

Effect of Elevated Temperature and Carbon Dioxide on Carbon Pool Dynamics in Semi-Arid Alfisol



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Abstract

Soil responses to the projected future levels of CO₂ and temperature was studied under Free Air Temperature Elevation (FATE) facility. Three levels- Ambient, elevated temperature (eT) (ambient +3°C ±0.5°C) and its interaction with eCO₂ (550ppm) (eT+eCO₂) was studied in rainfed pigeonpea and maize. The results reveal that eT and eT+eCO₂ reduced available water capacity in soil by 23% and 29%, respectively. Also, the eT and eT+eCO₂ lowered available N, P, B and Zn in soils as compared to A_c. However, there was no significant effect on soil pH, EC and CaCO₃ contents due to eT and eT+eCO₂. Enzymes such as dehydrogenase, urease and aryl sulphatase activities were higher under eT and eT+eCO₂ over ambient control (A_c). The eT showed a negative impact on SOC, MBC, POC, labile, non-labile C and carbon management index in soils. Interestingly, this negative effect was not observed in eT+eCO₂ conditions. The eT showed a negative impact on yield parameters in both pigeon pea and maize. However, in maize, total and fodder biomass production increased with eT by 3.2% and 11.7% but grain yield reduced with eT by 10%. This study clearly states that the eT conditions can have a negative impact on soil properties including carbon pools. While eCO₂ associated with eT (eT+eCO₂) can compensate the negative effect of eT on soil properties.

Keywords: Carbon pools; Elevated temperature; Elevated CO₂; FATE; Alfisol; Soil properties

Highlights

- Under eT and eT+eCO₂, soil water retention at FC decreased by 12.4% and 14.3%, respectively over A_c.
- The soil ammonical N decreased with eT by 5-9% but increased with eT+eCO₂ by 12-16% as compared to A_c.
- Under eT, Soil MBC, labile and non-labile C fractions were reduced by 28%, 14% and 5.6%, respectively over that of A_c.

Introduction

The atmospheric carbon dioxide concentration has increased globally to the extent of 47.2% as compared with the pre-industrial value of 280ppm [1] which may increase to 560ppm by 2050 [2]. Increasing atmospheric CO₂ concentration causes global warming as it traps long wave radiation emitted from earth's surface. The mean annual global surface temperature was projected to increase by 1.8°C - 5.8°C by the end of this century, depending on the greenhouse emission scenario [3]. The global warming effects are not only restricted to air temperature but can also alter rainfall patterns and soil temperature [4]. Changes in

soil temperature and rainfall distribution due to warmer climate may have intense effects on crop growth and soil properties in semi-arid regions.

Temperature above or below the optimum range for specific crop species often results in loss of yield due to rate-limited photosynthesis, reduced vegetative and reproductive growth [5]. Pigeonpea is the world's sixth most important legume crop and rich source of protein to more than a billion people in the developing world and a cash crop that supports the livelihoods of millions of resource poor farmers in Asia, Africa, South America, Central

America and the Caribbean. In India, it is cultivated in about 4.37 million ha mostly under rainfed conditions and contributed about 16% of the total pulse production with an average productivity of 0.66t ha^{-1} [6]. CROPAGRO-pigeonpea model showed that the climate change delayed anthesis by 9-20 days and maturity by 15-24 days and decreased yield by 14-66% with RCP8.5 in year 2095 in comparison to RCP2.6 in year 2010 [7]. Currently 1147.7 million t of maize is being produced jointly by over 70 countries from an area of 193.7 million ha. Earlier studies have indicated that 1°C increase in global temperature will lead to 17% reduction in maize productivity [8,9]. Vanaja et al. 2015 [10] found that the maize grown under 550ppm CO_2 had higher biomass and harvest Index (HI) due to higher photosynthesis rate. In general, eCO_2 positively affects crop yield but has negative effect on the nutritional quality particularly nutrient and protein contents [11]. Increase in plant growth due to eCO_2 leads to increased N uptake by plants thereby promoting a large reduction in plant available N in soil. Changes in soil nutrient availability induced by eCO_2 and eT during crop development can influence yield and nutritional quality. Thus, soil responses to eT and eCO_2 should also be considered when developing adaptation strategy for climate change.

Drivers of climate change such as elevated temperature, eCO_2 , variable precipitation and atmospheric N deposition will affect soil organic matter status, C and N nutrient cycling, plant available water and hence plant productivity which in turn will affect soil pH [12]. Using elevation gradient as a surrogate for increasing temperature and decreasing precipitation under climatic change scenarios, Smith et al. [13] found that electrical conductivity (EC) decreased and soil pH increased in a semi-arid environment. The findings on soil C sequestration have been inconsistent, with some studies showing an increase [14], no change [15] and a decrease [16] in soil C contents under eCO_2 conditions. Labile soil organic C was rapidly depleted as the temperature rises [17]. In addition, elevated CO_2 in the future may reduce sequestration of root derived soil C, a major source of labile light fraction C [18]. However, soil microbial C (SMC) similar to labile C has been shown to be responsive to short term environmental changes with recent studies revealing significant decline in SMC during long-term simulated climatic warming experiments [19].

Elevated temperature often increases soil N mineralization and availability while the effect of eCO_2 on soil N varies in direction and magnitude amongst ecosystems. Interaction of elevated temperature and elevated CO_2 potentially influence the demand and supply mechanism of P in a soil under changing climate [20]. A few available studies suggest the possibilities of both increase as well as decrease in available P in soil under elevated temperature and CO_2 . From this brief review of literature, it is understood that much of the earlier research confined to investigate the effect of eCO_2 on crop growth and soil properties under open top chambers (OTC) or in free air CO_2 enrichment (FACE). However, the effect of eT and interactive effect of eT and eCO_2 on soil properties and carbon pools dynamics and its processes has not been properly

understood particularly in rainfed Alfisol soils. Therefore, the present study was undertaken to study the effect of elevated canopy temperature (eT) ($+3^{\circ}\text{C}$) and its interaction with eCO_2 (550ppm) ($\text{eT}+\text{eCO}_2$) on changes in soil properties, C pool dynamics, soil moisture and nutrient availability and dry matter production of rainfed pigeonpea and maize grown in Alfisol soil.

Methods

Experimental site and design

A field experiment was conducted in monsoon season of 2017 and 2018 with pigeonpea and maize, respectively under three environmental conditions in Free Air Temperature Elevation (FATE) facility viz., (i) Ambient temperature and CO_2 concentration (380ppm) (i.e. Ambient Control, A_c), (ii) elevated canopy temperature (eT) of ambient $+3^{\circ}\text{C}\pm 0.5^{\circ}\text{C}$ (and ambient CO_2 concentration) and (iii) elevated temperature of ambient $+3^{\circ}\text{C}\pm 0.5^{\circ}\text{C}$ and elevated CO_2 concentration of 550ppm ($\text{eT}+\text{eCO}_2$). FATE facility is at Hayatnagar Research Farm, Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad between 17.20°N latitude and 78.3°E longitude. FATE facility consisting of nine rings with 8m diameter. Among the nine rings, six were fitted with 24 arrays of 2000W capacity ceramic infrared heaters (Elstein, model FSR – 1000) above the canopy to maintain elevated canopy temperature (eT) of ambient $+3^{\circ}\text{C}\pm 0.5^{\circ}\text{C}$. Three warming rings were also provided with CO_2 release system at 0.3m height from the base of the ring to study the interactive effect of elevated temperature and CO_2 ($\text{eT}+\text{eCO}_2$). The polyurethane tubing perforation releases the CO_2 within ring to maintain the elevated concentration of 550ppm. The CO_2 release was controlled by solenoid valves which in turn regulated by the SCADA based control system linked with CO_2 analyser, wind direction and wind speed. The CO_2 concentration at the centre of the ring was continuously monitored by IRGA based CO_2 analyser (Priva, modwl-200821), the duration of CO_2 release was based on the set CO_2 concentration for the specified area as well as wind direction and speed.

Infrared sensor (Ray teck Fluke, model-RAYCMLT33) is fitted in each ring to monitor the canopy temperature. The duration and intensity of heating is regulated by canopy temperatures of control plots and uses as proportional integral-derivative feedback system to maintain the heating treatment [21]. Signals from each sensor are being recorded and monitored and controlled by Program Logic Control (PLC) and Supervisory Control and Data Acquisition system.

Field experiment with pigeon pea, variety PRG 176 was taken up in 2017. Pigeon pea was planted at a spacing of 0.9m between rows and 0.2m between plants within a row. Recommended dose of farmyard manure (FYM) and fertilizer were applied @ 10 t FYM ha^{-1} , 30kg N ha^{-1} , 30kg P_2O_5 ha^{-1} and 25kg K_2O ha^{-1} , respectively. While, maize (var DHM 117) was taken up in 2018. Maize crop received FYM, N, P_2O_5 and K_2O at 10t ha^{-1} , 65, 75 and 50kg ha^{-1} ,

respectively. Urea, Diammonium phosphate and muriate of potash were the sources of N, P and K, respectively. Both pigeonpea and maize were grown in FATE rings as per the recommended agronomic practices. Manual weeding was done 2 to 3 times as per the need. No significant infestation of pests and diseases were observed in both pigeonpea and maize crops. In case of the pigeonpea, pod number, pod weight (g plant^{-1}), total biomass, vegetative biomass and seed yield (g plant^{-1}) were recorded after harvesting. Similarly in case of maize, cob weight (g plant^{-1}), total biomass, vegetative (fodder) biomass, kernel number and seed weight (g plant^{-1}) at harvesting were recorded. All these

components of both pigeonpea and maize were air dried in sun till the constant weight was obtained and then recorded dry weights.

Experimental soils were sandy loam in texture, neutral in reaction (pH 7.5), Non-saline (Electrical conductivity 0.20dS m^{-1}), low in organic C (4.1g kg^{-1}), low in available N (156kg ha^{-1}), high in available P (54kg ha^{-1}), high in available K (216kg ha^{-1}) and sufficient in available S (12mg kg^{-1}), available Zn (0.55mg kg^{-1}) and available B (1.4mg kg^{-1}). The rainfall, maximum and minimum temperature data recorded at the experimental farm during the pigeonpea and maize growing seasons are furnished in Figure 1.

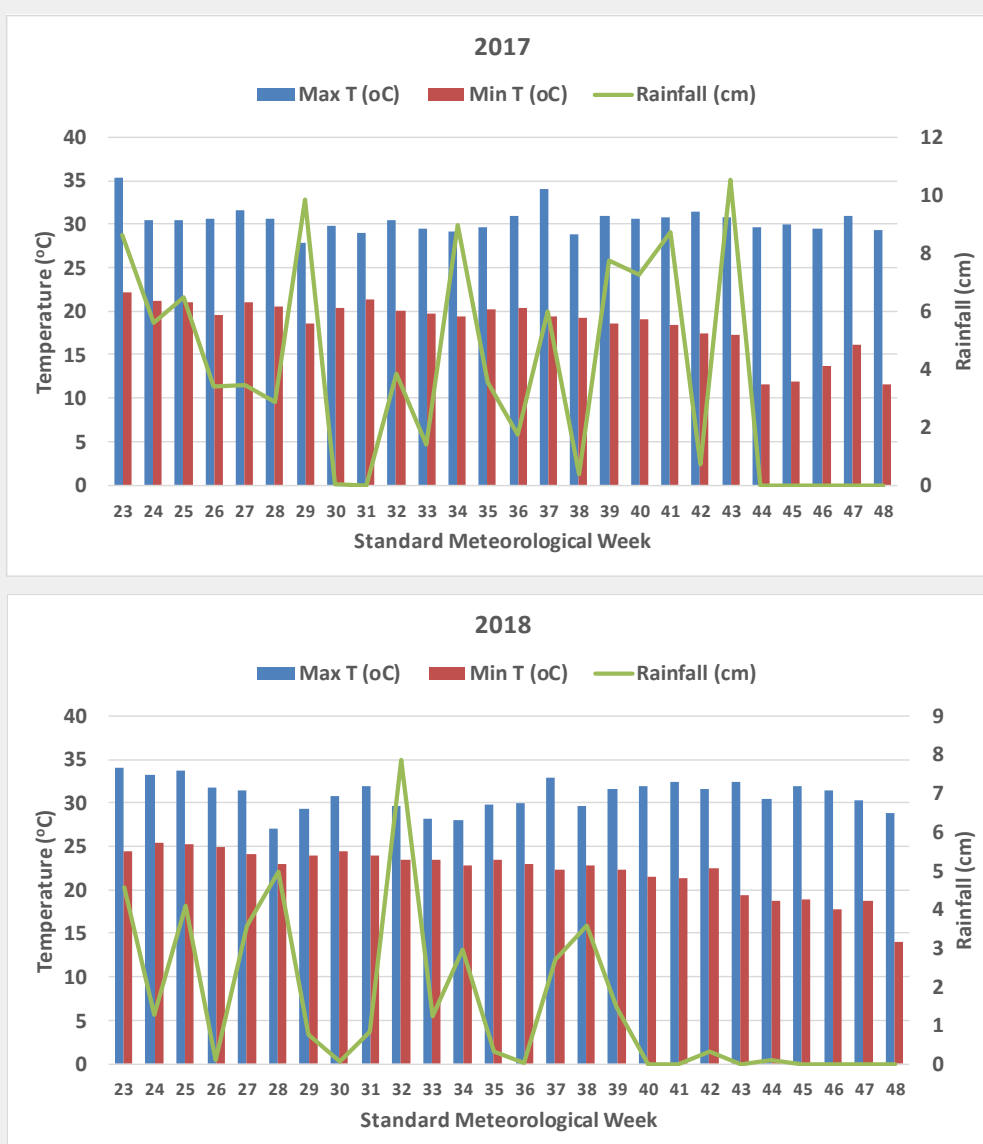


Figure 1: Rainfall, minimum and maximum temperature recorded during pigeonpea and maize growing seasons (4th June – 2nd December) at experimental farm.

Soil sampling and analysis

Field-moist soil samples were collected from the plough layer (0-15cm depth) from each ring after harvesting of pigeonpea in 2017 and after harvesting maize in 2018. Soil samples were collected from 3 rings for each of the 3 treatments. Four subsamples collected from each ring were bulked together on a ring basis to get a composite soil sample per ring. Soil samples were air-dried at room temperature and passed through a 2-mm sieve for chemical analyses. Soil samples thus collected after pigeonpea and maize were analysed for $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, available nutrients (N, P, K, Zn and B). Soil samples collected after harvesting maize were also analysed for pH, electrical conductivity, and CaCO_3 content. Water retention at 1/3 bar (Field capacity, FC) and water retention at 15 bar (Permanent wilting point, PWP) were also determined in soil samples collected after harvesting maize and computed available water content. Gravimetric soil moisture content was determined during pigeonpea and maize seasons periodically.

Determination of soil properties and plant available nutrients in soils

Each soil sample was analysed in triplicate for determination of pH, electrical conductivity (EC) [22], CaCO_3 and water retention [23]. Potentially available (mineralizable) N was determined by distilling the soil with alkaline potassium permanganate solution and measuring the $\text{NH}_4\text{-N}$ in the solution [24]. Soil samples were analyzed for Olsen-P by extracting with sodium bicarbonate (0.5M NaHCO_3 , pH 8.5, 1:20 soil to water extract ratio). Phosphate concentration in the extract was estimated colorimetrically by ascorbic acid blue colour method of Murphy & Riley [25]. Available K (1M ammonium acetate extractable) was determined according to the procedure of Hanway & Heidel [26]. Soil available Zn was extracted in 0.005M DTPA- CaCl_2 at pH 7.3 [27] and its concentrations in the extracts was determined by atomic absorption spectrophotometer (Perkin Elmer Model 700AA). Hot water extractable B (available B) was determined by azomethane yellow colour method [28].

Estimation of soil organic C and its fractions and computation of Carbon management index (CMI)

Total soil organic C (SOC) concentration was determined by dry combustion, using a CN analyser (Elementar Vario El Cube) in soil samples (0.25mm mesh) collected after harvesting maize. The microbial biomass carbon (MBC) was determined by the fumigation and extraction method of Vance et al. [29]. Particulate organic carbon (POC) was determined following Cambardella & Elliot [30] method. Soil labile C (C_L) was determined by the modified CMI method of Blair et al. [31] using 333mM KMnO_4 as the oxidizing agent. Non-labile C (C_{NL}) was determined as a difference between total SOC and the labile C (C_L). The relative amount of these two fractions and the total carbon in a cropped and reference soil have been used by Blair et al. [31] to calculate a CMI. Composite soil sample was collected from a neighboring

cultivated fallow plot and analyzed in triplicate for carbon fractions. The fallow plot soil was considered as the reference soil.

The CMI was computed according to the mathematical procedure used by Blair et al. [31], which are described below;

$$CMI = CPI \times LI \times 100$$

Where CPI is the carbon pool index and LI is the lability index

The CPI and the LI are calculated as follows;

$$CPI = \frac{C \text{ pool in treatment}}{C \text{ pool in reference}}$$

$$LI = \frac{\text{Lability of C in sample soil}}{\text{Lability of C in reference soil}}$$

Where Lability of C (L) is calculated as follows;

$$L = \frac{\text{Content of labile C}}{\text{Content of non-labile C}}$$

Estimation of soil enzymes

Aryl sulphatase activity (ASA) was estimated by measuring the p-nitrophenyl released after incubation of the buffered soil with p-nitrophenyl sulphate as substrate [32]. The soil urease activity was determined by incubating soil with urea [33], and the residual urea was determined titrimetrically. Dehydrogenase activity (DHA) was determined by using 2, 3, 5, triphenyl tetrazolium chloride as an electron acceptor, and methanol was used as an extractant for the formed formazan [34].

Farmyard manure (FYM)

The FYM applied to pigeonpea contained 0.74% N, 0.24% P, 0.70% K, 15mg Zn kg^{-1} and 12mg B kg^{-1} whereas the FYM applied to maize contained 0.8%N, 0.22% P, 0.68%K, 12mg Zn kg^{-1} and 10mg B kg^{-1} .

Statistical analysis

The SAS (2005) [35] was used to analyse the variance and determine the significance of treatment effects at $p < 0.05$ level of significance. The Duncan's multiple range test was used for means comparison.

Results

Crop yield parameters

Pigeon pea and maize were studied in the monsoon season of 2017 and 2018 respectively. In our study, eT negatively influenced the yield parameters in pigeonpea and maize to a larger extent as compared to eT+eCO₂. In pigeonpea, the total biomass production followed the order Ac > eT+eCO₂ > eT while in maize, the order was eT+eCO₂ > eT > Ac. Similar is the trend with fodder biomass in maize. However, cob weight, kernel number, grain weight and HI were lower in eT as compared to Ac. Maize being a C4 plant, it

could produce higher biomass under eT as compared to control. While pigeonpea being a C3 plant, eT had negative impact on total biomass as compared to A_c. (Table 1). Thus, the extent of decline is more in pigeon pea as compared to maize. The eT has reduced the harvest index (HI) by 5% over the A_c while eT+eCO₂ has decreased the HI by 7.7% over the A_c in Pigeonpea. While in maize, eT and eT+eCO₂ resulted in a decrease in the harvest index by 12.9 and 7.7%, respectively as compared to A_c. The eT has resulted in the reduction of 100 seed weight by 9.57% while the combined effect (eT+eCO₂) has resulted in reduction

upto 1.99% in pigeon pea. This suggests that along with raised temperatures, if there is elevated CO₂ (eCO₂) condition, then this may have minimal impact on 100 seed weight in pigeon pea in the climate change scenario. Similarly, in maize, the extent of reduction was 10.27% under eT. A non-linear relationship was found between harvest index (Y) and the interactive effect of elevated temperature and elevated CO₂ concentration (X) in pigeon pea ($Y = 1.15x^2 - 5.15x + 38.5, r = 0.99$) and in maize ($Y = 4x^2 - 17.7x + 57.7, r = 0.99$) indicating that both eT and also eT+eCO₂ can directly impact HI.

Table 1: Effect of eT and eT+eCO₂ on pigeonpea and maize.

Pigeon Pea							
Treatment	Total biomass (g pl ⁻¹)	Pod Number per Plant	Pod Weight (g pl ⁻¹)	Seed Number per Plant	Seed yield (g pl ⁻¹)	100 seed weight (g)	HI (%)
Ambient Control	433.3a	537.3a	205.2a	1496a	149.3a	10.03a	34.5a
eT	360.8b	420.3b	163.3b	1305a	117.9b	9.07a	32.8a
eT+eCO ₂	422.2a	544.3a	205.3a	1432a	140.6a	9.83a	33.4a
Maize							
Treatment	Total biomass (g pl ⁻¹)	Fodder Biomass (g pl ⁻¹)	Cob Weight (g pl ⁻¹)	Kernel Number per Plant	Kernel weight (g pl ⁻¹)	Grain weight (g pl ⁻¹)	HI (%)
Ambient Control	422.7b	198.4b	252b	577b	32.2a	185.9ac	44.0a
eT	436.2b	221.7a	233c	517c	32.4a	166.8bc	38.3b
eT+eCO ₂	463.5a	227.2a	265a	630a	29.9a	188.0a	40.6b

Table 2: Effect of eT and eT+eCO₂ on soil moisture content of Alfisol during rainfed pigeonpea and maize.

Treatment	Soil Moisture Content (%)									
Pigeonpea (Monsoon Season, 2017)										
Date	6-Jul-17 (7 DAS*)	12-Jul-17 (21 DAS)	19-Jul-17 (28 DAS)	25-Jul-17 (35 DAS)	1-Aug-17 (42 DAS)	16-Aug-17 (57 DAS)	2-Sep-17 (75 DAS)	23-Sep-17 (95 DAS)	23-Oct-17 (125 DAS)	23-Nov-17 (155 DAS)
Ambient Control	12.03±0.40a	17.24±0.36a	18.34±0.63a	14.36±0.49a	15.36±0.40a	13.62±0.53a	15.12±0.41a	7.83±0.24a	4.65±0.03a	3.60±0.03a
eT	10.52±0.38b	15.34±0.55b	15.83±0.40b	13.63±0.33a	14.21±0.28b	13.09±0.38a	14.40±0.24ab	6.61±0.22b	3.58±0.02b	2.45±0.02b
eT+eCO ₂	10.27±0.370	15.06±0.44b	12.88±0.32c	13.57±0.41a	13.70±0.25b	12.28±0.32a	14.09±0.28b	6.37±0.20b	3.50±0.02b	2.23±0.01b
Maize (Monsoon Season, 2018)										
Date	18-Jul-18 (23 DAS)	8-Aug-18 (31 DAS)	23-Aug-18 (46 DAS)	9-Sep-18 (63 DAS)	24-Sep-18 (78 DAS)	10-Oct-18 (93 DAS)	25-Oct-18 (108 DAS)			
Ambient Control	13.73±0.48a	14.31±0.35a	14.21±0.33a	15.51±0.40a	12.56±0.32a	5.28±0.24a	2.91±0.10a			
eT	13.15±0.33a	12.45±0.24b	13.54±0.20a	13.18±0.30b	10.81±0.25b	4.39±0.19b	2.34±0.11b			
eT+eCO ₂	12.83±0.27a	11.27±0.28c	11.96±0.20b	12.62±0.15b	9.00±0.14c	5.26±0.25a	2.03±0.09b			

*DAS: Days after sowing

Impact of eT and eCO₂ on Soil moisture content

The impact of eT and eT+eCO₂ on volumetric soil moisture content in surface soil (0-15cm) was studied at every week during initial stages and at 15-30 days interval during the later stages (Table 2). When pigeonpea was grown, soil moisture content significantly decreased by 4-32% with eT as compared to A_c throughout the growing season except on 25th July 2017 (35 DAS) and 16th Aug 2017(57 DAS). The soil moisture was further decreased by 6-38% under eT+eCO₂ as compared to A_c at 8 sampling stages except at 35 DAS and 57 DAS. The difference in soil moisture contents of soils subjected to eT and eT+eCO₂ were not significant at all sampling stages except at 28 DAS. Soil moisture content was drastically reduced in the month of October and November 2017 due to with drawl of monsoons on 30 September 2017. More or less similar effects were obtained in the maize crop grown in 2018. Soil moisture content was decreased by 5-20% significantly with eT as compared to A_c throughout the maize season except at 23 DAS and 46 DAS. Soils subjected to eT+eCO₂ also maintained significantly lower moisture content by 14-30% in comparison to A_c. In our study, eT+eCO₂ maintained low soil moisture as compared to eT but was not significant statistically.

Also, water retention and available water content was studied and it was found that the eT and eT+eCO₂ had significant effect on soil moisture constants such as water retention at field capacity (FC), water retention at permanent wilting point (PWP) and available water capacity of soils collected in post-harvest soil

samples. Soil water retention at FC decreased with eT and eT+eCO₂ by 12.4% and 14.3%, respectively over A_c with corresponding increase in water content at PWP by 21% and 34%, respectively (Table 3). This influence of eT and eT+eCO₂ on water retention at FC and PWP resulted in decrease in available water capacity of soil by 22.6% and 29.2%, respectively as compared to A_c. The eT and eT+eCO₂ were at par with each other in influencing soil moisture content.

Impact of eT and eCO₂ on Soil and plant nutrient status

In our study, available N, P, K, Zn and B status of soils for both the study years are given in Table 4. The eT and eT+eCO₂ decreased the available N, P, and K nutrients in soil as compared to A_c. However, the decrease with eT+eCO₂ was significant. The mean decline in available N during the experimental period under eT and eT+eCO₂ was 5.50 and 11.58% respectively over A_c. The mean decline in available P during the experimental period under eT and eT+eCO₂ was 14.36 and 29.8% respectively. While the decline in available K was 2.35 and 1.56% respectively under eT and eT+eCO₂. Available Zn status in soil after harvesting pigeonpea and maize was decreased with eT and eT+eCO₂ however, the decrease with eT was significant after pigeonpea. But decline in available Zn status of soils after harvesting maize with eT+eCO₂ was significant as compared to A_c. The eT+eCO₂ maintained lower available Zn status in soil after harvesting maize as compared to eT.

Table 3: Effect of eT and eT+eCO₂ on physico-chemical properties of Alfisol after harvesting maize.

Treatment	pH	EC (dS m ⁻¹)	Calcium Carbonate (%)	Water Retention at 1/3 rd Bar (%)	Water Retention at 15 Bar (%)	Available Water Content (%)
Ambient Control	6.63±0.25a	0.26±0.02a	0.47±0.04a	13.24±0.40a	3.10±0.22b	10.14±0.42a
eT	6.58±0.23a	0.26±0.03a	0.51±0.05a	11.60±0.48b	3.75±0.16a	7.85±0.41b
eT+eCO ₂	6.38±0.15a	0.23±0.06a	0.42±0.02a	11.35±0.24b	4.17±0.24a	7.18±0.26b

Table 4: Effect of eT and eT+eCO₂ on available nutrient status of soil after harvesting pigeonpea and maize.

Treatment	NH ₄ -N (kg ha ⁻¹)	NO ₃ -N (kg ha ⁻¹)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Available Zn (mg kg ⁻¹)	Available B (mg kg ⁻¹)
After Harvesting Pigeon Pea							
Ambient Control	17.9±0.9ab	32±3.5a	179±7.5a	58.3±3.7a	205.8±6.4a	0.66±0.03a	1.63±0.11a
eT	17.0±0.78a	28±2.9ab	170±7.0ab	51.1±1.6ab	278.7±9.1a	0.56±0.02b	1.49±0.09ab
eT+eCO ₂	20.0±0.75b	21±2.2b	157±5.3b	40.5±1.5b	205.7±6.8b	0.52±0.01b	1.32±0.07b
After Harvesting Maize							
Ambient Control	19.9±0.82b	37.0±3.7a	184±7.3a	62.3±2.3a	208.5±7.8b	0.77±0.02a	1.69±0.11a
eT	18.2±0.62b	31.7±3.3ab	173±6.7ab	52.10±1.5b	283.2±9.8a	0.71±0.03a	1.54±0.08ab
eT+eCO ₂	23.0±1.01a	22.2±2.4b	164±5.7b	44.20±1.6c	206.3±6.4ab	0.61±0.03b	1.36±0.07b

Treatments had significant effect on inorganic N. The ammonical N in soils after harvesting both the crops decreased with eT by 5-9% but increased with eT+eCO₂ by 12-16% as compared to A_c. While nitrate N in soils after harvesting decreased with eT by 14% and by 34-40% under eT+eCO₂. The eT+eCO₂ maintained the lowest NO₃-N content in soils after harvesting pigeonpea and maize crops.

SPAD readings

SPAD readings were taken during 43,60,90, 120 and 150 days after sowing in pigeon pea. In this study, the SPAD reading ranged from 39.33 to 54.27, 34.93-48.27 and 36.07-51.67 in aT, eT and eT+eCO₂. This study clearly suggests that SPAD reading were low in eT as compared to AC and eT+eCO₂.

Soil enzyme activities

Activities of soil enzymes viz., dehydrogenase, urease and aryl sulphatase in soils exposed to eT were significantly higher as compared to ambient control (Table 5). The eT+eCO₂, similar to eT, also increased the activities of dehydrogenase (10.66 ug TPF g⁻¹ h⁻¹) and urease (18.21ug NH₄ g⁻¹ h⁻¹) as compared to ambient control. The effect of eT+eCO₂ on aryl sulphatase (16.95ug p-NP g⁻¹ h⁻¹) was not significant. Activity of aryl sulphatase in soils exposed to eT+eCO₂ was significantly lower by 10% as compared to eT. The activities of dehydrogenase and urease under eT and eT+eCO₂ were at par with each other.

Soil carbon pools and carbon management index

After two years of cropping, the treatment plots maintained higher soil organic carbon (SOC) content as compared to fallow plot (Table 6). The eT had reduced the soil organic carbon and its fractions such as microbial biomass carbon (MBC), particulate organic carbon (POC), labile and non-labile C contents as compared to ambient control. Soil MBC, labile and non-labile C fractions were reduced with eT by 19%, 14%, 14.3% and 5.6%, respectively over that of A_c. But the reduction in MBC due to the effect of eT was significant. On the other hand, eT+eCO₂ increased significantly organic carbon, MBC, labile and non-labile C contents of soils as compared to ambient control by 6.4%, 20%, 28%, 19% and 5%, respectively. The soils exposed to eT+eCO₂ maintained significantly higher lability of C, lability index and carbon management index over the ambient control and eT. The eT reduced the carbon pool index (CPI) while eT+eCO₂ enhanced the CPI over ambient control but the affect was not significant. Soil carbon management index (CMI) was higher in soils subjected to eT+eCO₂ (127.9) and lower in soils exposed to eT (88.9) as compared to ambient control (105.9). But the effect of eT was not significant. These results clearly showed that in short term the eCO₂ associated with eT not only compensated the negative effect of eT on soil organic matter but also maintained at par with ambient control.

Discussion

Soil moisture content during pigeonpea and maize seasons

Understanding the effect of eT and eCO₂ on soil moisture status during the cropping season under rainfed conditions is essential due to large temporal variability in rainfall and the preponderance of small precipitation events. Elevated temperature increases potential evaporation (E) and transpiration (T) loss of water from the soil which might have resulted in low soil moisture content in eT plots (Table 2). The eT+eCO₂ maintained significantly lower soil moisture as compared to A_c but at par with the soil moisture content of eT despite higher biomass production in this treatment as compared to eT. Earlier studies have shown that eCO₂ reduced evapotranspiration (ET) and increased soil moisture content in semi-arid shortgrass steppe of North America [36]. High evaporation demand was offset by the reduced plant transpiration on soil moisture under CO₂ enrichment. The stable isotope partitioning of ET in the semi-arid shortgrass steppe shown that the evaporation component of ET was significantly lower under eCO₂ [37] and resulted in percolation of more water into deeper layers of soil under eCO₂ condition. But in the present investigation, association of eT with the eCO₂ has changed the dimension. The association of eT offset the beneficial effect of eCO₂ in reducing the evaporation component of ET. Thus, in dryland regions, simultaneous occurrence of climate change drivers (eT+eCO₂) might increase the water requirement of rainfed crops. Therefore, the supplemental irrigation to rainfed crops through harvested rainwater might be crucial for meeting high ET demand of higher drymatter production with eT+eCO₂ under changing climate conditions.

Soil Physico-chemical properties

Investigating the influence of climate change on soil health indicators help in developing adaptation strategies for climate change. After two cropping seasons, soil pH non-significantly reduced by eT and eT+eCO₂ as compared to A_c (Table 3). According to Celia et al. (2002) [38], the increase in the CO₂ concentration influences soil pH which consequently influence the rate of weathering and to some extent, the availability of plant nutrients. When CO₂ was introduced into the soil, Ravi et al. (2010) [39] found insignificant change in soil pH but Smith et al. (2005) [40] observed a decrease in soil pH.

Changes in electrical conductivity (EC) affects the structural condition and biological activity of soil under rainfed conditions [41]. Thus, more emphasis should be given to assess the impact of drivers of climate change on soil EC. Smith et al. (2002) [13] found a decrease in EC with increasing temperature and decreasing precipitation in a semi-arid environment. Pariente (2001) [42] investigated the dynamics of soluble salt concentration in soils from Mediterranean, semi-arid, mildly arid and arid climatic

regions and found a non-linear relationship between soluble salts concentration and precipitation. In the present study, the EC was not affected by the eT and eT+eCO₂ after two seasons of the cropping which might be due to very low initial EC of the Alfisol soil (Table 3).

The arid climatic adversaries favour the sequestration of inorganic C as CaCO₃ with concomitant development of soil sodicity due to rise in mean annual temperature (MAT) and decrease in mean annual rainfall (MAR). In SAT environments, the water loss through evapotranspiration (ET) was considered as a primary mechanism in precipitation of pedogenic CaCO₃ (PC). PC found in ferruginous Alfisols of Southern India due to the present day semi-arid climate. The formation of PC resulted in concentration of sodicity in clay rich Vertisols [43]. In present study, the CaCO₃ content was very low in Alfisol and negligibly affected by eT and eT+eCO₂ owing to a short period of experimentation.

Available nutrient status of soil after harvesting

Soil nutrient transformations are primarily carried out through microbial activities which are further influenced by fluctuations in temperature and CO₂ concentration. Climate change causes high intensity rainfall in the short time which causes waterlogged condition in soils without proper drainage. Under changing climatic condition, soils become waterlogged, hypoxic and produce phytotoxic organic solutes which impair the root growth and function due to high intensity rainfall in short time.

Available N, P, Zn and B status decreased with eT and eT+CO₂ as compared to A_c in post-harvest soils (Table 4). The decrease in available N with eT may be due to increasing volatilization losses from soil. Higher temperature can increase nutrient sequestration by soil microorganisms to their increased growth and activity in soils which may induce a reduction in the amount of available nutrients in soil [44]. Microbial N immobilization was stimulated by CO₂ enrichment which was responsible for transformation of large amounts of N into organic forms rendering less available to plants. The increase in temperature from 15 to 45°C increased cumulative ammonia losses from 3.3 to 19.6mg kg⁻¹ soil [45]. They also reported a drastic decline in NO₃-N in crop rhizosphere under elevated CO₂ in wheat crop. Figueiredo et al. (2015) [46] observed decline in the NH₄-N fixation rate in clayey soil with the co-elevation of temperature and CO₂. In the present study, the increase in NH₄-N status of soil might be due to reduction in NH₄-N fixation under eT+eCO₂.

Few of available literature on the effect of eT and eCO₂ on plant available P in soils suggest the possibilities of increasing or decreasing in soil under eT and eCO₂. A possible increase in the activity of P solubilizing rhizo-chemicals due to eT and eT+eCO₂ may increase the available P in the soil. Contrarily, increased microbial activity in rhizosphere under eT and eCO₂ due to increased deposition of organic substrates in rhizosphere may

reduce the availability of P in soil owing to P immobilization by soil microorganisms [47,48]. The decrease in the available P status of post-harvest soils due to eT and eT+eCO₂ (Table 4) might be ascribed to P immobilization by soil microorganisms. Further decrease in available P status of soil due to eT+eCO₂ as compared to eT might be attributed to higher removal of P by crops due to higher biomass production in eT+eCO₂ over eT (Table 1). Phosphorus uptake by wheat grown on Inceptisol increased with eCO₂ and decreased with eT and with overall increase of 17.4% under eCO₂+eT signifying higher P requirements by plants due to climate change [20]. Available K in soils increased with eT as compared to A_c and eT+eCO₂. Similar to available P, available Zn and B in post-harvest soils after pigeonpea and maize decreased with eT as compared to A_c. eT+eCO₂ resulted in further decrease in the status of available Zn and B which may be due to higher removal by higher biomass yield.

Soil enzyme activities

Soil enzymes play an important role in transformations of soil organic matter, nutrient cycling and availability of plant nutrients in soil ecosystem. The activity of dehydrogenase is considered as an indicator of the oxidative metabolism in soils and thus of the microbiological activity [49]. The conversion of organic N to inorganic N through hydrolysis of urea to ammonia and CO₂ by urease is an important pathway of N transformation in soil. Thus, measurements of enzyme activity in soils were useful in examining the impacts of environmental changes. In the current study, eT and eT+eCO₂ increased the activities of dehydrogenase, urease and aryl sulphatase activities in soil as compared to ambient control (Table 5). Increased activity of soil enzymes indicates the higher microbial activity with eT & eT+eCO₂ which led to sequestration of available nutrients in microorganisms. This might be the reason for reduction in the status of available N, P and Zn with eT and eT+eCO₂ (Table 4). Das et al. [50] reported a significant increase in the enzyme activities (dehydrogenase, B-glucosidase, urease, alkaline and acid phosphatases) at higher temperature (45°C) and elevated CO₂ (600ppm) in four soil types and thereby accelerated the turnover of organic C fractions of the soil due to increase in microbially mediated processes. The activities of dehydrogenase, urease and aryl sulphatase increased in rainfed Alfisol with elevated CO₂ up to 550ppm in open top chambers [51].

Soil organic carbon dynamics

How climate change impact soil organic matter is the main concern of debate. On one hand that a rise in air temperature and that of the soil would be consistent with an increase in decomposition and loss of soil organic matter in the form of CO₂ to atmosphere. On the other hand, the global warming and increasing CO₂ concentration in the atmosphere can favour increased plant growth, which in turn could provide more organic matter to the soil. Thus, there a lot of interest was generated to study the effect of climate change drivers viz., eT and eCO₂ over a short- and long-term on transformation of SOC fractions and

sequestration in soil. The balance of opinion presently is that in the absence of mitigation action, soil organic matter losses through decomposition are likely to exceed levels gained from

increased plant growth thus emission of CO₂ into atmosphere and greenhouse effect.

Table 5: Effect of eT and eT+eCO₂ on soil enzyme activity in Alfisol after harvesting of maize.

Treatment	Dehydrogenase activity ($\mu\text{gTPF g}^{-1} \text{h}^{-1}$)	Urease ($\mu\text{g NH}_4 \text{g}^{-1} \text{h}^{-1}$)	Arylsulphatase ($\mu\text{g p-NP g}^{-1} \text{h}^{-1}$)
Ambient Control	9.57±0.35b	15.30±0.70b	17.70±0.98ab
eT	10.56±0.33a	20.31±0.97a	18.82±0.90a
eT+eCO ₂	10.66±0.16a	18.21±0.89ab	16.95±0.65b

Elevated temperature resulted in a reduction in SOC by 6.4%, MBC by 28%, POC by 20%, labile C by 14%, and non-labile C by 5.6% over the ambient control soil. Except MBC, the decreases were not significant statistically (Table 6). The reduction in labile pools due to eT was more as compared to decline in non-labile C. But when the eCO₂ combined with eT increased the contents of SOC by 6.4% and labile pools i.e., POC, MBC & labile C by 20%, 28% and 19%, respectively over the ambient control soil. The increase in soil organic carbon under eT+eCO₂ suggests a prospective soil C sequestration. Higher root biomass produced in the presence of eCO₂ might have contributed higher C input into the soil which would lead to higher C sequestration. It appears that the amount of C input into soil under eT+eCO₂ exceeded the amount of SOC loss under eT. The improved photosynthesis and plant growth under elevated CO₂ concentration could lead to increase C input to the soil [52]. Though soil microorganisms are often carbon limited, more C input would be expected to increase

the soil microbial biomass and activity [53,54]. The increased C assimilation by plants and its subsequent sequestration in soil may counter balance to some extent the CO₂ emissions. However, the enhanced C sequestration due to eT+eCO₂ in soil could only sustain if increases in the C input are sustained [55] and increase in the C input exceeds the soil C mineralization over a longer period of time [56].

The soil organic C pool and the C lability directly influence soil physical, chemical and biological attributes as well as the structural capacity of soils [57]. Therefore, the integration of both soil organic C pool and C lability into the C management index (CMI) can provide a useful parameter to assess the capacity of management systems to promote soil quality [58]. In the present short term study, the increase in CMI with eT+eCO₂ indicates that if recommended rates of fertilizers and manure are applied to crops, the reduction in SOC, C pools and CMI due to eT could be minimized in semi-arid Alfisol soils (Table 6).

Table 6: Effect of eT and eT+eCO₂ on soil carbon fractions and indices in Alfisol after harvesting of maize.

Treatment	Carbon Fractions (g kg ⁻¹)					Lability of C	Lability Index	Carbon Pool Index (CPI)	Carbon Management Index (CMI)
	Total SOC	Labile C	Non-labile C	MBC ($\mu\text{g g}^{-1}$)	POC (g kg ⁻¹)				
Ambient Control	4.7±0.26ab	0.42±0.03ab	4.28±0.25a	160.4±3.4b	3.5±0.23b	0.098±0.006b	0.938±0.08b	1.12±0.11a	105.9±16.9ab
eT	4.4±0.24ab	0.36±0.02b	4.04±0.22ab	130.4±2.0c	3.0±0.11b	0.089±0.001b	0.849±0.03b	1.05±0.08a	88.9±3.1b
eT+eCO ₂	5.0±0.24a	0.50±0.05a	4.50±0.19a	205.2±4.0a	4.2±0.13a	0.111±0.005a	1.056±0.08a	1.20±0.12a	127.9±22.5a
Fallow plot	4.2±0.22b	0.40±0.03b	3.80±0.19b	156.40±3.1b	3.2±0.20b	0.105 ±0.007ab			

Our results showed that the increase in soil enzyme activity including dehydrogenase activity with eT caused reduction in the SOC, MBC, labile C and non-labile C contents. But eT+eCO₂ resulted in higher contents of these carbon pools in soil even though soil enzyme activity increased with the eT+eCO₂. In the present study, sufficient quantity of farmyard manure (10t ha

¹) and recommended rates of deficient plant nutrients applied to both pigeonpea and maize. With the application of manure and deficient nutrients at recommended rates, eCO₂ combined with eT resulted in higher biomass production as compared to ambient control and eT. This might have contributed more root, plant residues, and root exudates to soil exposed to eT+eCO₂ and

thereby maintained higher organic C and its fractions in soil over the ambient control, eT and fallow plots. These results clearly showed that the loss of soil organic matter and crop productivity due to global warming could be arrested by the application of all deficient plant nutrients and organic manures at recommended rates to different crops grown on rainfed soils.

Biomass production of pigeonpea and maize

The rising CO₂ concentration in atmosphere and increase in surface temperature have a direct linkage with the growth and metabolism of plants. As CO₂ is a primary raw material in the process of photosynthesis, increase in atmospheric CO₂ concentration causes fertilization effect resulting in enhanced biomass and yields. This has been primarily attributed to the enhanced rate of photosynthesis upon exposure to higher CO₂ levels. It is important to note that CO₂ concentration and atmospheric temperature would increase concurrently under the future climate changing scenarios [59]. The CO₂ fertilization effect may be modified under increased surface temperature conditions. In the present study, the increased temperature decreased the total biomass, vegetative biomass, pod number and weight, seed number and weight and harvest index of pigeonpea (Table 1). The eT+eCO₂ produced higher total and vegetative biomass, seed number and seed weight and harvest index as compared to eT. But the effects of eT and eT+eCO₂ on seed number and HI were statistically not significant. The effect of eT+eCO₂ on all these parameters was statistically similar to that of A_c except seed yield. These results clearly indicated that the elevated CO₂ ameliorated negative effect of eT on biomass and grain production in pigeonpea. Lenka et al. (2017) [60] reported higher seed yield and 100 seed weight of soybean under eT+eCO₂ over A_c and eT. In maize, the elevated temperature increased the total and vegetative biomass but decreased the grain weight thereby reduced the HI. While the eT+eCO₂ increased total and vegetative biomass and grain yield of maize (Table 1). The increased temperature reduced the reproductive biomass of maize while it improved the vegetative biomass [61]. Evaluation of climate change impact on maize yield under different N management strategies revealed that there was more reduction in yield under RCP 8.5 compared to RCP 4.5. Maize yields in sub-tropical climate of Central India in future could be improved by 3t ha⁻¹ by providing optimum dates of sowing and good management practices [62].

Conclusion

Our results revealed that

a) The eT and eT+eCO₂ maintained lower soil moisture content during most of the period of pigeonpea and maize seasons as the association of eT offset the beneficial effect of eCO₂ in reducing the evaporation component of ET.

b) Soil quality parameters such as pH, EC and CaCO₃ contents were not significantly affected by eT and eT+eCO₂.

But the activities of dehydrogenase, urease and aryl sulphatase were significantly higher with eT and eT+eCO₂. eT and eT+eCO₂ maintained the lower status of available N, P, B and Zn in post-harvest soils as compared to AC. But the available nutrient status in soils under eT and eT+eCO₂ were higher than initial nutrient status of soils which indicates buildup due to application of farmyard manure and fertilizers.

c) The eT reduced the status of SOC, MBC, labile and non-labile C in post-harvesting soils while eT+eCO₂ enhanced their status as compared to AC. Soil carbon management index was higher under eT+eCO₂ and lower in eT.

d) The eT and eT+eCO₂ had differential effects on pigeonpea and maize. In pigeonpea, total biomass, pod weight, seed yield and harvest index were significantly reduced due to eT but eT+eCO₂ produced total biomass, pod number, pod weight, seed yield, 100 seed weight and harvest index at par with that of AC. In maize, total and fodder biomass production increased with eT by 3.2% and 11.7% but grain yield reduced with eT by 10%. While the eT+eCO₂ increased total and fodder biomass and grain yield of maize.

e) Thus, these results have clearly brought out that in short-term, the eCO₂ associated with eT not only compensated negative effect of eT on soil organic matter but also produced higher yield of maize than AC and pigeonpea yield at par with AC.

f) In this study, recommended rates of farmyard manure and plant nutrients (N, P, and K) were applied to both pigeonpea and maize. Therefore, it can be concluded that the deleterious effect of elevated temperature on soil organic matter and crop production in semi-arid areas could be minimized by enhancing CO₂ fertilization through integrated and balanced nutrient management.

Conflicts of Interest

The authors declare no conflict of interest.

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