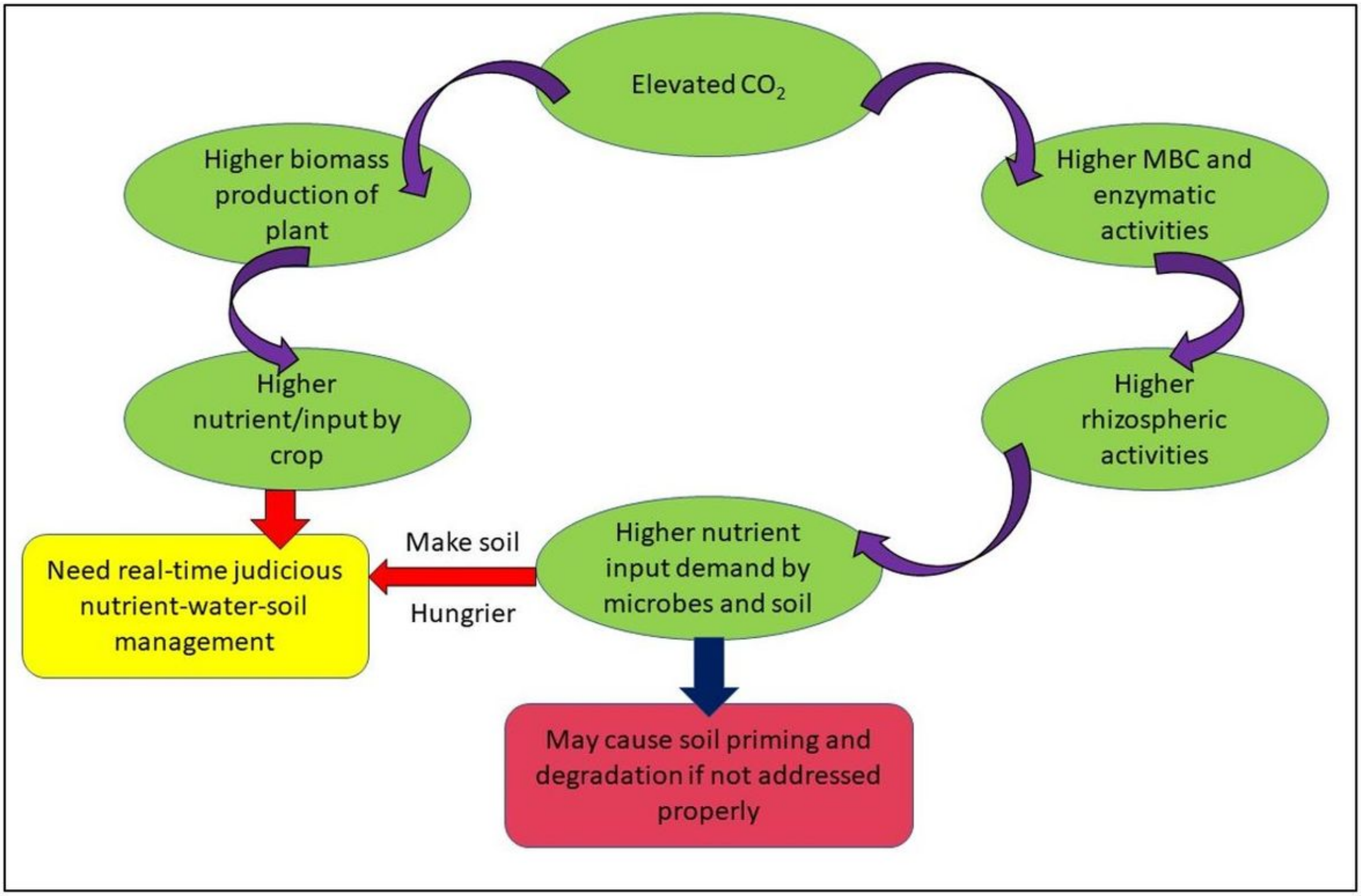

Figure 5

Conceptualization the impact of elevated CO2 on crop yield and microbial diversities.

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