



Canopy Structure Amplifies the Role of Radiation in Vegetation Responses Under Stratospheric Aerosol Injection

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Abstract. Stratospheric aerosol injection (SAI) is a climate intervention approach that would inject aerosols into the stratosphere, reflecting a fraction of incoming sunlight and reducing surface temperatures to mitigate impacts of climate change. While ecological studies of SAI have largely focused on temperature and precipitation, observations following volcanic eruptions suggest that radiation changes may be a primary driver of vegetation responses to atmospheric aerosols. Here, we leverage two global land surface models with different complexity to isolate the effects of radiation under SAI. The big-leaf model, which represents vegetation as a single bulk canopy, suggests that radiation has little influence on vegetation, whereas the cohort-based model, which resolves vegetation size structure and canopy stratification, finds that radiation changes are a major driver of plant responses. In the cohort-based model, radiation changes increase global net primary production by 3.9% for broadleaf trees, 9.7% for needleleaf trees, and 2.6% for C3 grasses, but reduce it by 1.3% for C4 grasses, while the big-leaf model shows little overall response to radiation. These findings suggest that vegetation and agricultural impact studies that do not explicitly account for changes in radiation, or rely on simplified big leaf models, may not capture the full response to SAI.

1. Introduction

Worsening impacts of climate change, along with the increasing likelihood of exceeding the temperature targets set by the Paris Agreement, have motivated growing research into climate intervention strategies (NASEM, 2021). Among proposed climate intervention strategies, the injection of sulfate aerosols into the stratosphere has received the most attention in literature. This approach aims to mimic the effects of large volcanic eruptions by increasing the reflection of incoming sunlight, thereby reducing surface temperatures (UNEP, 2023).

Stratospheric aerosol injection (SAI) would increase planetary albedo by reflecting some of the incoming shortwave radiation back to space before it reaches the troposphere, thereby reducing surface incident photosynthetically active radiation (PAR), which could inhibit photosynthesis (Proctor et al., 2021). However, this enhanced scattering would also increase the fraction of diffuse radiation reaching the surface, promoting more uniform light penetration within plant canopies, reducing light saturation at the canopy top, and increasing canopy light use efficiency, which could promote photosynthesis (Mercado et al., 2009). The net effect to plants of these opposing radiation impacts is ambiguous.

Only four studies have isolated the impacts of SAI-driven radiation changes on plants, all focused on agriculture. Proctor et al. (2018) used a statistical model based on observations following the Mount Pinatubo eruption and found



that changes in net radiation would negatively affect maize, rice, soybean, and wheat, offsetting most benefits from reduced temperatures. Clark et al. (2023) used the Community Land Model (CLM) and found minimal effects of changes in total and diffuse radiation on global yields of these crops. Clark et al. (2025) similarly found insignificant responses to changes in the diffuse-to-direct radiation ratio (hereafter dif/dir) across two global crop models. Fan et al. (2021) used MLR to assess radiation effects from crop model simulations and found opposing effects of total and diffuse radiation, resulting in a negligible net response. The muted responses in Clark et al. (2023, 2025), however, may partly reflect their use of an SAI scenario with deployment concentrated in the Southern Hemisphere (Richter et al., 2022).

All previous land modeling studies have used “big leaf” models, where the entire plant canopy in a grid cell is represented as one leaf (Glienke et al., 2015; Xia et al., 2016; Parry et al., 2026). This means these models used to assess impacts of SAI in the past have either had no representation of diffuse fertilization or parameterized it in a simplified manner. Gu et al. (2003) found that following the Mount Pinatubo eruption, changes in radiation increased photosynthesis by 23% at a deciduous forest site, while temperature and vapor pressure deficit had minimal influence. This suggests the radiative effects of SAI could be the most important factor driving changes in forests, making it necessary to evaluate the effects of radiation using global models that simulate SAI deployment in detail. Previous Earth system model (ESM) studies that assess changes to global forest productivity under SAI have never isolated the individual climate effects (radiation, temperature, precipitation) making it difficult to understand what may drive changes to forest growth under a possible SAI deployment (Glienke et al., 2015; Xia et al., 2016; Parry et al., 2026). It is not clear whether the big leaf models used in these studies, and the way they parameterize radiation, are fit to capture the large perturbations induced by SAI.

Here we use ESM simulations of SAI with equal SO₂ deployment in both hemispheres to maintain global temperatures 1.5 K above preindustrial under a medium emissions scenario (Lee et al., 2026). We use the resulting climate output to force two global land models: CLM5 (Lawrence et al., 2019), representing the big-leaf approach used in previous SAI assessments, and the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) (Fisher et al., 2015; Koven et al., 2020; Clark et al., 2026). FATES explicitly represents vegetation size structure, canopy stratification, and competition among plant cohorts, allowing radiation effects on light interception, photosynthesis, and productivity to be simulated with fewer bulk parameterizations. Because FATES is run within CLM5’s framework, and uses CLM5 as a host model, the models share the same photosynthesis code, allowing us to attribute differences primarily to canopy structure. We assess whether FATES shows larger productivity impacts than big-leaf models and compare radiation-driven effects with those from SAI-induced changes in temperature and precipitation. If radiation is a major driver of plant impacts, a full understanding of the impacts of a SAI deployment should consider radiation changes and vegetation feedbacks more explicitly to avoid damages to forests and agriculture.

2. Results

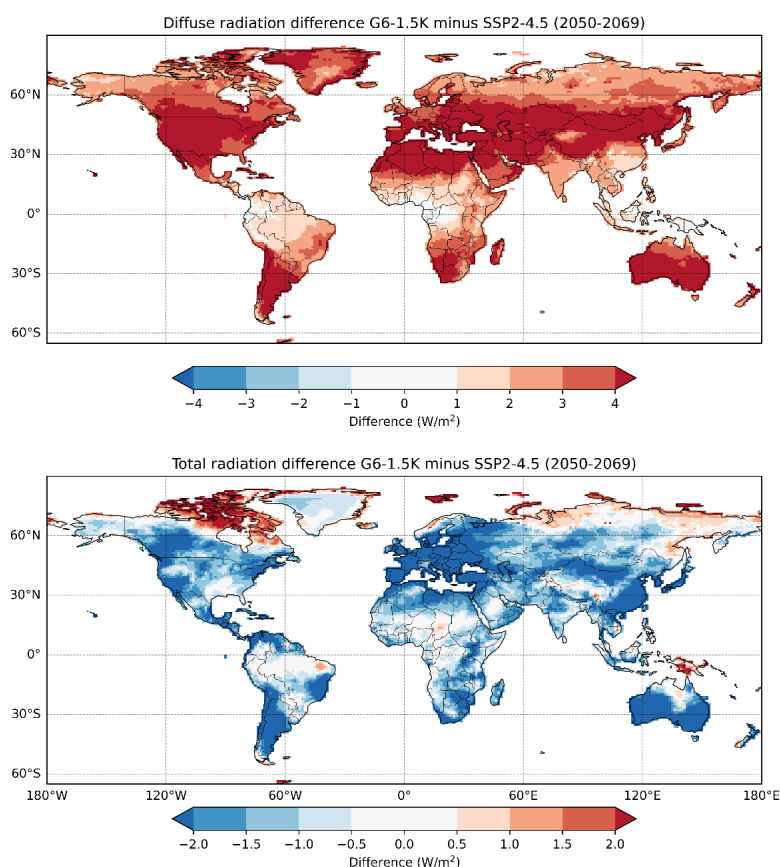


Figure 1. Impact of SAI on diffuse radiation (top) and total radiation (bottom) under G6-1.5K-SAI relative to SSP2-4.5 during years 2050-2069.

Under the G6-1.5K scenario, SAI is deployed equally at 30°N and 30°S to achieve similar cooling across hemispheres (Lee et al., 2026). This primarily increases diffuse radiation and reduces total radiation at midlatitudes, with minimal changes in the tropics (Figure 1). Changes in total radiation reduce global CLM NPP for broadleaf trees (-1%), needleleaf trees (-4%), and C3 grasses (-3%), likely due to reduced photosynthetically active radiation (Figure 2). Needleleaf trees show the largest radiation response in both CLM and FATES because their evergreen foliage is exposed to the perturbation year-round. In contrast, lower total radiation increases C4 grass NPP by reducing leaf temperature and VPD, thereby alleviating heat and moisture stress (Figure S1). This may also contribute to the greater sensitivity of needleleaf than broadleaf trees, as needleleaf trees are more VPD-sensitive in FATES (Clark et al., 2026). In CLM, increased diffuse radiation increases C3 NPP and partly offsets the effects of reduced total radiation, but decreases C4 NPP in both models (Figure 2). This reflects the adaptation of C4 plants to high-intensity direct radiation and their more linear photosynthetic response to increasing light (Figure S2).

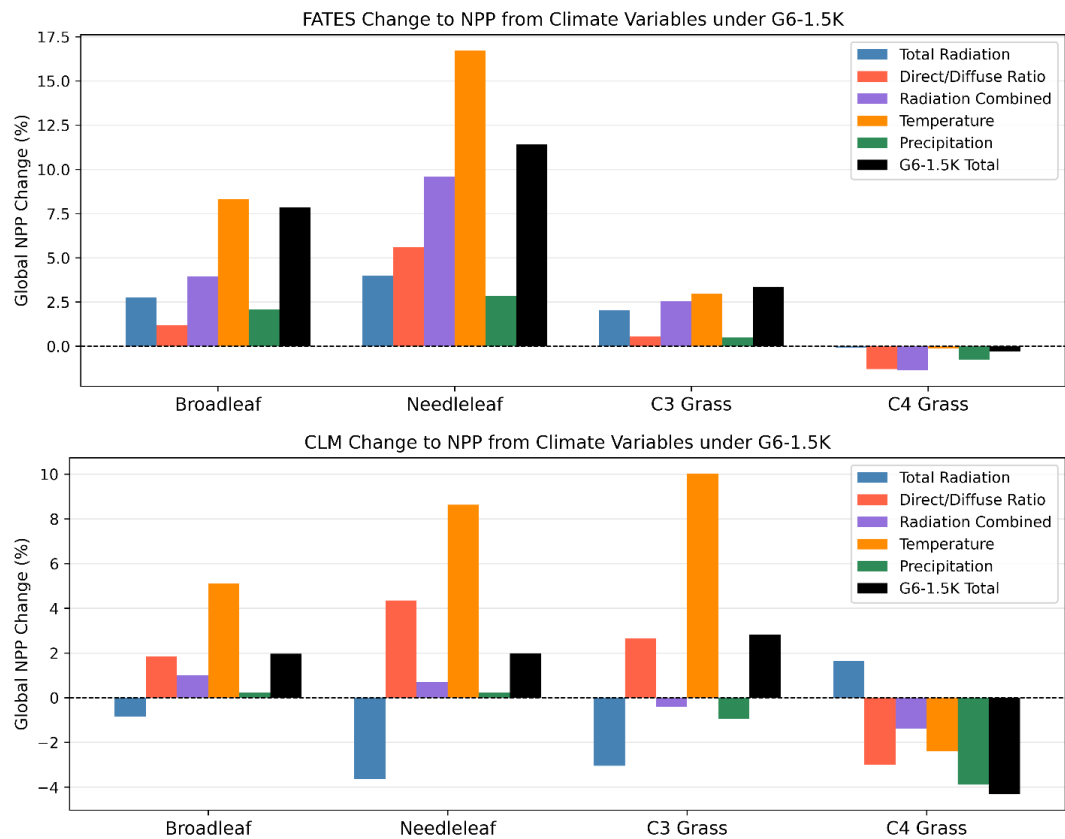


Figure 2. The impact to global average NPP from the individual effect of just changing total solar radiation, the ratio of direct/diffuse radiation, the net radiation effect, temperature, and precipitation on different plant functional groups in CLM5 and FATES under G6-1.5K relative to SSP2-4.5 during years 2050-2069.

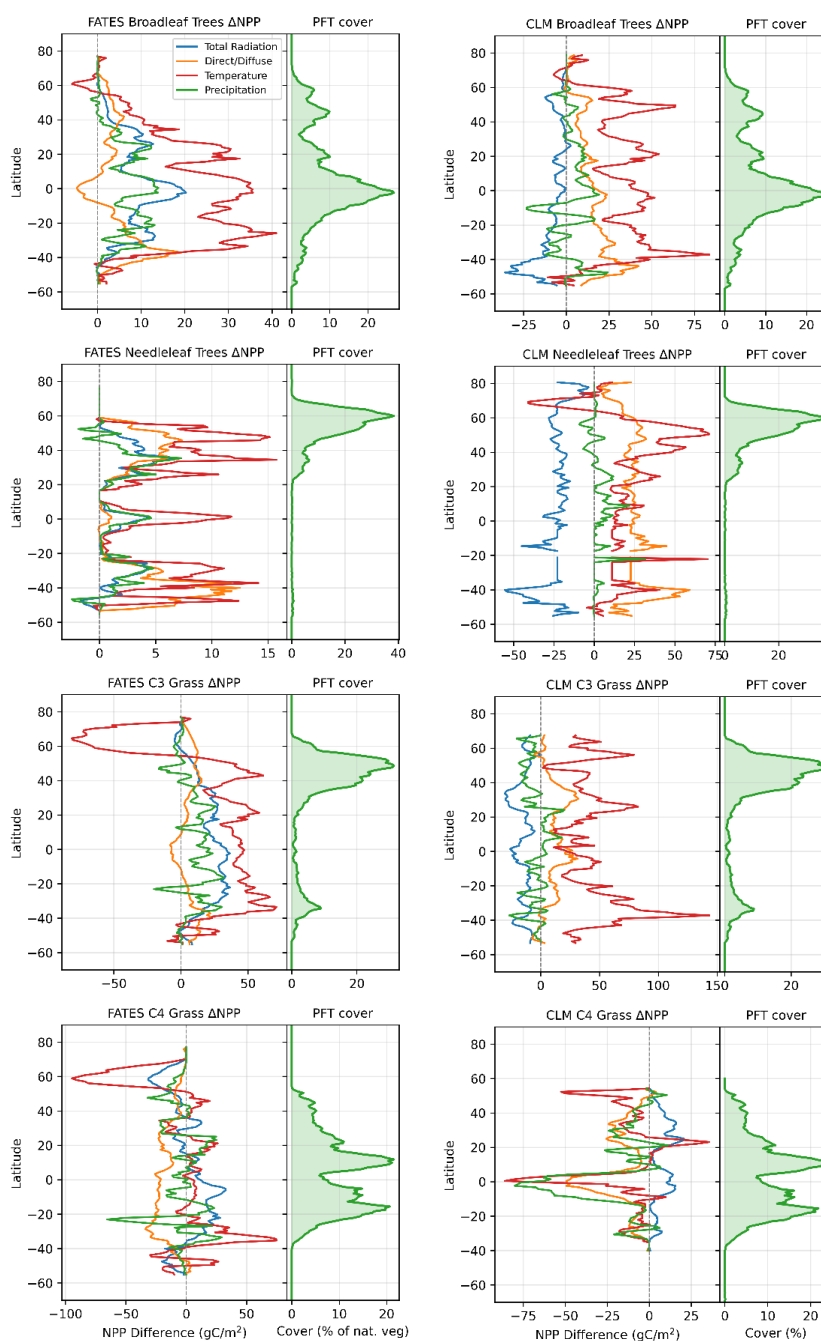
FATES, like CLM, shows that temperature reduction causes the largest benefit to tree plant functional types under G6-1.5K-SAI, with minimal impacts from changing precipitation (Figure 2). In FATES, the most notable difference from CLM is its response to radiation, specifically the net radiation effect. In CLM, the opposing responses to total radiation reduction and increases in ratio of diffuse to direct radiation (dif/dir) tend to counterbalance each other for all plant functional types (Figure 2). However, while FATES shows similar increases to global NPP from increasing dif/dir, it also shows benefits from reducing total radiation for all plant functional types. Because CLM and FATES share much of the same code used to calculate photosynthesis, the primary difference between the two models is how they represent canopy structure. In both models, lowering total radiation, without modifying dif/dir, should produce a negative carbon response based on the shared photosynthesis code. This means that the positive response exhibited in FATES is a secondary response to lower radiation reducing VPD and temperature, which outweighs the negative effect of reduced PAR (Figure S1). The response in NPP from lower total radiation is governed by how light saturated the carbon dominated leaves are. In FATES, most canopy carbon is produced by large, tall trees whose leaves operate



107 near the light-saturated portion of the photosynthetic light-response curve (Figure S2). As a result, modest reductions
 108 in radiation have little effect on their carbon uptake, as they are already light saturated. Although understory vegetation
 109 would experience larger reductions in carbon uptake, it contributes relatively little to total canopy carbon, so its
 110 response has only a minor effect on overall canopy productivity. In CLM's big-leaf scheme, the leaf area for each
 111 plant functional type is represented as a grid cell average. This combines light-saturated canopy leaves with light-
 112 limited understory leaves into a single "average" leaf that operates lower on the photosynthetic light-response curve.
 113 As a result, the same fractional reduction in radiation produces a larger loss of carbon uptake than in FATES. In
 114 FATES, less total radiation reduces leaf temperature and VPD (Figure S1), and this relief from lower heat and water
 115 stress dominates over the minimal carbon loss from less PAR. In CLM, the reduction in PAR dominates over this
 116 secondary effect, causing net reductions to global NPP.

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 118 Regional impacts to NPP are variable across the two models. In general, for CLM, lower total radiation causes
 119 decreases to NPP at all latitudes, with lower temperature causing increases to NPP at all latitudes, except for C4
 120 grasses (Figure 3). Precipitation effects are generally noisy and small, whereas the impact of changing dif/dir causes
 121 benefits in CLM at all latitudes (Figure 3). C4 grasses in CLM see large reductions to NPP near the equator from
 122 changes to temperature, precipitation, and the ratio of direct to diffuse, which is not as pronounced in FATES (Figure
 123 3). FATES exhibits strong positive responses to NPP from lower temperatures at most latitudes for C3 plants.
 124 However, FATES exhibits strong reductions to NPP at latitudes around 60°N for C3 and C4 grasses (Figure 3). In
 125 FATES, the effect of reducing total radiation, changing precipitation, and dif/dir under G6-1.5K-SAI tends to be
 126 positive at nearly all latitudes. For both CLM and FATES, benefits from increasing the amount of diffuse relative to
 127 direct radiation has only minimal benefits in equatorial regions, suggesting that benefits to vegetation from SAI could
 128 be even larger if more shading occurred closer to the tropics, where most of the world's carbon and dense canopy
 129 forests are located.

130



131
 132 **Figure 3.** Zonal mean changes to Net Primary Production from individual climate effects under G6-1.5K relative to
 133 SSP2-4.5 during years 2050-2069 in CLM and FATES.



In FATES, the canopy structure representation causes the global impact of G6-1.5K-SAI to be higher than CLM by 5.9% for broadleaf trees, 9.4% for needleleaf trees, 0.5% for C3 grasses, and 4.1% for C4 grasses (Figure 2). While the total effect of SAI tracks the individual changes, these do not linearly sum to the total effect (Figure 2). This is not unexpected, as vegetation responses to climatic drivers are highly nonlinear and mutually dependent, and some potential secondary impacts have not been included in our analyses, such as humidity. Importantly, both models show net negative impacts to C4 grasses globally under SAI. These decreases are driven by different processes at different locations, with CLM exhibiting the strongest decreases to C4 grasses at low latitudes, driven by changes to temperature, precipitation and dif/dir (Figure 3). In FATES, reductions to global C4 grass NPP is locally driven mainly by high-latitude cooling, with reductions at all latitudes driven by increasing the amount of diffuse radiation relative to direct (Figure 3). This highlights process-level uncertainty and the need to assess impacts across a larger model ensemble, and field experiments to inform model development.

3. Discussion and Conclusions

Here we compared a traditional “big leaf” land model with a state-of-the-art cohort model that explicitly resolves canopy structure. While the big leaf model shows that the net effect of radiation under SAI has almost no impact to global NPP across plant functional types, the cohort model shows that radiation is more important than precipitation, and as important as temperature for grasses, globally. The cohort model suggests that impacts to vegetation from reducing total radiation are driven by secondary impacts that reduce temperature and vapor pressure deficit, making the net effect of radiation changes under SAI positive for broadleaf trees, needleleaf trees, and C3 grasses. However, both models consistently show negative impacts to C4 grasses under SAI, suggesting potential implications for food security. Our results highlight that radiation should be considered more explicitly when designing SAI scenarios, and that vegetation impact studies that neglect radiation effects provide an incomplete picture. Additional model intercomparisons and field experiments are needed to further reduce uncertainties.

We evaluate the individual contributions of the main effects of climate changes produced by SAI for natural vegetation. This study uses only one SAI scenario, and the impacts of radiation changes on vegetation would likely depend strongly on the SAI deployment strategy (e.g., injection location, timing, and amount) as well as the aerosol size distribution simulated by the climate model. Global land surface models only consider visible and near infrared shortwave, longwave, and diffuse radiation in units of W/m² at each grid cell. Since aerosol scattering also modifies different wavelengths in the spectrum of light differently (de Graff et al., 2007), which can impact vegetation (McCree, 1971), future work should focus on improving land models to integrate wavelength-specific response functions. Further, comparing the model light response curves shown here with that derived from observations could help constrain uncertainty of SAI impacts. Additional model intercomparisons, especially those that isolate individual effects of SAI, could help further constrain model related uncertainty and identify the main drivers of model spread.

One of the interesting findings of this study is that modest reductions in total radiation seen under SAI can have a net positive impact on canopy carbon assimilation. There is observational evidence from biomass burning aerosols over



tropical forests that is consistent with the response simulated by FATES, where reductions in total radiation cool the canopy and produce a net increase in canopy photosynthesis (Malavelle et al., 2019). It has also been shown that too much solar radiation can increase temperatures and evaporative demand, which can increase water stress and plant mortality (Nunes et al., 2026). While modest reductions in total radiation appear to benefit vegetation in FATES and observations, larger reductions would eventually decrease carbon assimilation enough to outweigh any benefits from reduced heat and water stress, which has been documented in agrivoltaic farms (Hosseini et al., 2026). It remains unclear at what SAI magnitude this threshold may be reached. CLM and FATES differ in several aspects of their configurations, including plant functional type distributions, nitrogen deposition, and land use, which may contribute to differences between them, although the distribution of plant functional type groupings between the models were very similar. However, within each model, all analyses compare a background scenario with a climate perturbation scenario while holding all other inputs constant. Consequently, the differences presented here primarily reflect the effects of climate perturbation rather than differences in inputs. Comparisons with observations and direct experiments of climatic analogues to SAI are needed to evaluate and constrain model behavior, particularly the representation of radiation impacts. Although radiation is not typically considered a dominant driver of vegetation responses under climate change, it will play a much larger role under SAI.

Beyond uncertainty in land model responses, substantial uncertainty remains in the aerosol properties produced by SAI, particularly their spatial and particle size distributions. These properties determine the magnitude and character of radiation changes, including total and diffuse radiation. Proctor et al. (2018) found that Pinatubo-induced radiation changes negatively affected agriculture, offsetting the benefits of cooling. Pinatubo produced larger, more absorbing particles than those typically simulated for SAI, resulting in a greater reduction in direct sunlight for a given increase in diffuse radiation. Despite this, the increased diffuse fraction of Pinatubo substantially enhanced forest productivity (Gu et al., 2003). The aerosol size distribution under SAI remains uncertain because models use simplified representations of aerosol microphysics and optical properties, with injection rate, plume dynamics, coagulation, condensation, chemical transformations, sedimentation, and transport all potentially affecting the resulting radiation perturbations (Lee et al., 2026). Together with uncertainties in land surface processes, this makes vegetation responses difficult to constrain. However, the available evidence suggests that radiation changes from SAI are likely to have a positive impact on forested ecosystems globally, but could have pontifically negative impacts on some grasses and crops.

Appendix

The climate change and climate intervention scenarios were simulated using output from the Community Earth System Model (CESM2) using the Whole Atmosphere Community Climate Model Version 6 (WACCM6) configuration (Danabasoglu et al., 2020; Gettelman et al., 2019), run with a resolution of $0.95^\circ \times 1.25^\circ$ with 70 vertical layers. CESM2(WACCM6) has comprehensive stratospheric and tropospheric chemistry and dynamics (Davis et al., 2024) to simulate the impact of climate change and SAI on surface temperature, precipitation, humidity, and direct and diffuse radiation. The background climate change scenario follows the Shared Socioeconomic Pathway (SSP) 2, with



208 Representative Concentration Pathway 4.5, hereafter SSP2-4.5 (Meinshausen et al., 2020). SAI simulations follow the
 209 G6-1.5K-SAI scenario (Lee et al., 2026; Vioni et al., 2026). This scenario injects SO₂ in the model grid boxes at 21
 210 km altitude, with equal amounts at 30°N and 30°S. The amount of injected SO₂ is determined each year to maintain
 211 global mean surface temperature at levels reached during the years 2020-2039 under SSP2-4.5, which serves to
 212 represent 1.5K above preindustrial levels (Lee et al., 2026).

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214 CLM5 and FATES were run with 3-hourly output from CESM2(WACCM6). The models were run with SSP2-4.5
 215 transient CO₂ concentrations. Scenarios to isolate climate effects of SAI were run by replacing individual forcings
 216 from SSP2-4.5 with that of G6-1.5K. To isolate the effect of changing total radiation a ratio, r , was first calculated.
 217 Then, r was multiplied by the original SSP2-4.5 direct and diffuse radiation inputs, and the resulting radiation was
 218 used to force the models to compare to the original SSP2-4.5 simulation to understand changing total radiation, while
 219 ignoring dif/dir. Then, another simulation was run, replacing the direct and diffuse radiation of SSP2-4.5 with that of
 220 G6-1.5K, again keeping all other inputs the same as SSP2-4.5. This simulation was then compared to the simulation
 221 using radiation inputs multiplied by r , to understand the impact of dif/dir, while ignoring changes to total radiation.

222

223 Results were aggregated into needleleaf and broadleaf plant functional type (PFT) groups. In CLM, the needleleaf
 224 group comprised needleleaf evergreen temperate trees, while the broadleaf group comprised broadleaf evergreen
 225 tropical, broadleaf evergreen temperate, broadleaf deciduous tropical, and broadleaf deciduous temperate trees.
 226 Because FATES uses a different PFT classification, its needleleaf group comprised needleleaf evergreen extratropical
 227 and needleleaf deciduous extratropical trees, while its broadleaf group comprised broadleaf evergreen tropical,
 228 broadleaf evergreen extratropical, broadleaf deciduous tropical, and broadleaf deciduous extratropical trees. CLM
 229 specifies PFT land area fraction according to the land use file for SSP2-4.5, which changes over time according to
 230 SSP2. FATES was run with constant land area fractions based on year 2000 data, however, both are almost identical
 231 during the time period analysed.

232

233 CLM, like most land models, simulates the fraction of each PFT on a grid cell as one big leaf, to represent leaf level
 234 photosynthesis, which it scales up to the canopy. CLM splits each PFT's leaf into two sections, with one representing
 235 shaded, and the other representing a sunlit fraction. This two stream approximation where the sunlit fraction sees
 236 direct beam radiation plus diffuse radiation, while the shaded fraction sees only the diffuse portion (Sellers, 1985).
 237 With more scattering from aerosols, more diffuse can reach the shaded leaf, simulating light being spread more evenly
 238 through the canopy, boosting photosynthesis. However, CLM cannot represent vertical canopy structure, competition
 239 for light among plants or between plant functional types, or the distinct light environments of the canopy, understory,
 240 and forest gaps.

241

242 Unlike CLM, FATES builds a canopy from cohorts (groups of same-size, same-PFT individuals) that live together in
 243 patches (areas of common disturbance history) and then arranges those cohorts vertically, so tall plants physically
 244 shade the short ones beneath them. FATES has an overstory and an understory canopy layer, with each canopy layer



containing multiple cohorts of different PFTs and heights. Since FATES does not track where a plant physically stands on a grid cell, each PFT in a canopy layer receives the same light from the top of that layer, and each PFT's foliage filters that light as it travels downward, independently of its neighboring PFTs. The filtered light streams from all PFTs are only pooled when light travels to the next canopy layer. CLM solves radiation analytically for a single canopy layer (Sellers, 1985), whereas FATES iteratively solves radiation transfer through multiple canopy layers according to Norman (1979). By explicitly resolving vertical canopy structure, light competition, and heterogeneous light environments, FATES is better suited than CLM to capture the ecological consequences of aerosol induced changes in direct and diffuse radiation, especially large perturbations seen under SAI.

Data Availability

Land model output to support this work has been archived via the Zenodo online repository at <https://doi.org/10.5281/zenodo.23216508>. Figure generation scripts can be found at https://github.com/bjc204/ESD_Figures. CESM2-WACCM6 G6-1.5K-SAI data is available from Lee et al. (2026).

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Author Contributions

BC conceptualized the study, conducted land model simulations, and wrote the first draft. DV contributed to editing and revising the manuscript.

Competing Interests

The authors declare no competing interests.

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