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Earth System Dynamics
Discussions

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

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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). Previous studies have shown that longer photoperiods facilitate the bud break and flowering in tropical forests(Borchert et al., 2005; Rivera et al., 2002). A greenhouse study in 1978 showed that a tropical tree species grown for one year under a 15-hour photoperiod treatment had an average stem length twice that of the same species grown under an 8-hour photoperiod treatment(Stubblebine et al., 1978). These studies suggest that longer photoperiods might have a positive effect on vegetative growth in tropical forests.

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. Results

2.1 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. African and Asian tropical forests showed similar responses.

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108 **Fig. 1.** Amazonian tropical forest responses for 24 hours since the start of the nighttime lighting
109 experiment at 12:00 am January 1st, 2015 (UTC time) under various nighttime lighting powers.
110 Panel (a) refers to surface downward shortwave radiation. Nighttime NEP (b) reached the peak at
111 200W/m^2, suggesting that 200W/m^2 is optimal in terms of activating additional photosynthesis.

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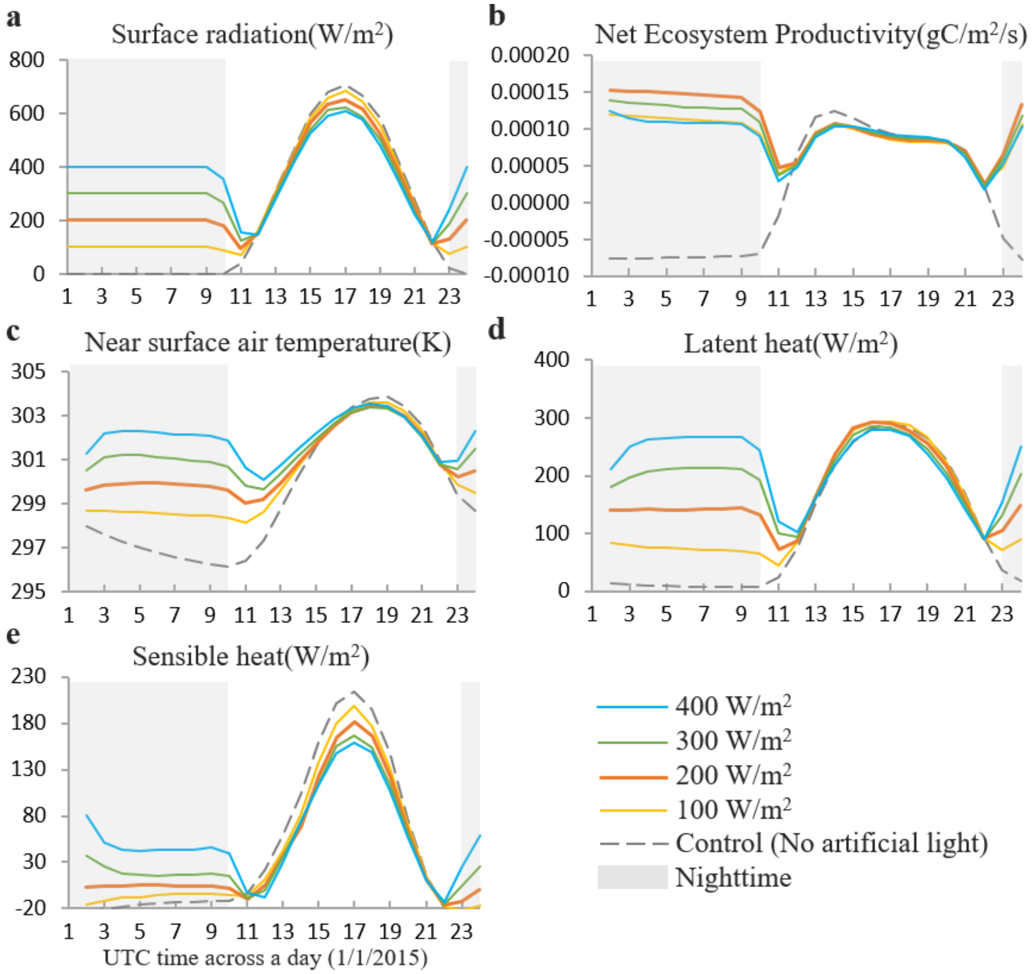

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2.2 16-year lighting experiment with the optimal lighting power from 2015 to 2030

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. However, the expansion of the coarse woody debris and litter carbon pool could provide more burning materials and increase wildfire risks. 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).

149 **Fig. 2.** Global tropical forest carbon flux and climate responses under and after the lighting
150 experiment. Ta in panel (g & j): Near surface air temperature. Shaded areas represent
151 uncertainties, except those in panel (f) which denote carbon released back to atmosphere after the
152 termination of the lighting experiment.

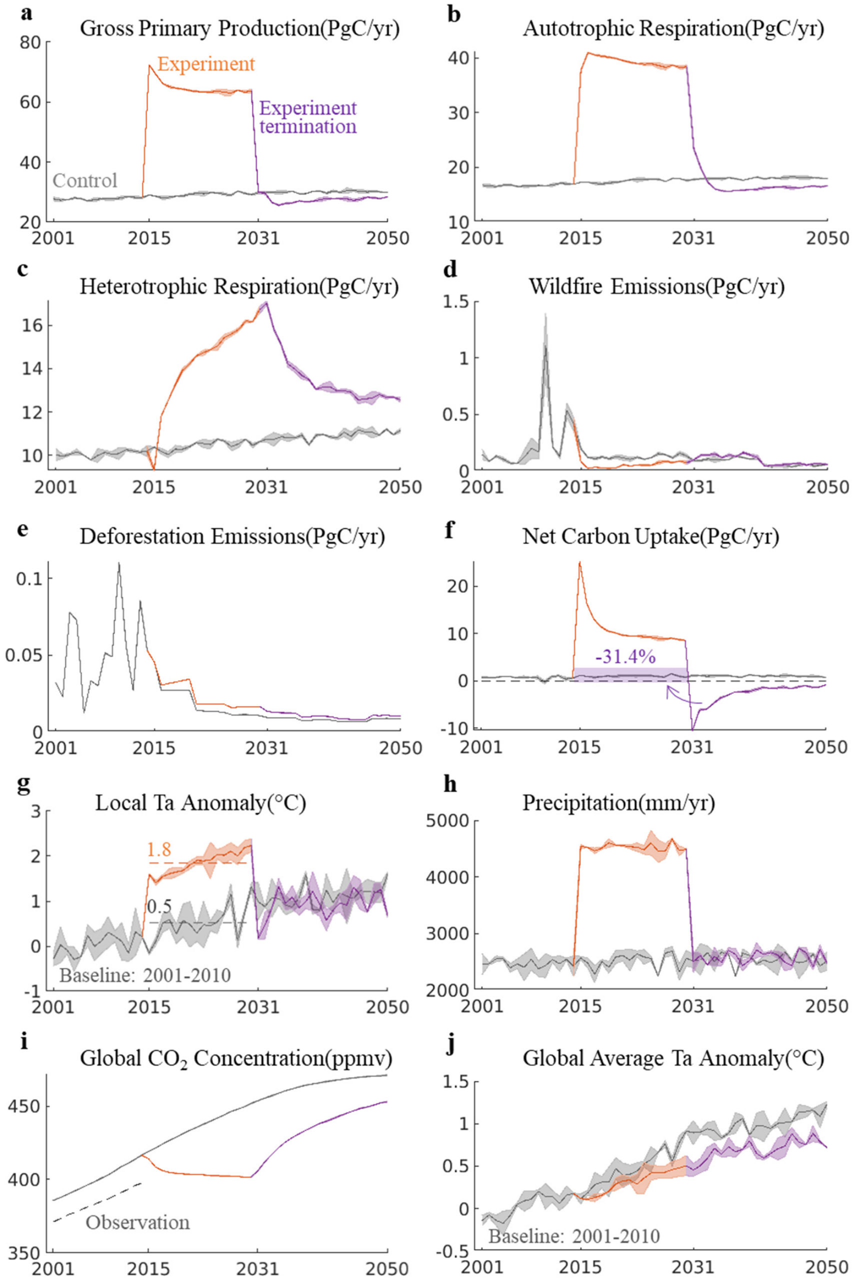

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Fig. 3. Where Did the Net Absorbed Carbon Go? Global Tropical Forest Carbon Amount Responses. Panel (a): the current carbon amount in different carbon pools. Panel (b): carbon amount in 2030 after 16-year lighting experiments. Panel (c): carbon amount 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.

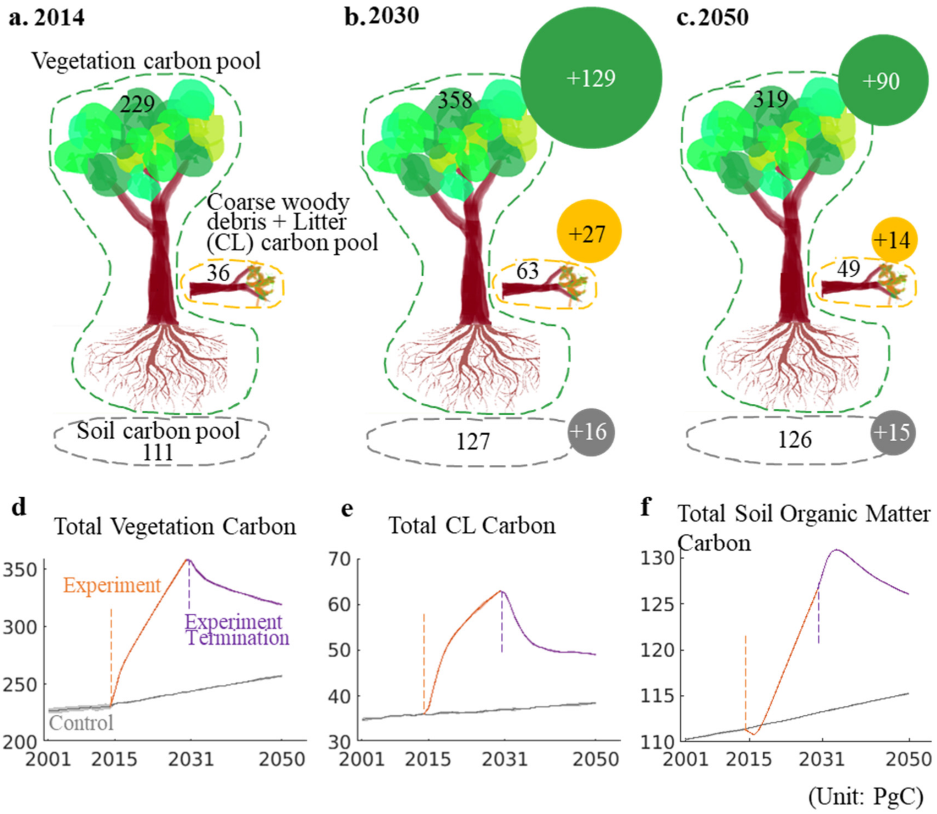
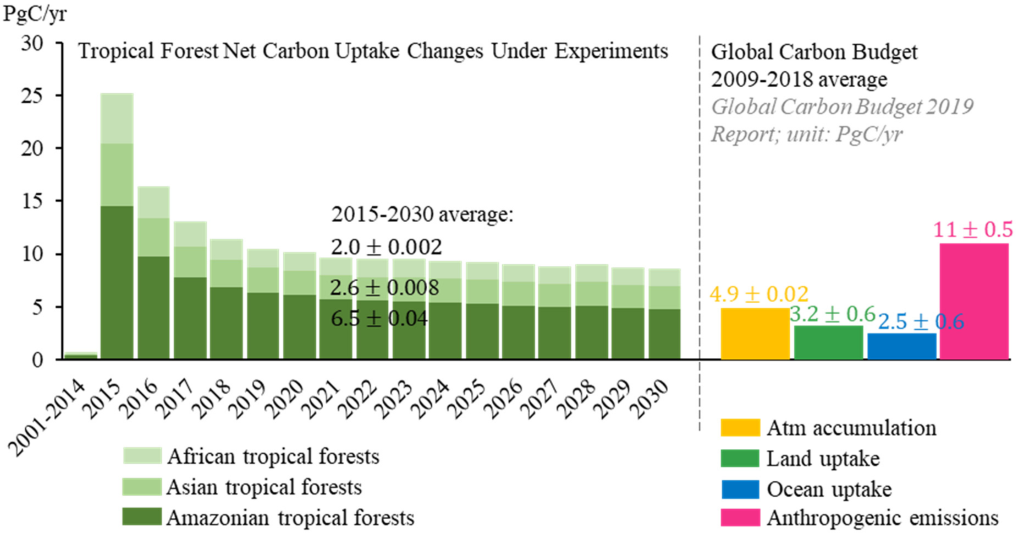
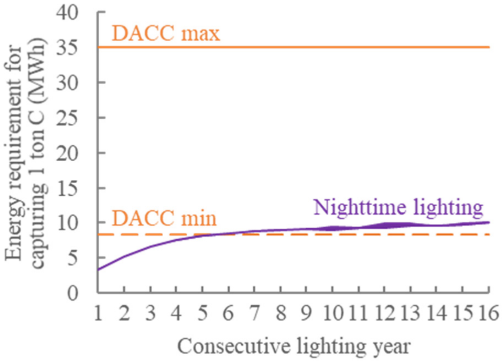


Fig. 4. Capabilities of Amazonian, African, and Asian tropical forests to offset annual atmospheric carbon accumulation.



We estimated the energy requirement of this strategy for capturing one ton of carbon, 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.

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



2.3 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.

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3. Discussion

Physiological responses of tropical trees to near 24-hour 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 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:

$$-\vec{S}_v + \vec{L}_v(T_v) + H_v(T_v) + \lambda E_v(T_v) = 0 \qquad (1)$$

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.

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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.

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

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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.

4. 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).

4.1 Historical Control Simulation 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.

4.2 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.

4.3 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 judges if a grid column is at daytime or nighttime by calculating its cosine (solar zenith angle) at each time step. If the cosine is positive, the land module calculates and passes the surface albedo to the atmosphere module and the atmosphere module calculates the radiation fluxes with the surface albedo and the incoming solar radiation. We made modifications in all active modules to assign tropical forests' cosine a positive value (could be any number from 0 to 1) 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 solar insolation 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 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 surface albedo and the specified solar insolation.

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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