Exploration of a novel geoengineering solution: lighting up tropical forests at night

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Abstract

Plants primarily conduct photosynthesis in the daytime, offering an opportunity to increase photosynthesis and carbon sink by providing light at night. We used a fully coupled Earth System Model to quantify the carbon sequestration and climate effects of a novel carbon removal proposal: lighting up tropical forests at night via lamp networks above the forest canopy. Simulation results show that additional light increased tropical forest carbon sink by 10.4±0.05 petagrams of carbon per year during a 16-year lighting experiment, resulting in a decrease in atmospheric CO_2 and suppression of global warming. In addition, local temperature and precipitation increased. The energy requirement for capturing one ton of carbon is lower than that of Direct Air Carbon Capture. When the lighting experiment was terminated, tropical forests started to release carbon slowly. This study suggests that lighting up tropical forests at night could be an emergency solution to climate change, and carbon removal actions focused on enhancing ecosystem productivity by altering environmental factors in the short term could induce post-action CO_2 outgassing.

Short summary

Numerical experiments with a coupled Earth System Model show that large-scale nighttime artificial lighting in tropical forests will significantly increase carbon sink, local temperature, and precipitation, and requires less energy than Direct Air Carbon Capture for capturing 1 ton carbon, suggesting that it could be a powerful climate mitigation option. Side effects include the CO_2 outgassing after the termination of the nighttime lighting and the impacts on local wildlife.

Keywords: climate change; Earth system model; geoengineering; carbon cycle; tropical forests

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions have led the global mean temperature to increase by approximately 1.1 degree Celsius since the industrial revolution(IPCC, 2013, 2018; IPCC AR6 WGI, 2021). Changes in climate have caused impacts on natural ecosystems and human societies, such as mass ice sheet melt(Jevrejeva et al., 2016), devastating heat waves(Dosio et al., 2018), and increase in extreme climate events(Kirchmeier-Young and Zhang, 2020), exposing natural and human systems to uncertainties and the risks of unsustainable development(Gao et al., 2019, 2020). Despite the scientific consensus on climate change, emission-reduction efforts have made slow or little progress with global GHG emissions continuing to rise(IPCC AR6 WGI, 2021). In this context, geoengineering options are increasingly being considered as means of deliberately intervening in Earth's climate system in the second half of the 21st century(IPCC AR6 WGI, 2021; Moore et al., 2015).

Existing geoengineering proposals tend to align with two fundamentally different strategies: Solar Geoengineering (SG)(Abatayo et al., 2020; Proctor et al., 2018; Robock et al., 2009) and Carbon Capture and Sequestration (CCS)(IPCC, 2005; Jones, 2008; Leung et al., 2014). SG and related techniques reduce the amount of incoming radiation from the sun typically via stratospheric aerosol injection, subsequently affecting the planet's temperature. Although they may be able to offset temperature increase rapidly, previous studies indicate the potential for political instability(Abatayo et al., 2020) and negative impacts on human health(Robock et al., 2009) and agriculture(Proctor et al., 2018). Comparatively, CCS removes carbon from the global carbon cycle by artificial machines and saves it for long-term storage or for industrial reutilization(IPCC, 2005). While technically feasible, the environmental risks for the transport and storage of CO_2, limited carbon storage capability, and high cost remain large obstacles of implementing CCS(IPCC, 2005; Jones, 2008; Leung et al., 2014).

In this study, the authors propose a novel geoengineering solution: lighting up tropical forests at night by installing lamp networks above the forest canopy(Graham et al., 2003), which lengthens photoperiods and leads to greater photosynthesis and carbon sequestration, and helps mitigate climate change. Contrasting to traditional CCS techniques, this strategy utilizes nature carbon sink to capture and sequester CO_2 from air and avoids long-distance transport and geological storage.

Structurally intact tropical forests are by far the most efficient carbon-capture method(Mitchard, 2018), and they act as an important carbon sink against rising CO_2 levels(Pan et al., 2011;

Sullivan et al., 2020). Although intact tropical forest growth is likely suffering from warming and moisture stress induced by anthropogenic greenhouse gas emissions(Aguirre-Gutiérrez et al., 2020; Doughty et al., 2015; Gatti et al., 2021; Hubau et al., 2020), light is still the primary factor limiting tropical tree growth due to cloud cover, especially during the rainy season(Boisvenue and Running, 2006; Graham et al., 2003). Studies on the photoperiodic control of tropical trees' growth typically fall into two categories: physiological field observations under seasonal variations of day length(Borchert et al., 2005; Pires et al., 2018; Rivera et al., 2002), and physiological greenhouse observations under experimental variations of the photoperiod(Dixit and Singh, 2014; Djerrab et al., 2021; Luo et al., 2021; Stubblebine et al., 1978). Field observations have shown that longer photoperiods facilitate the bud break and flowering in tropical forests(Borchert et al., 2005; Pires et al., 2018; Rivera et al., 2002). Greenhouse experiments either lengthen or shorten photoperiods, and results suggest that short photoperiods reduce plant growth rate and lead to thinner leaves and lower chlorophyll content(Djerrab et al., 2021; Luo et al., 2021), while long photoperiods increase stem growth rate and stimulate tree growth(Dixit and Singh, 2014; Stubblebine et al., 1978). These studies are more focused on specific tropical plant species and tend to agree that longer photoperiods might have a positive effect on vegetative growth in tropical forests. Ecosystem-level field experiments are critical for taking into account key environmental factors that are missing in greenhouse experiments (e.g. water and nutrition constraints), and for informing model parameterizations, although they are lacking so far.

Earth System Models provides state-of-the-art computer simulations of key processes and climate states across the Earth(Danabasoglu et al., 2020). In this study the authors used a fully coupled Earth System Model, Community Earth System Model version 2 (CESM2) developed by the U.S. National Center for Atmospheric Research(Danabasoglu et al., 2020), to test the carbon sequestration and climate effects of this geoengineering measure by conducting numerical lighting experiments. Briefly, we added additional diffuse visible light to tropical forest canopy at night (see Supplementary Figure 1) assuming that trees will receive light from multiple directions (e.g., multiple lamps). Tropical forest grids were defined by "Broadleaf Evergreen Tree Area Percentage" being greater than 60% between 20°N and 20°S. The lighting experiment started from 12:00 am on January 1st, 2015 (UTC time), and the simulation exercise was conducted across numerous timescales and lighting levels:

(1) Historical control simulation from 2001 to 2014
(2) 24-hour lighting experiment with various lighting powers on January 1st, 2015

(3) 16-year lighting experiment with the optimal lighting power from 2015 to 2030
(4) 20-year simulation after the experiment termination from 2031 to 2050
(5) Future control simulation from 2015 to 2050

Both experiment and control simulations in the future from 2015 to 2050 were on top of the Shared Socioeconomic Pathways (SSP) 126 scenario(Riahi et al., 2017). Each simulation has a spatial resolution of 1° and has two members (created from small perturbations to initial conditions) to provide uncertainty estimation. (See Methods for detailed experimental design)

2. Methods

The CESM2 is an open-source community coupled model consisting of atmosphere, ocean, land, sea-ice, land-ice, river, and wave models that exchange states and fluxes via a coupler(Danabasoglu et al., 2020). In this study, we used standard CESM2 configurations and enabled all modules including the Community Atmosphere Model version 6 (CAM6), the Parallel Ocean Program version 2 (POP2) with an ocean biogeochemistry component, the Community Land Model version 5 (CLM5) with a land biogeochemistry component, CICE version 5.1.2 (CICE5), the Community Ice Sheet Model Version 2.1 (CISM2.1), the Model for Scale Adaptive River Transport (MOSART), and the NOAA WaveWatch-III ocean surface wave prediction model version 3.14 (WW3). The CESM2 is part of the Couple Model Intercomparison Project Phase 6 (CMIP6) core simulations as well as about 20 Model Intercomparison Projects (MIPs) within CMIP6. Extensive evaluation suggests that the CESM2 simulations exhibit agreement with satellite era observations of the climate mean state, seasonal cycle, and interannual variability, which has identified CESM2 as among the most realistic climate models in the world(Danabasoglu et al., 2020).

2.1 Historical control simulations from 2001 to 2014

CESM2 has published its official historical simulation datasets from 1850-2014 on the Earth System Grid Federation (ESGF; https://esgf-node.llnl.gov/search/cmip6). This study analyzed the historical simulation datasets of two members from 2001 to 2014 produced by the CESM2 esm-hist-BPRP case.

2.2 Future experiment and control simulations from 2015 to 2050

The selection of 2015 as the start year of the lighting experiment follows CMIP6 future scenario simulation rules. The future experiment simulations and control simulations were both based on the Shared Socioeconomic Pathways (SSP) 126 scenario(Riahi et al., 2017), which is a low-emission (low fossil fuel combustion and deforestation) scenario. The Earth's climate state under SSP126 is close to the current climate state with respect to high-emission scenarios. Therefore, the selection of SSP126 controlled variables and allowed us to see how the lighting experiment along influences tropical forest carbon fluxes and climate. This study ran the CESM2 esm-SSP126-BPRP case with the official restart files from historical simulations (esm-hist-BPRP case). Thus, no model spin up was needed. All simulations were forced with specified greenhouse gas emissions rather than atmospheric greenhouse gas concentrations, so the atmospheric CO_2 concentration was prognostic and land and ocean carbon cycles feed back on atmospheric CO_2. Each simulation has a nominal horizontal resolution of 1° and has two members created from small perturbations to initial climate states to estimate uncertainties.

2.3 The lighting experiment design

The authors modified the radiation module (Rapid Radiative Transfer Model for General circulation models, RRTMG) of CESM2 to add diffuse visible light to tropical forest canopy at night. CESM2 determines if a grid column is at daytime or nighttime by calculating its cosine (solar zenith angle) at each time step. A negative cosine indicates the grid column is at nighttime and the incoming solar radiation would be assigned with zero. A positive cosine indicates daytime, and the cosine value would be used to calculate incoming solar radiation. The land module then calculates and passes the surface albedo to the atmosphere module and the atmosphere module calculates the radiation fluxes with the surface albedo and the model-calculated incoming solar radiation. We made modifications in all active modules to switch the sign of tropical forests' cosine from negative to positive when tropical forests were at night. As a result, all modules regarded tropical forests to be at daytime at every time step.

CESM2 divides the incoming solar radiation into four components: direct visible light, diffuse visible light, direct near infrared light, and diffuse near infrared light. The authors assume that the artificial light would be provided by a lamp network above the forest canopy and that trees receive light from multiple directions. Therefore, the artificial light was specified as diffuse visible light for simplification. In the model, we assigned the diffuse visible light component of the incoming solar radiation with 100, 200, 300, or 400 and other components with 0. The surface albedo was still calculated by the land module and passed to the atmosphere module. The radiation fluxes were then calculated by the model-calculated surface albedo and manually-specified solar insolation.

2.4 The calculation of the energy requirement for capturing one ton of carbon

$$E = (Power \times Area \times Hours)/Carbon \tag{1}$$

where E is the energy requirement for capturing one ton of carbon per year; Power is 200W/m^2 (nighttime lighting power); Area is the tropical forest area 10.71×10^{10}m^2 (CESM2 output); Hours is the amount of nighttime lighting hours per year: 365×11; Carbon is the net carbon uptake per year (Fig. 2-f) simulated by CESM2. There is no assumed data in this calculation.

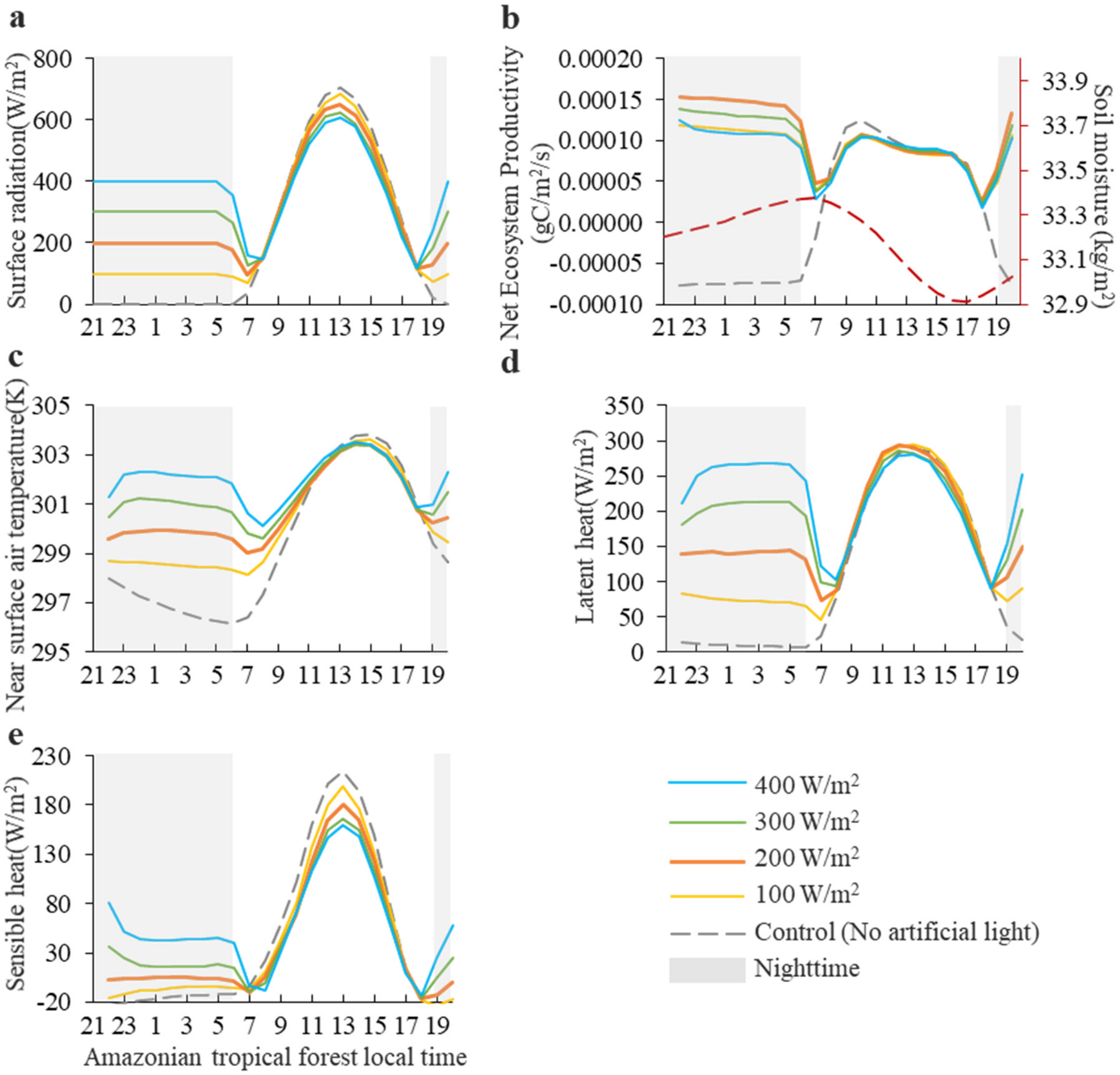
3. Results

3.1 24-hour lighting experiment with various lighting powers on January 1st 2015

Figure 1 shows the changes in carbon and energy fluxes of Amazonian tropical forests for 24 hours since the start of the nighttime lighting experiment at 12:00 am January 1st, 2015 (UTC time; See Supplementary Figure 2 and 3 for African and Asian tropical forest responses). Tropical forests had a significant response to nighttime radiation, but the response was different under 100, 200, 300, and 400 W/m^2 lighting powers. The lighting experiment altered the nighttime energy balance and increased near surface air temperature, latent heat, and sensible heat. Higher lighting powers led to greater increases in air temperature, latent heat and sensible heat. Meanwhile, the additional light activated photosynthesis and increased Net Ecosystem Productivity (NEP). Nighttime NEP reached the peak at $200W/m^2$ and seemed to be suppressed when the lighting power was higher. Comparison of NEP across lighting powers suggests that $200W/m^2$ is optimal in terms of activating additional photosynthesis. The nighttime NEP is higher than daytime because nighttime surface radiation is solely diffuse visible light while daytime surface radiation is composed of direct NIR (~16%), diffuse NIR (~30%), direct visible light (~15%), and diffuse visible light (~39%). African and Asian tropical forests showed similar responses.

During daytime in the control simulation, the maximum NEP shows up around 9:00-11:00 am (Fig. 1-b). It is not likely to be due to clouds according to the diurnal pattern of the surface downward shortwave radiation (Fig.1-a). We examined the diurnal curve of the soil moisture (the red dash line in Fig. 1-b), and it seems to be due to soil moisture stress. Soil moisture was consumed quickly in the morning which led to water stress for plant growth in the afternoon. The soil moisture pattern also explains the biased distribution of daytime surface air temperature (Fig.1-c), and slightly biased daytime latent heat (Fig.1-d), and daytime sensible heat (Fig.1-e).

Fig. 1. Amazonian tropical forest responses for 24 hours since the start of the nighttime lighting experiment at 12:00 am January 1st, 2015 (UTC time) under various nighttime lighting powers. Panel (a) refers to surface downward shortwave radiation. Nighttime NEP (b) reached the peak at 200W/m^2, suggesting that 200W/m^2 is optimal in terms of activating additional photosynthesis.



3.2 16-year lighting experiment with the optimal lighting power from 2015 to 2030

The yellow lines in Figure 2 show that tropical forest carbon fluxes and climates were significantly altered by a 16-year continuous lighting experiment at night with a 200W/m^2 power. The annual gross primary production and autotrophic respiration increased by twice near instantaneously, while the heterotrophic respiration had a slower response and increased continuously over a longer period. We purport these changes to be due to the increase in local temperature and the gradual accumulation of organic matter in the soil. Simulation results show that the lighting experiment also decreased wildfire emissions as soil moisture increased despite the expansion of the coarse woody debris and litter carbon pool that provides potential burning materials. Overall, the net carbon uptake increased to around 25 petagrams of carbon per year (Pg C yr^{-1}) in the beginning of the lighting experiment, although it decreased with time due to the continuous increase in heterotrophic respiration. The lighting experiment increased the net carbon uptake in tropical forests by 15.3 times over the simulation period (from 0.68±0.02 Pg C yr^{-1} over 2001-2014 to 11.1±0.05 Pg C yr^{-1} over 2015-2030). Among all the absorbed carbon, 75% entered the vegetation carbon pool, 16% entered the coarse woody debris and litter carbon pool, and 9% entered the soil carbon pool (Figure 3-b).

Simulation results show that local climates were also significantly impacted (Figure 2-g,h). The annual average air temperature increased by around 1.3℃, and annual precipitation almost doubled. The temperature and precipitation increase showed no significant seasonal trend (Supplementary Figure 4). Globally, the atmospheric CO_2 concentration dropped quickly in the first several years, while turned flat in the latter of the lighting experiment. As a result, the global average air temperature increase was suppressed by around 0.5℃.

Amazonian, African, and Asian tropical forests present different capabilities to offset annual atmospheric carbon accumulation during the lighting experiment (Figure 4). In the current global carbon budget(Friedlingstein et al., 2019) (averaged from 2009 to 2018), approximately 11±0.5 Pg C yr^{-1} was released into atmosphere by anthropogenic activities including fossil fuel combustion and land use, among which 2.5±0.6 Pg C yr^{-1} was absorbed by ocean, 3.2±0.6 Pg C yr^{-1} was absorbed by land, and 4.9±0.02 Pg C yr^{-1} was accumulated in atmosphere resulting in the concerned warming and climate change. The lighting experiment enhanced Amazonian tropical forest net carbon uptake to 6.5±0.04 Pg C yr^{-1} (averaged during 2015 to 2030), suggesting that lighting up Amazonian tropical forests along could completely offset anthropogenic carbon emissions. African and Asian tropical forests showed lower capabilities with the net carbon uptake being approximately 2.0 ± 0.002 and 2.6 ± 0.008 Pg C yr^{-1} respectively (see Supplementary Figure 5, 6, and 7 for Amazonian, African, and Asian tropical forest carbon flux, carbon amount, and climate responses respectively).

Fig. 2. Global tropical forest carbon flux and climate responses under and after the lighting experiment. Ta in panel (g & k): Near surface air temperature. Soil moisture in Panel (i) refers to the mass of water in the 10cm soil surface. Shaded areas represent uncertainties.

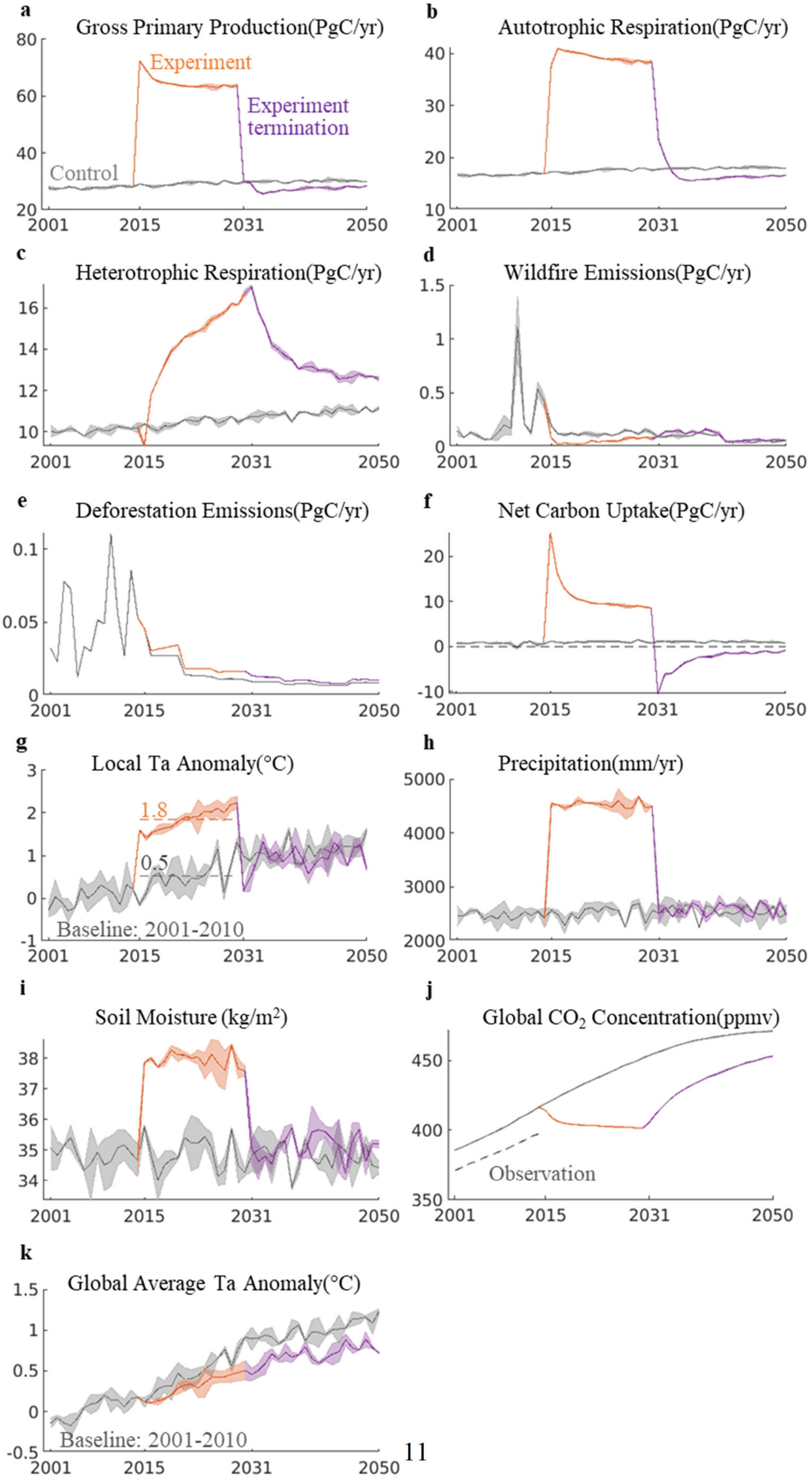

a
Gross Primary Production(PgC/yr)
80
60
40
20
Experiment
Experiment termination
Control
2001
2015
2031
2050
b
Autotrophic Respiration(PgC/yr)
40
30
20
10
2001
2015
2031
2050
c
Heterotrophic Respiration(PgC/yr)
16
14
12
10
2001
2015
2031
2050
d
Wildfire Emissions(PgC/yr)
1.5
1
0.5
0
2001
2015
2031
2050
e
Deforestation Emissions(PgC/yr)
0.1
0.05
0
2001
2015
2031
2050
f
Net Carbon Uptake(PgC/yr)
20
10
0
-10
2001
2015
2031
2050
g
Local Ta Anomaly(°C)
3
2
1
0
-1
1.8
0.5
Baseline: 2001-2010
2001
2015
2031
2050
h
Precipitation(mm/yr)
5000
4000
3000
2000
2001
2015
2031
2050
i
Soil Moisture (kg/m²)
38
37
36
35
34
2001
2015
2031
2050
j
Global CO₂ Concentration(ppmv)
450
400
350
Observation
2001
2015
2031
2050
k
Global Average Ta Anomaly(°C)
1.5
1
0.5
0
-0.5
Baseline: 2001-2010
2001
2015
2031
2050

Fig. 3. Where Did the Net Absorbed Carbon Go? Global Tropical Forest Carbon Amount Responses. Panel (a): the current carbon amount in different carbon pools. Panel (b): carbon amount in 2030 after 16-year lighting experiments. Panel (c): carbon amount in 2050 after 20 years since the termination of the lighting experiments. The solid circles in panel (b) and (c) refer to carbon amount changes with respect to panel (a). The numbers in panels (a-c) are based on panels (d-f). Tree drawing courtesy of © Ning Zeng.

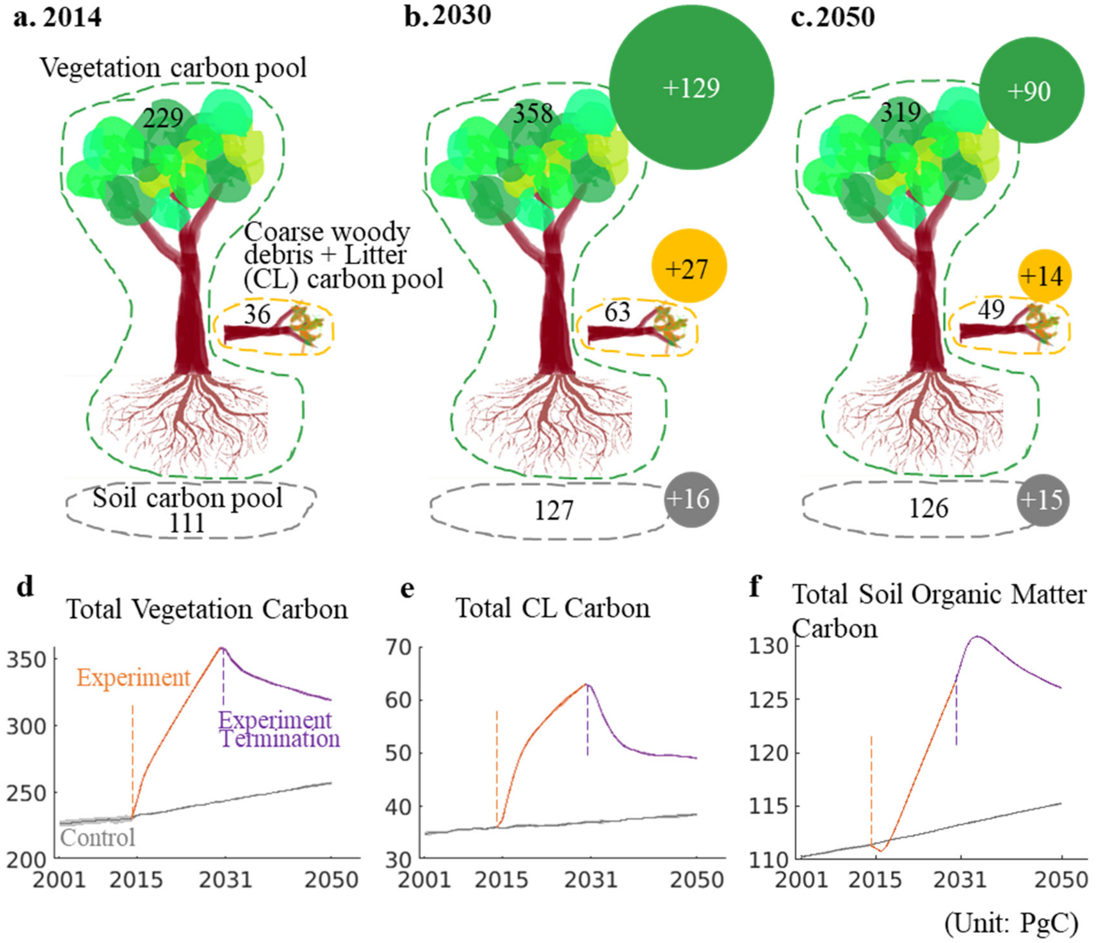
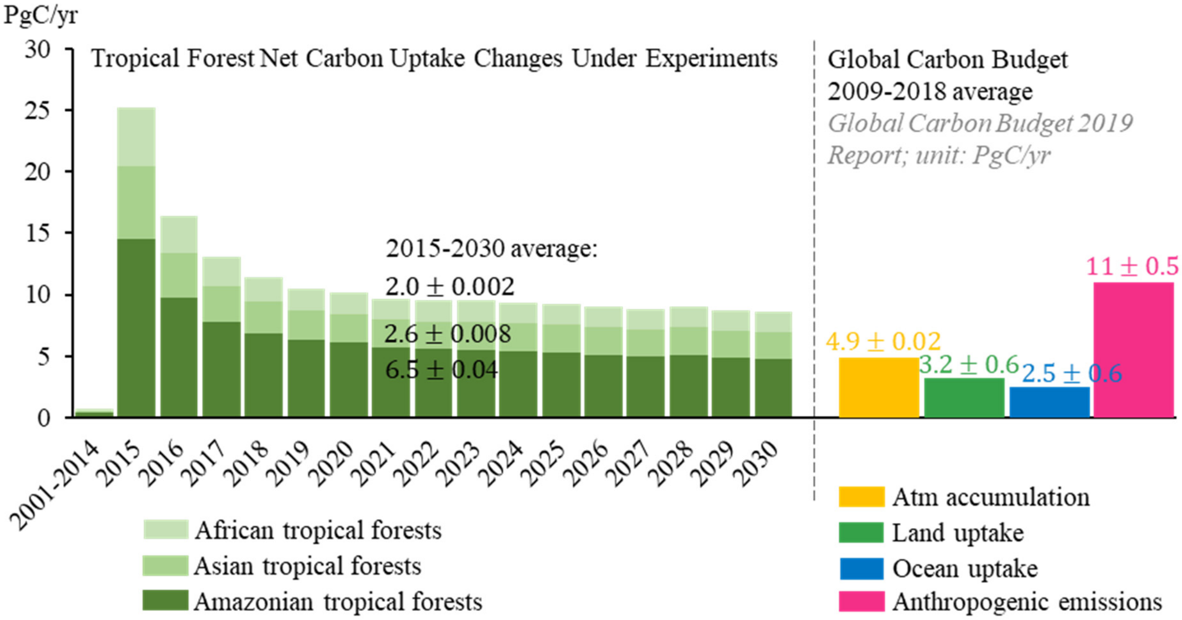
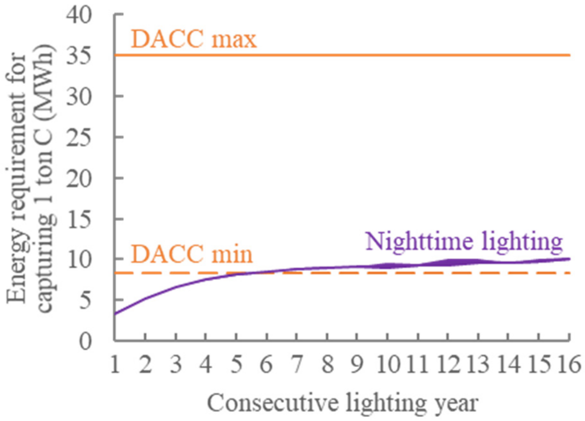


Fig. 4. Capabilities of Amazonian, African, and Asian tropical forests to offset annual atmospheric carbon accumulation.



We estimated the energy requirement of this strategy for capturing one ton of carbon (see Methods), and compared it to that of Direct Air Carbon Capture (DACC) estimated by recent studies(Chatterjee and Huang, 2020; Realmonte et al., 2019). As the carbon uptake efficiency of the tropical forest ecosystem decreases with time when under consecutive nighttime lighting, the energy requirement for capturing one ton of carbon increases (Figure 5 purple line). Nevertheless, the energy requirement of this strategy is lower than that of DACC, or is equivalent to the most optimistic estimation of DACC's energy requirement that excludes the energy costs required for carbon transport, storage, and utilization. (See Discussion)

Figure 5. Energy requirement for DACC and the nighttime lighting strategy



3.3 20-year simulation after the experiment termination from 2031 to 2050

The lighting experiment was terminated at 12:00 am January 1st, 2031 (UTC time), and model simulations continued for 20 years to 2050 (see the purple lines in Figure 2). The annual gross primary production and autotrophic respiration dropped quickly, ultimately reaching levels that were even lower than the control period due to a reduction in atmospheric CO_2 (CO_2 has fertilization effect in the model). Heterotrophic respiration remained high and decreased much slower at a speed 10 times lower than gross primary production and autotrophic respiration. The soil organic matter carbon pool continued to expand due to the entering of litter carbon during the first 2-3 years following the experiment termination (Figure 3-f). The vegetation carbon pool shrunk as trees produced less leaves (Figure 3-d). As a result, tropical forests turned into a net carbon source and remained so until the end of the simulation in 2050 (Figure 2-f). 31.4% of the carbon that had been absorbed during the lighting experiment was released back to the atmosphere. This number would likely be higher if the simulation continued. As a result, the global atmospheric CO_2 concentration returned to a level slightly lower than the control scenario. Local air temperature and precipitation returned to control levels.

4. Discussion

Physiological responses of tropical trees to longer photoperiods at the ecosystem level remains one of the biggest uncertainties in model simulations. Some field experiments indicate that higher CO_2 did not increase carbon sequestration of forests without added nutrients(Oren et al., 2001), suggesting tree growth might be limited by nutrient supply. The simulated local warming might also suppress tree growth(Gatti et al., 2021). Some observational evidence shows that intact tropical forest carbon sinks have been negatively influenced by warming and moisture stress(Doughty et al., 2015; Gatti et al., 2021) and might be reaching saturation(Hubau et al., 2020). However, the model predicted increase in precipitation and soil moisture, and previous studies have shown hydro climate plays a key role in deciding the effects of warming on tree growth(Guan et al., 2015; Reich et al., 2018). No direct evidence exists to verify the simulation results. Ecosystem-level field experiments are needed to understand how tropical forest ecosystems respond to longer photoperiods.

CESM2 likely overestimated the local air temperature increase in tropical forests for the omission of chemical energy stored during photosynthesis(Sellers, 1992). In CESM2 and other modern Earth System Models(Sellers, 1992), the canopy energy equation(Danabasoglu et al., 2020) uses the solar radiation absorbed by the vegetation to calculate temperature:

$$-\vec{S}_v + \vec{L}_v(T_v) + H_v(T_v) + \lambda E_v(T_v) = 0 \qquad (2)$$

where $\vec{S}_v$ is the solar radiation absorbed by the vegetation, $\vec{L}_v$ is the net longwave radiation absorbed by vegetation, and H_v and λE_v are the sensible and latent heat fluxes from vegetation, respectively. $\vec{L}_v$,H_v, and λE_v depend on the vegetation temperature T_v.

The chemical energy that is stored during photosynthesis and released by respiration is ignored as the net chemical energy usually amounts to less than 1% of absorbed insolation (around 0.6%(Trenberth et al., 2009)). In our lighting experiment from 2015 to 2030, however, 17% of absorbed insolation was fixed in the ecosystem as chemical energy (Figure 2-f) and did not contribute to local air temperature increase. The model failed to exclude this chemical energy storage from the energy equation. Therefore, the model overestimated the local temperature increase. This suggests that the temperature simulation results should be treated carefully when Earth System Models are used to do extreme scenario experiments associated with biogeochemistry.

Tropical forests experienced significant increase in carbon sink during the lighting experiment, but ultimately transitioned from a sink to a source after the experiment was terminated (Figure 2-f). Studies(Koven et al., 2021; Tokarska and Zickfeld, 2015) investigating the effects of overshoot future scenarios (positive carbon emissions followed by net-negative emissions) on terrestrial carbon cycle have observed similar phenomenon. During a positive emissions phase, terrestrial carbon cycles tend to absorb some fraction of added CO_2; however, during a removal phase they tend to release CO_2. The mechanism of these phenomena is the different responding rates of vegetative primary productivity and heterotrophic respiration to lengthening and shortening photoperiods, or increasing and decreasing atmospheric CO_2, with primary productivity responding much quicker than heterotrophic respiration. It is understandable when considering the diurnal pattern of forest carbon uptake. In the daytime, forests act as a carbon sink because photosynthesis is greater than respiration. In the nighttime respiration continues while photosynthesis abates, making forests a carbon source. Additional light/CO_2 would increase carbon sink by increasing both photosynthesis and respiration (sometimes referred to as a fertilization effect). When the additional light/CO_2 is removed, photosynthesis decreases quickly while respiration remains high, making forests a greater carbon source. It suggests that carbon removal actions focused on enhancing ecosystem productivity by altering environmental factors in the short term could induce this post-action CO_2 outgassing.

The global average surface air temperature remained below the control level after the termination of lighting experiments due to a reduction in atmospheric CO_2 concentration (Fig.2-k). However, the local air temperature went back to the control level and seems to be not influenced by CO_2 reduction (Fig.2-g). We attribute it to two possible reasons. First, different regions tend to have diverse air temperature responses to global CO_2 changes. Arctic regions show a much larger temperature increase in response to CO_2 increase, while the temperature increase in tropical regions is not that significant. Similarly, the CO_2 reduction may exert diverse impacts on temperature changes in different regions. Second, the temperature change in tropical forests at the termination of the experiment is controlled by two factors in this study, decreased incoming shortwave radiation and reduced CO_2. The former has a much larger impact on the local energy balance than the latter. Therefore, the influence of CO_2 reduction on local tropical forests is not as large as on the global scale.

Large clean energy requirements have always been a hurdle to large-scale deployment of any Carbon Dioxide Removal (CDR) techniques, including DACC and the strategy we discuss in this study. Our estimation suggests that the energy requirement of this strategy for capturing one ton of carbon is less than that of DACC. Specifically, if we give DACC 100 units of energy (100MWh) per year, DACC could fix 3-12 ton carbon per year. If we give forests 100 units of extra energy per year, forests could fix around 19.5 ton carbon per year on average (15-year average: 29 ton carbon in the first year and 10 ton carbon in the 15th year due to an increase of soil respiration); however, only 17 units of energy are actively used to fix carbon, and the rest 83 units of energy end up as heat which increases local temperature. Therefore, the energy use efficiency of this strategy is low, which is a major drawback.

Other than the direct lighting energy, this strategy requires additional energy associated with manufacturing and installing lamp networks, constructing electricity transmission devices, so on and so forth. To make a direct comparison to DACC, we only focus on the energy requirement specifically for carbon capture. Therefore, we didn't include the energy costs associated with engineering aspects, as the estimation of DACC's energy requirement does not include the energy costs required for carbon transport, storage, and utilization. In this study, we also mainly focus on the physical understanding of tropical forest ecosystem's responses to nighttime artificial lighting, so we didn't have much discussion on engineering aspects (how such a network of lamps could be constructed) as well as costs estimates. Nevertheless, the estimation of additional energy costs and the engineering feasibility are important, and we will attempt to address these issues in future studies.

As to the energy source, we assume this strategy only uses clean energy coming from solar, wind or nuclear farms to avoid extra carbon emissions when providing light to forests. In terms of technical analysis, more clean energy can be acquired by deploying more low-carbon energy generation plants across the globe (e.g., building large-scale solar and wind farms in the Sahara Desert(Li et al., 2018)). In terms of economic analysis, however, both DACC and this strategy are energetically and financially costly, and therefore, are unrealistic at present(Chatterjee and Huang, 2020). Moreover, even if the clean energy generation capacity increases, we cannot expect the global clean energy supply to only be invested to absorb CO_2. Nevertheless, if society has urgency to intervene in Earth's climate by removing CO_2 from the atmosphere in the late half of the 21th century, and/or an energy revolution realizes and we achieve the status of a significant surplus of clean energy, CDR would still be a powerful and effective climate mitigation strategy.

Another critical negative impact of this strategy is the potential threat to local wildlife and biodiversity. Tropical forests are the repository of a large proportion of Earth's biodiversity, and many of the organisms in the tropics are nocturnal or crepuscular, with organisms and interactions occurring in darkness. An extension of photoperiods could disrupt the habit of nocturnal creatures and have unexpectedly large impacts on ecosystem biodiversity. In addition, the disruption, disturbance and habitat fragmentation resulting from installing lights throughout tropical forests and throughout the forest canopies could exacerbate the negative impacts of this strategy. Given the potentially inverse relationship between more light at night and ecosystem health, policy makers may consider extending the photoperiod to an appropriate level to increase carbon sequestration meanwhile protecting local biodiversity from disastrous impacts. The tradeoff between nighttime carbon sequestration and biodiversity preservation should be rigorously evaluated and weight in the decision making process.

Overall, lighting up tropical forests at night has led to significant increase in carbon uptakes, decrease in atmospheric CO_2 concentration, and suppression of global warming as simulated by Earth System Model. However, it has strong side effects after the termination of nighttime lighting. In addition, local ecosystem changes could have negative impacts on local wildlife. Practical issues include the large demand for clean energy and the difficulties for implementation. From a positive standing it might be treated as an emergency climate solution if the society relies heavily on carbon removal to adjust the Earth's climate in the future. Paris Agreement set climate goals to limit global warming to well below 2 degree Celsius and preferably to 1.5 degree Celsius compared to pre-industrial levels(Lawrence et al., 2018). To accomplish the Paris Agreement's climate goals, different engineering levels (lighting powers, areas, and periods) might be needed under various anthropogenic emission scenarios, with high-emission scenarios possibly requiring high engineering levels. This study investigated the highest engineering level (lighting up global tropical forests at night with the optimal power) under a low-emission scenario (see Methods). Further research is needed to investigate the relationship between engineering levels and emission scenarios in the context of global climate goals set out by the Paris Agreement(Lawrence et al., 2018).

Current geoengineering studies mainly focus on the evaluation of climate goals that a potential solution might or might not accomplish; however, the changes in Earth's climate after terminating a geoengineering measure tend to be overlooked. This study suggests the importance of post-geoengineering analysis in geoengineering studies.

Code and Data Availability

CESM2 is an open-source community climate model preserved at https://doi.org/10.1029/2019MS001916. All data have been included in the manuscript.

Author contribution

XG designed the study and performed the simulations. XG, SL, DW, YL, BH, and AJ contributed to the data interpretation. XG drafted the original version of the manuscript. SL and DW reviewed and edited the manuscript.

Competing interests

Authors declare that they have no competing interests.

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