



Interactive Effect of Elevated Temperature and Carbon Dioxide on LAI and NDVI in Wheat Crop

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Climate change, characterized by elevated temperature and increased atmospheric carbon dioxide (CO₂) concentration, poses significant challenges to global agricultural systems. This study investigates the effects of elevated temperature and CO₂ on key growth parameters, including Leaf Area Index (LAI) and Normalized Difference Vegetation Index (NDVI) in wheat (*Triticum aestivum* L.). Controlled environment experiments were conducted to simulate future climate conditions, combining varying temperature regimes with elevated CO₂ level. Maximum LAI found under ECO₂ condition followed by AMB, ECT and ET respectively. LAI showed the same trend with respect to treatments irrespective of the CO₂ and temperature level i.e. SCU> NCU> NANO> CONTROL. NDVI also maximum at anthesis stage compared to maximum tillering and near maturity stage. With

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respect to fertilizer treatments, NDVI showed the same trend as LAI under different interactions of elevated CO₂ and temperature. However, higher temperatures alone negatively affected these parameters by accelerating senescence and reducing leaf expansion. When elevated CO₂ and temperature were combined, a partial mitigation of temperature stress was observed, although the extent of mitigation varied depending on the growth stage. This study highlights the complex interactions between temperature and CO₂, underscoring the need for adaptive agronomic strategies to sustain wheat productivity in changing climate.

Keywords: LAI; NDVI; elevated CO₂; elevated temperature; climate change.

1. INTRODUCTION

Agriculture is the primary sector on which majority of the Indian population relies upon and it is entirely dependent on regional climatic conditions. It is well known that changing climate definitely has an impact on global agricultural patterns and food security but the impact will vary according to regions and crops (Anderson et al., 2020). Global food production has to be accelerated by at least 50% in order to meet the estimated demand of world population by 2050 (Chakraborty et al., 2011). Meeting this projected demand has put forth the challenge in front of all researchers throughout the world. Already the concentration of major greenhouse gases like CO₂, CH₄ and N₂O are continuously increasing in the atmosphere and reached the annual averages of 410 ppm, 1866 ppb and 332 ppb respectively (IPCC AR6, 2021). Intergovernmental panel on climate change (IPCC) stated that increasing temperature of

earth surface due to global warming slightly offset by the increasing concentration of aerosol in atmosphere (cooling) but still net positive radiative forcing is there (warming). In addition to this, out of 0.43 W/m² increase in radiative forcing relative to 5th report, 0.34 W/m² is caused due to increase in GHG concentrations. Due to warming of the atmosphere, frequency of occurrence of extreme events like heat waves, flood and agricultural drought is increasing (IPCC AR6, 2021). Effect of drought on growth and yield of wheat crop is much more severe under high temperature compared to low temperature (Shah et al., 2003). Besides this phenological stages duration of wheat crop is reducing by 5.50 and 5.70 days per decade from sowing to anthesis and sowing to maturity, respectively, due to increasing temperature (Ahmed et al., 2019). Elevated temperature also hastened the crop maturity and reduced the grain yield and protein content of crop (Nuttall et al., 2017).

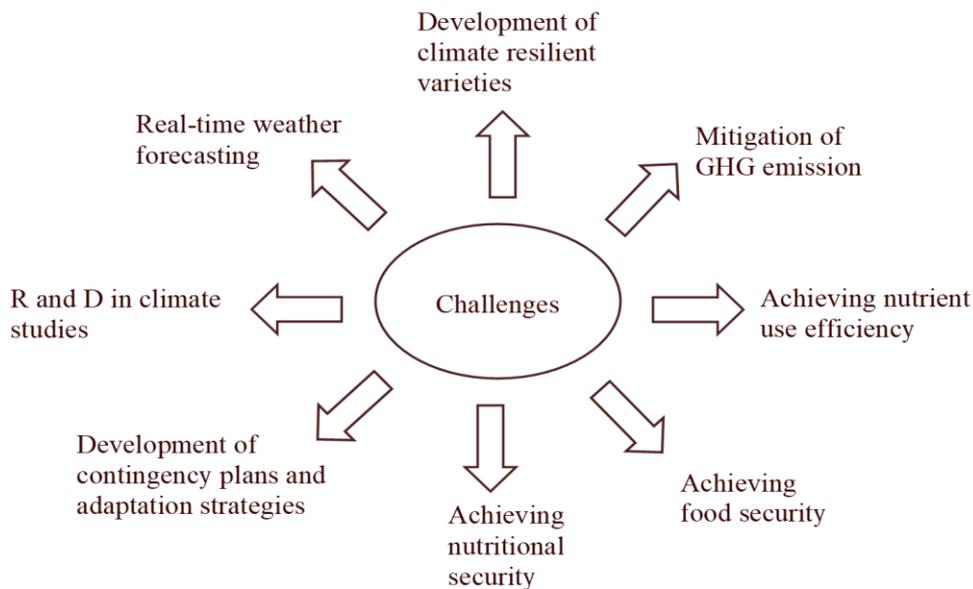


Fig. 1. The challenges faced by the agricultural sector under future CO₂ and temperature levels

Climate change is real and its impacts on human, livestock, agriculture and environment is clearly visible on the earth. Elevated atmospheric CO₂ is a major component of climate change and has increased from the pre-industrial level of 280 ppm to 415 ppm at present. Air temperature is an important factor determining the spatiotemporal patterns of phenology of wheat crop (Ren et al., 2019). Variations in the temperature leads to uncertainties in the global rainfall pattern which may have an impact on the yield of the wheat crop (Gul et al., 2020). For each degree rise in temperature, 7% decrease in the wheat yield was reported by Fatima et al., (2020). On the other hand, increasing CO₂ levels are known to be beneficial for crop growth and improving the crop yields (Yadav et al., 2021). However, consistent yield reduction in wheat was predicted for many parts of Mexico due to increasing temperature despite the stimulating effect of elevated CO₂ concentrations (Hernandez – Ochoa et al., 2018). Increasing CO₂ concentration in the atmosphere has increased the plant growth and productivity but interactive effect of both elevated CO₂ and temperature is poorly studied (Pan et al., 2018; Zarnetske et al., 2021). There are various studies on growth parameters like photosynthetic rate and stomatal conductance (Wang et al., 2020, Huang et al., 2021) and yield of different crops (Ben mariem et al., 2021, Lenka et al., 2021). But very studies focused on LAI and NDVI which are indirectly helps us to know about photosynthesis efficiency and carbohydrate assimilation (Parida et al., 2024). Hence this study was conducted with the objective:

To measure the LAI and NDVI of wheat crop at different crop growth stages in different fertilizer treatments under interactions of elevated temperature and CO₂.

2. MATERIALS AND METHODS

The present work was carried out at an experimental field of Division of Environmental Sciences, ICAR-Indian Agricultural Research Institute (IARI), New delhi.

Details of materials used and methods followed in the study are described below:

2.1 Study Area

The experiment work was carried out at Genetic-H field of Division of Environmental sciences, IARI-New Delhi. The experiment field is situated at 28°35' N and 77°12' E, at an altitude of 228 m above mean sea level. The region has semi-arid and subtropical type of climate with mean annual rainfall of 750 mm.

2.2 Experimental Setup

Wheat crop (HD2967) was taken for experiment during the Rabi season of the year 2021-2022 during November-April in free air temperature and carbon dioxide enrichment facility (T-FACE) under two levels of temperature (Elevated+ ambient) and two levels of carbon dioxide (Elevated+ ambient).

Four different fertilizer treatments of neem coated urea (NCU), sulphur coated urea (SCU), liquid Nano-urea (Nano) and no fertilizer (Control) were applied to each of the T-FACE rings. The whole experiment was conducted in a Completely Randomised design (CRD). Both P and K fertilizer applied only as basal dose i.e. DAP and MOP respectively. Total amount of N fertilizer applied was 120 kg ha⁻¹. Nitrogen applied in 3 split doses as 33% at each crop growth stage i.e. 40 kg ha⁻¹ at Crown root initiation stage (21DAS), Tillingering stage (62DAS) and Booting stage (85DAS) respectively.



Fig. 2. wheat crop grown in T-FACE facility at Genetic-H field, ICAR-IARI, New Delhi

2.3 Experiment Details

Each T-FACE ring had a circular area of 28m². The experimental area was divided into four different quadrants to take the four different fertilizer treatments viz. NCU, SCU, Nano and control. Two levels of temperature: ambient and elevated (ambient +1.5°C) and two levels of CO₂ concentrations: ambient (398-418 ppm CO₂) and elevated (550±25 ppm of CO₂) was maintained in the rings. In order to study the interactive effects of both CO₂ and temperature along with different N fertilizer, four interactive levels were taken viz. 1. Elevated CO₂ and ambient temperature (EC), 2. Elevated CO₂ and elevated temperature (ECT), 3. Ambient CO₂ and ambient temperature (AMB), 4. Ambient CO₂ and elevated temperature (ET). Required concentration of CO₂ was maintained inside the free air temperature (FACE) rings using rota meters and solenoid valves. The temperature inside the free air temperature (FATE) and free air temperature and carbon dioxide (T-FACE) rings was elevated using infra-red heaters. An infra-red radiometer (Apogee SI-111) was used for monitoring the canopy temperature inside each of the rings. There were total 16 different treatment under 4 different temperature and CO₂ interactions.

FACE system is for elevated CO₂ concentration (EC), FATE for elevated temperature (ET), TFACE for both elevated temperature and elevated CO₂ (ECT), AMB is normal field condition.

2.4 Crop Management

Wheat crop (variety- HD2967) was grown inside the T-FACE rings (Fig. 2) in Rabi season of the

year 2021 during November month at Genetic-H field, IARI- New delhi. The crop was sown manually on 15th November at a seed rate of 10g/m² at a spacing of 15cm*10 cm. Recommended dose of phosphorous was applied through Di ammonium phosphate (10g/m²) and potassium was applied as Muriate of potassium (6g/m²) as a basal dose as soil application. Recommended dose was applied only to provide the minimum nutrient requirement of crop i.e. 120:60:60 kg ha⁻¹. NCU (Neem coated urea), SCU (Sulphur coated urea), liquid Nano Urea (IFFCO developed) and control (No N fertilizer) were the four fertilizer treatments taken in each of the T- FACE rings. The different nitrogen (N) fertilizers were applied in 3 split doses at crown root initiation (CRI), tillering and booting stages, respectively. Each split of N fertilizer was applied @ 40 kg according to the different treatments. Treatments details are given in Table 2.

2.5 Canopy Analyzer and Green Seeker Recordings

Leaf area index was calculated by using canopy analyser and readings are taken at maximum tillering and anthesis stages. Besides this NDVI (Normalized Difference Vegetation Index) values for each treatment are taken by using handheld green seeker at maximum tillering and anthesis stages of wheat.

$$NDVI = (NIR-Red) / (NIR+ Red)$$

Where NIR and Red is near infra-red and visible red light respectively.

Table 1. Treatment details

T1	Elevated CO ₂ and ambient temperature - NCU
T2	Elevated CO ₂ and ambient temperature - SCU
T3	Elevated CO ₂ and ambient temperature – Nano liquid urea
T4	Elevated CO ₂ and ambient temperature - Control
T5	Elevated CO ₂ and elevated temperature - NCU
T6	Elevated CO ₂ and elevated temperature - SCU
T7	Elevated CO ₂ and elevated temperature - Nano liquid urea
T8	Elevated CO ₂ and elevated temperature - control
T9	Ambient CO ₂ and ambient temperature - NCU
T10	Ambient CO ₂ and ambient temperature - SCU
T11	Ambient CO ₂ and ambient temperature – Nano liquid urea
T12	Ambient CO ₂ and ambient temperature - Control
T13	Ambient CO ₂ and Elevated Temperature -NCU
T14	Ambient CO ₂ and Elevated Temperature -SCU
T15	Ambient CO ₂ and Elevated Temperature - Nano liquid urea
T16	Ambient CO ₂ and Elevated Temperature - control



Fig. 3. Using the canopy analyser and green seeker at Genetic-H field, IARI-New delhi

2.6 Statistical Analysis

The design of the experiment was completely randomized design (CRD). There were total 16 treatments with 3 replications. The data obtained from the treatments were analyzed using SPSS software. Analysis of variance was done to test whether the differences were statistically significant. The differences were considered significant at $P \leq 0.05$.

3. RESULTS

3.1 Leaf area index (LAI)

LAI was measured four times (T1= 57DAS, T2= 73DAS, T3= 87DAS, T4= 114DAS) during the entire crop duration by using a Canopy analyzer. LAI showed the same trend with respect to all N fertilizers along with control irrespective of the CO₂ and temperature levels i.e. SCU > NCU > NANO > Control (Fig. 4). SCU treatment recorded highest values under all interactions with increasing values from 57- 87 DAS and thereafter value decreased compared to 87DAS (Table 2). Highest LAI recorded under SCU at 87DAS in decreasing order was EC > AMB > ECT > ET (Fig. 4). Maximum LAI was recorded in SCU treatment under ECO₂ condition at 87DAS i.e. 5.36 and minimum at 57DAS in control treatment under ECT condition i.e. 2.10 (Table 2). Highest values of LAI were recorded under EC conditions irrespective of the treatments and days after sowing. Lowest LAI was recorded at 57DAS irrespective of the treatments and days after sowing. LAI values reached peak around anthesis stage (Patel et al., 2011).

3.2 Normalized Difference Vegetation Index (NDVI)

NDVI values were directly recorded by using the Green Seeker instrument at three different crop

growth stages i.e. at maximum tillering, anthesis and near maturity stage in wheat crop. Highest NDVI values were observed at the anthesis stage. Overall NDVI values ranged from 0.51-0.83 (Table: 3). Highest NDVI values were recorded in the SCU treatment under EC condition at all the stages as compared to other treatments. Maximum greenness showed at anthesis stage irrespective of the treatments and CO₂, temperature levels while minimum at near maturity stage. Maximum NDVI value recorded in SCU under EC condition at anthesis stage i.e. 0.83. Minimum NDVI value recorded in control treatment under ECT condition at near maturity stage i.e. 0.51. Higher NDVI values are recorded under SCU treatment in contrasting to control irrespective of CO₂ and temperature levels (Table:3). Nano and NCU showed average performance under all the levels of CO₂ and temperature at all the stages by considering SCU and control performance as two extremes. Both LAI and NDVI decreased under elevated temperature condition (ET) due to accelerated phenological development and increased stress, which limits the crop's photosynthetic capacity and biomass accumulation.

4. DISCUSSION

Growth of wheat crop was measured in terms of leaf area index (LAI), normalized difference vegetation index (NDVI) at maximum tillering and anthesis stage. Both LAI and NDVI values were higher under elevated CO₂ concentrations and resulted in higher total dry matter (Han et al., 2023). SCU showed the highest total biomass which was 73% greater than the control under EC condition. This is may be due to slow release property of Sulphur coating made nutrient gradually available to the crop, therefore, good growth of crop and increased leaf area were reflected in NDVI and LAI respectively. In contrast, the control recorded lowest total

biomass under ET condition which was 32%, 37% and 28% less than NCU, SCU and NANO respectively due to the negative effect of temperature and no nutrient was applied in this treatment which was also recorded lowest NDVI and LAI. The LAI was observed to be higher under EC treatment in our study. Increasing CO₂ concentrations under FACE system has been reported to increase the LAI by 4 up to 22% with increased N supply in wheat crop (Dier et al., 2018). Normalized difference vegetation index (NDVI) usually measures the reflectance in NIR region. Higher reflectance means higher canopy cover which has higher NDVI value (Venkatesh et al., 2022). In our study too higher NDVI was observed under EC. Among the fertilizers SCU performed the best under EC condition. The slow release of coated fertilizer enabled higher plant

uptake of N resulting in higher NDVI and LAI in this treatment. However, elevated CO₂ often counteracts some of these adverse effects by enhancing photosynthesis due to CO₂ enrichment and water-use efficiency by closing stomata, leading to an increase in LAI and NDVI under ECT compared to ET alone (Table 2&3) because lower stomata conductance was reported in all fertilizer treatments under ECT in the range of 0.17-0.25 mmol/m²/s compared to ET. Understanding these interactions is crucial for predicting the performance of wheat under future climate scenarios and for developing adaptive management strategies, such as optimizing planting dates, selecting heat-tolerant varieties, and adjusting irrigation practices, to sustain productivity (Ahmad et al., 2019).

Table 2. LAI of different N fertilizers under interaction of elevated CO₂ and elevated temperature

N Fertilizer	Ambient CO ₂		Elevated CO ₂	
	Ambient temp.	Elevated temp.	Ambient temp.	Elevated temp.
NCU	2.98	2.79	3.19	2.82
SCU	3.00	2.78	3.45	2.81
NANO-UREA	2.66	2.41	2.98	2.37
CONTROL	2.20	2.12	2.16	2.10
Mean (57DAS)	2.71	2.53	2.95	2.52
CD (p≤0.05)	CO ₂ : NS; Temp: NS; Fertilizer: 0.27; CO ₂ X temp: NS; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			
NCU	3.21	2.90	3.35	2.96
SCU	3.43	3.10	3.53	3.14
NANO-UREA	2.89	2.61	3.01	2.67
CONTROL	2.03	2.14	2.25	2.16
Mean (73DAS)	2.89	2.69	3.04	2.73
CD (p≤0.05)	CO ₂ : NS; Temp: NS; Fertilizer: 0.27; CO ₂ X temp: NS; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			
NCU	4.81	4.10	4.97	4.74
SCU	5.11	4.64	5.36	5.05
NANO-UREA	4.05	3.85	4.48	4.17
CONTROL	2.79	3.09	3.15	3.10
Mean (87DAS)	4.19	3.92	4.49	4.26
CD (p≤0.05)	CO ₂ : NS; Temp: NS; Fertilizer: 0.27; CO ₂ X temp: NS; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			
NCU	4.36	4.08	4.57	4.30
SCU	4.56	4.29	4.79	4.35
NANO-UREA	4.08	3.62	3.91	3.94
CONTROL	2.55	2.73	2.85	2.77
Mean (114DAS)	3.89	3.68	4.03	3.84
CD (p≤0.05)	CO ₂ : NS; Temp: NS; Fertilizer: 0.27; CO ₂ X temp: NS; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			

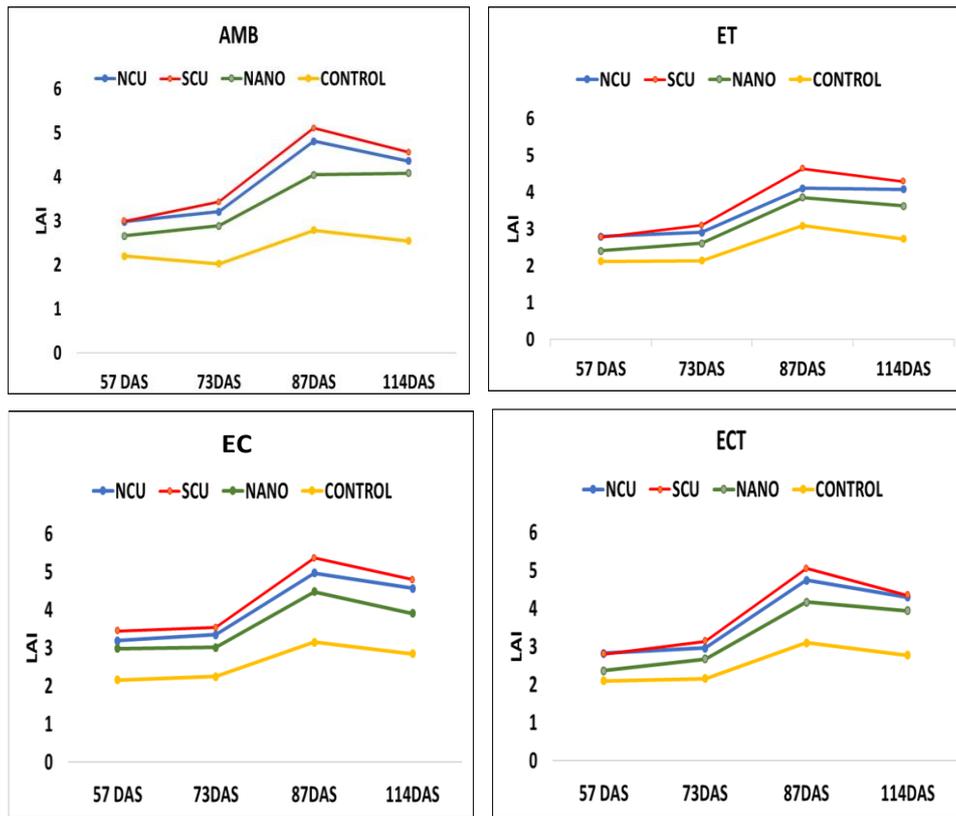


Fig. 4. Leaf area index of different treatments under ambient CO₂ and ambient temperature condition on different days after sowing

Table 3. NDVI values of different treatments under interaction of elevated CO₂, temperature and N fertilizer in wheat crop taken through Green seeker at three different crop growth stages

N Fertilizer	Ambient CO ₂		Elevated CO ₂	
	Ambient temp.	Elevated temp.	Ambient temp.	Elevated temp.
NCU	0.75	0.71	0.77	0.73
SCU	0.78	0.73	0.81	0.77
NANO-UREA	0.74	0.70	0.79	0.71
CONTROL	0.59	0.57	0.65	0.57
Mean (max tillering)	0.71	0.68	0.76	0.70
CD (p≤0.05)	CO ₂ : 0.03; Temp: NS; Fertilizer: 0.04; CO ₂ X temp: 0.04; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			
NCU	0.78	0.76	0.80	0.73
SCU	0.82	0.78	0.83	0.76
NANO-UREA	0.68	0.69	0.71	0.68
CONTROL	0.57	0.57	0.68	0.59
Mean (Anthesis)	0.71	0.70	0.76	0.69
CD (p≤0.05)	CO ₂ : 0.03; Temp: NS; Fertilizer: 0.04; CO ₂ X temp: 0.04; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			
NCU	0.71	0.68	0.74	0.69
SCU	0.75	0.72	0.77	0.70
NANO-UREA	0.65	0.62	0.66	0.62
CONTROL	0.53	0.52	0.56	0.51
Mean (near maturity)	0.66	0.64	0.68	0.63
CD (p≤0.05)	CO ₂ : NS; Temp: NS; Fertilizer: 0.05; CO ₂ X temp: 0.05; CO ₂ X Fertilizer: NS; Temp X fertilizer: NS; CO ₂ X Temp X Fertilizer: NS			

5. CONCLUSION

Study showed that elevated carbon dioxide enhances both LAI and NDVI, leading to greater total dry matter production. Total biomass recorded under different interactions irrespective of the treatments was in the order of EC> AMB> ECT> ET. The use of slow-release fertilizers, such as sulphur-coated urea (SCU), has shown improved performance under EC conditions. The gradual release of nutrients enhances N uptake, contributing to higher LAI and NDVI. Conversely, ET often reduces these indices due to stress-induced physiological limitations. Understanding the interaction between EC, ET, and nutrient management is vital for predicting wheat performance under future climate scenarios. Adaptive strategies, including the development of heat-tolerant cultivars, optimization of fertilizer use, and modification of agronomic practices, are essential for sustaining productivity in the face of climate change. The Variety HD2967 which we selected for our experiment also a heat tolerant variety showed good performance with respect to growth and yield parameters under SCU treatment in all CO₂ and temperature treatments whereas NANO treatment recorded less yield and growth parameters i.e. LAI and NDVI due to less amount of nutrient uptake and volatilization losses under elevated temperature and wind movement.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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