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### Key Points:

- Soil albedo differences between hyperspectral and broadband representations over desert areas can reach  $\pm 20\%$
- Spectrally integrated radiative forcing biases can reach up to  $30 \text{ W m}^{-2}$  over desert areas
- Climate simulations show impacts on global energy fluxes and photosynthesis due to hyperspectral versus broadband soil albedo differences

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## The Importance of Hyperspectral Soil Albedo Information for Improving Earth System Model Projections

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**Abstract** Earth system models (ESMs) typically simplify the representation of land surface spectral albedo to two values, which correspond to the photosynthetically active radiation (PAR, 400–700 nm) and the near infrared (NIR, 700–2,500 nm) spectral bands. However, the availability of hyperspectral observations now allows for a more direct retrieval of ecological parameters and reduction of uncertainty in surface reflectance. To investigate sensitivity and quantify biases of incorporating hyperspectral albedo information into ESMs, we examine how shortwave soil albedo affects surface radiative forcing and simulations of the carbon and water cycles. Results reveal that the use of two broadband values to represent soil albedo can introduce systematic radiative-forcing differences compared to a hyperspectral representation. Specifically, we estimate soil albedo biases of  $\pm 0.2$  over desert areas, which can result in spectrally integrated radiative forcing divergences of up to  $30 \text{ W m}^{-2}$ , primarily due to discrepancies in the blue (404–504 nm) and far-red (702–747 nm) regions. Furthermore, coupled land-atmosphere simulations indicate a significant difference in net solar flux at the top of the atmosphere ( $>3.3 \text{ W m}^{-2}$ ), which can impact global energy fluxes, rainfall, temperature, and photosynthesis. Finally, simulations show that considering the hyperspectrally resolved soil reflectance leads to increased maximum daily temperatures under current and future  $\text{CO}_2$  concentrations.

**Plain Language Summary** Due to computational and observational constraints, scientists must make approximations when modeling the climate system. One simplification is to reduce soil background albedos to two broad spectral bands, which can cause biases in climate models by not fully accounting for the changing color of sunlight throughout the day. The limitations of the broadband approximation also affect predictions of the global carbon and water cycles due to differences in radiation absorbed by vegetation.

## 1. Introduction

Soil background albedo serves as the lower boundary condition of vegetation radiative transfer schemes in Earth system models (ESMs). In most ESMs, soil albedo is treated as fixed values in two spectral broadbands, namely, the photosynthetically active radiation band (PAR, 400–700 nm) and the near infra-red band (NIR, 700–2,500 nm). These two broadbands are resolved by efficient radiative transfer schemes in the land component of current ESMs, the so-called two-stream scheme (Braghieri et al., 2019; Sellers, 1985). However, recent advances in imaging spectroscopy have allowed for better modeling of hyperspectral reflectance of the canopy-soil system (Braghieri et al., 2021a; Jiang & Fang, 2019). In addition, particular wavelengths within the PAR spectrum have varying quantum yields, impacting photosynthesis and transpiration differently (Cernusak & Kauwe, 2022; Liu & van Iersel, 2021). Hyperspectral data can also be used to map different vegetation properties, such as canopy water content, leaf nitrogen and phosphorus compositions (Knyazikhin et al., 2013), and a range of traits related to photosynthesis, respiration, and decomposition of plant material (Butler et al., 2017; Cawse-Nicholson et al., 2021). However, current ESMs usually cannot calculate radiative transfer at a high spectral resolution ( $\sim 10 \text{ nm}$ ) (Poulter et al., 2023), which limits their ability to utilize the additional information provided by hyperspectral measurements for model calibration (Braghieri et al., 2021a).

Recent developments have moved away from the broadband approach, allowing for direct inversion of ecosystem properties from high spectral resolution remotely sensed data (Dutta et al., 2019) and reducing uncertainty in surface albedo (Majasalmi & Bright, 2019). However, these advances require explicit information of

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hyperspectral soil reflectance globally and at spatial resolutions as high as 50 km. Currently, ESMs determine soil background albedo through optimization methods (“soil colors”) to replicate remote sensing observations of snow-free surface albedo at local noon (P. J. Lawrence & Chase, 2007), which may conceal compensating errors. However, broadband radiative transfer schemes are used to calculate the model equivalent surface albedo based on climatological monthly soil moisture along with vegetation parameters of plant functional types, leaf area index (LAI), and stem area index (SAI), generating highly parameterized global maps of soil albedo with two associated fixed values (PAR and NIR reflectances), with a strong spectral discontinuity at 700 nm (Figures 1a and 1b).

Global data sets of soil spectroscopy (Viscarra Rossel et al., 2016) and new hyperspectral soil algorithms (Jiang & Fang, 2019) allow the development of continuous soil reflectance curves across the shortwave radiation spectrum (400–2,500 nm). This capability enables global calculations using hyperspectral radiative transfer schemes in ESMs. Moreover, differences in soil albedo between the highly resolved and more coarsely resolved spectral curves highlight systematic divergences in surface albedo and radiative forcing. These divergences in surface reflectance propagate into other radiative partitioning terms, such as absorptance and transmittance, impacting sun-induced fluorescence (Braghieri et al., 2021a), photosynthesis (Braghieri et al., 2020a), and evapotranspiration (Viskari et al., 2019).

We aim to demonstrate sensitivity and quantify biases in surface albedo and following divergences in radiative forcing globally, by focusing on soils in a desert scheme without vegetation. We also investigate how the addition of vegetation on top of soils worldwide affects canopy reflectance and the resulting radiative forcing at the top of the atmosphere (TOA). To address these questions, we compare a global hyperspectral land model, CliMA-Land (Braghieri et al., 2021a; Wang et al., 2021), using a broadband representation of soil albedo to one that is hyperspectrally resolved. Our analyses involve a few different scenarios, including a global desert scheme with barren soil, an actual simulation with vegetation on top of the soil, and the photosynthetic response of the land surface, which is driven by differences in the amount of absorbed radiation by the vegetation.

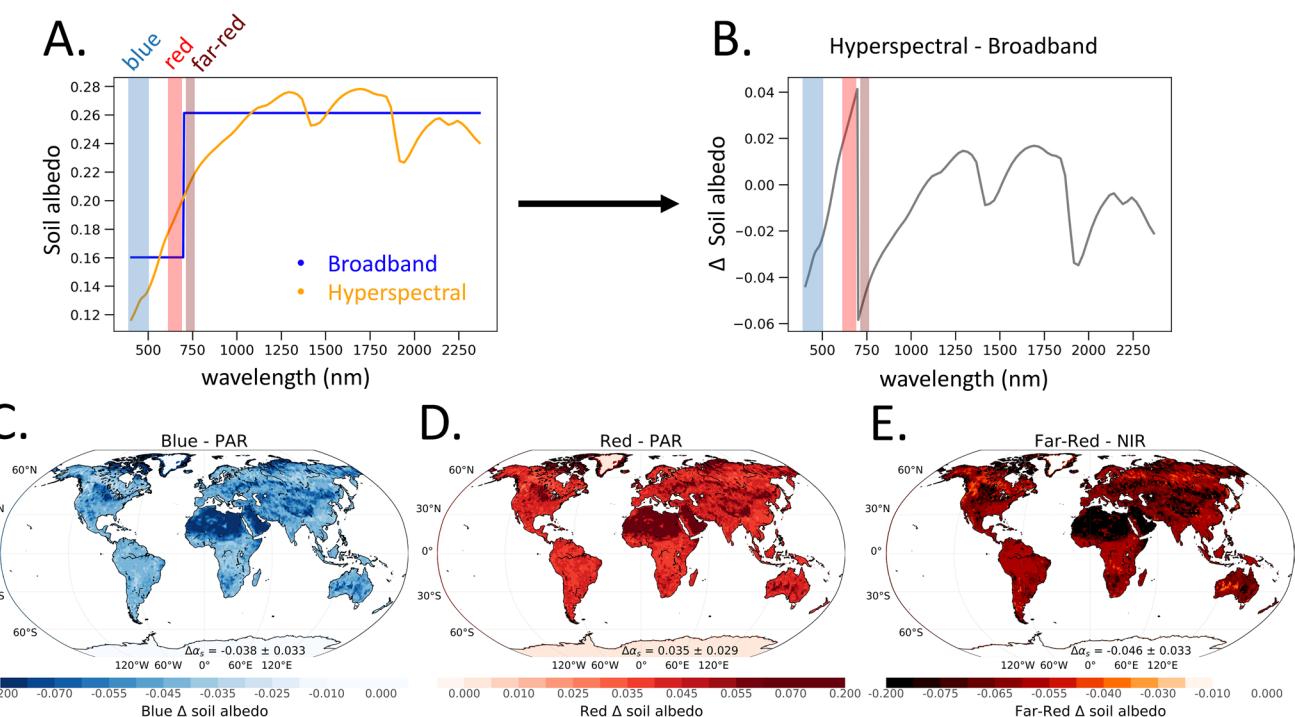
Furthermore, we perform coupled atmosphere-land simulations with an ESM to evaluate the impacts of blue versus red light on surface fluxes and climatological variables in the present climate and under the influence of elevated CO<sub>2</sub>. Particles in the atmosphere smaller than the incident electromagnetic radiation induce Rayleigh scattering, where short wavelengths (blues) are scattered more efficiently than long wavelengths (reds); this is the effect that gives the sky its blue hue. At large solar zenith angles (>60°), light must pass through more atmospheric mass, leading to blue light being scattered out and making the sky appear red. Rayleigh scattering effects mean that longer wavelengths make up a higher portion of incident PAR (Kravitz et al., 2012), the implications of which cannot be estimated by ESMs with only two broad spectral bands. Diurnal variations in the red/blue ratio of incoming PAR are usually accounted for by atmospheric radiative transfer models, but not by the broadband land surface radiative transfer model, which might cause diurnal shortwave forcing divergences.

The aim of this study is to show how incorporating a more continuous, hyperspectral representation of shortwave soil albedo affects the surface radiative forcing and simulations of the carbon and water cycles in ESMs. The objectives of the study are to estimate soil albedo biases between hyperspectral and broadband representations, to identify the spectrally integrated radiative forcing divergences between both cases, and to analyze the impacts of these differences on global energy, water and carbon fluxes. By achieving these objectives, the study enables the incorporation of hyperspectral soil background albedo information in ESMs, which will reduce uncertainty in surface reflectance.

## 2. Methods

### 2.1. Global Map of Hyperspectral Albedo

Soil albedo depends on soil intrinsic characteristics (e.g., mineral composition, color, organic matter, soil roughness) and extrinsic characteristics, such as volumetric water content. The soil color and water dependencies are usually modeled empirically in land surface models in two broadbands. In this study, we represent the effects of soil color and water content globally at high spectral resolution using a combination of the Community Land Model version 5 (CLM5) soil color scheme (P. J. Lawrence & Chase, 2007; D. M. Lawrence et al., 2019) and the General Spectral Vector (GSV) soil albedo model (Jiang & Fang, 2019) based on previous work by Condit (1972) and Price (1990). The GSV model simulates hyperspectral soil reflectance from multispectral



**Figure 1.** (a) Global average broadband soil albedo following the “soil color” scheme presented in P. J. Lawrence and Chase (2007) at 1° spatial resolution and the equivalent hyperspectral soil albedo calculated following the hybrid method (see Section 2) based on all four spectral vectors of the General Spectral Vector model (Jiang & Fang, 2019). (b) Difference between the continuous hyperspectral soil albedo and the discontinuous broadband albedo ( $\Delta\alpha_s$ ). Global spatial deviations between the hyperspectral and the broadband cases in (c) blue (404–504), (d) red (624–697), and (e) far-red (702–747 nm) spectral regions, respectively.

soil reflectance by fitting a discrete number of coefficients associated with known soil albedo values at different wavelengths to a linear combination of known spectral vectors. The spectral vectors were derived from dry and humid observed soil reflectance data, which included 23,871 soil spectra from 400 to 2,500 nm, using a common matrix decomposition method. Four vectors were provided, three of which are from databases for completely dry soils ( $v_{dry}$ ), and one vector from databases for soils at different humidity levels ( $v_{wet}$ ). Soil albedo was modeled as a linear combination of  $i = 1, \dots, 4$  spectral vectors and their associated coefficients  $c_{dry_i}$  and  $c_{wet}$ .

The broadband spectral curve needed to fit the GSV coefficients was obtained from the global soil color map in CLM5 (see Supporting Information S1). The soil moisture function was modified as follows:

$$\alpha_{band} = \alpha_{band,dry} \cdot (1 - \theta) + \alpha_{band,wet} \cdot (\theta) \quad (1)$$

where band corresponds to PAR or NIR, either dry or wet (saturated) in Table S1 in Supporting Information S1, and  $\theta$  is the volumetric soil water content ( $m^3 m^{-3}$ ) at the top of the soil (0–7 cm, the surface is at 0 cm) from ERA5 (Hersbach et al., 2020).

The fitting method minimizes the sum of the square error of: (a) two GSV vectors fitting points (2P); (b) two GSV vectors fitting curves (2C); (c) two GSV vectors, fit-ting one point and one curve, or hybrid method (2H); (d) four GSV vectors fitting two curves (4C); and (e) four GSV vectors fitting a point for PAR and a curve for NIR (4H). “Point” refers to when the whole spectral window (either PAR or NIR) are considered single points (the average), “curve” refers to when the whole spectral window (either PAR or NIR) are considered flat lines (on the average), and “hybrid” means the PAR albedo was considered a point and the NIR albedo was considered a flat line. The associated numbers indicate how many GSV vectors were used in the fitting method. A detailed description of the method is given in Note S1 in Supporting Information S1.

All four GSV vectors were used to upscale two broadbands into a hyperspectral curve using a hybrid methodology, where the PAR albedo was considered a point and the NIR albedo was considered a flat line. See Supporting Information S1 for a diagram of the fitting method.

## 2.2. Reanalysis Data

The total surface downward shortwave radiation flux (SW), the direct (clear-sky) surface downward shortwave radiation flux ( $SW_{dir}$ ), and the incoming solar radiation flux at TOA were extracted from the fifth generation ECMWF global reanalysis, ERA5 (Hersbach et al., 2020) for 2020. The diffuse surface downward radiation flux was calculated as the difference between the total and the direct fluxes at the surface. The spectral atmospheric transmissivity was calculated as the ratio between SW and the downward shortwave radiation flux at TOA ( $R_{TOA}^d$ ). The volumetric soil water content ( $m^3 m^{-3}$ ) at the top of the soil from ERA5 was used to calculate changes in soil albedo due to soil moisture following Equation 1.

## 2.3. Field Sites

Hyperspectral soil reflectance was acquired with a GER 3700 spectroradiometer (Geophysical Environ. Res. Corp., Millbrook, NY) over the 400–2,500 nm wavelength region at 1.5 nm intervals in the 400–1,050 nm region and at 9 nm intervals in the region >1,050 nm taken from Lobell and Asner (2002). The samples were illuminated by two 300 W quartz-halogen lamps mounted on the arms of a camera copy stand 50 cm above the sample at a 45° illumination zenith angle. The spectroradiometer was positioned 40 cm from the sample surface at a 0° view zenith angle. With the 3° optics on the spectroradiometer, the diameter of the field of view at the sample was 2.1 cm. The illumination and view angles were chosen to minimize shadowing and emphasize the fundamental spectral properties of the soils.

Five topsoil samples were used in this study and provided a range of colors and textures (Table S2 in Supporting Information S1). Spectral data were acquired at nine evenly spaced locations on each sample. After acquiring the spectral reflectance data from the oven-dried soils, the soils in the trays were saturated with water. The relative water content was calculated as the water content divided by the maximum water content of each sample. For further details on data acquisition refer to Daughtry (2001).

## 2.4. AVIRIS and SMAP Data

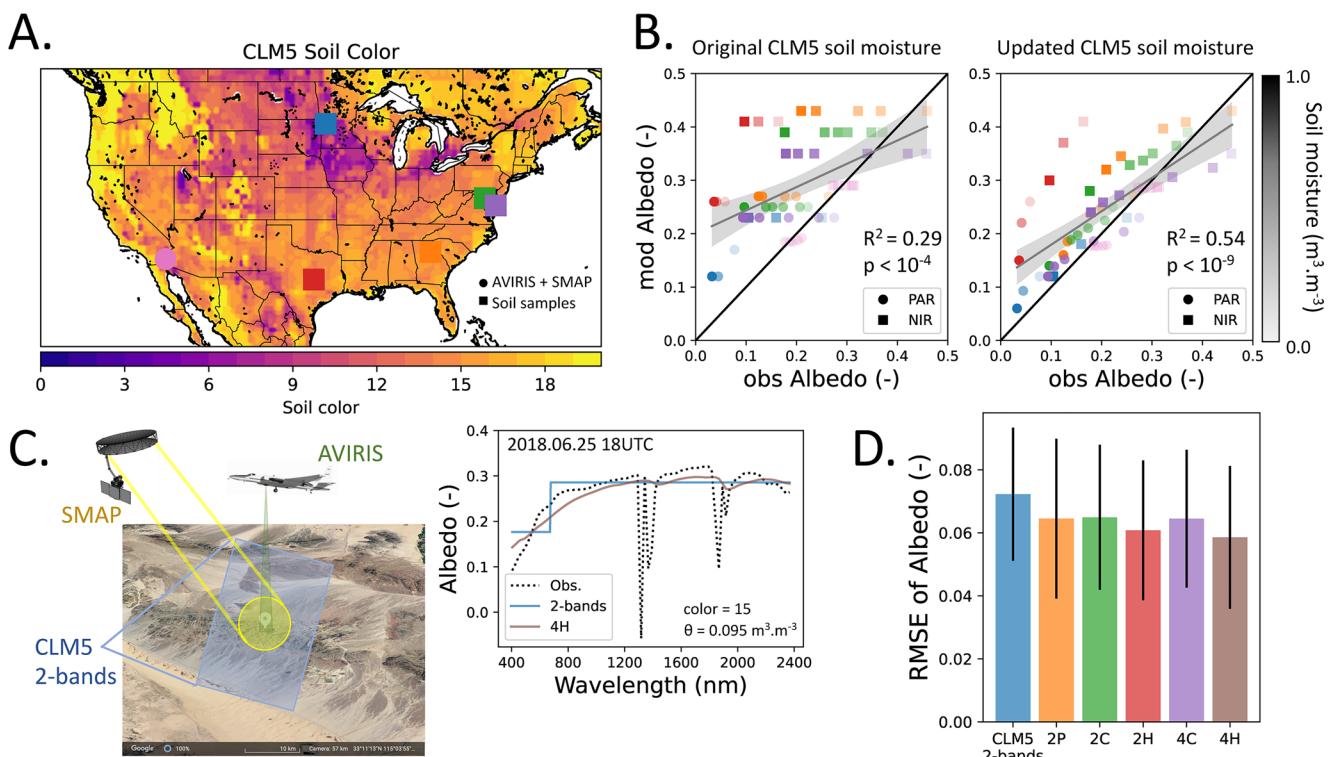
As part of Western Diversity Time Series, the Airborne Visible Infrared Imaging Spectrometer “Classic” (AVIRIS-C) was flown on the ER-2 high-altitude research aircraft in Niland, Southern California (33.2°N, 115.1°W) on 25 June 2018 around 18:00 UTC. AVIRIS-C is a whiskbroom spectrometer that measures radiance from 380 to 2,500 nm with a spectral sampling of approximately 10 nm, for a total of 224 contiguous bands (Green et al., 1998). The hemispherical-directional reflectance factor was estimated using an open-source implementation of optimal estimation, Isofit v2.9.2, accelerated with radiative transfer and local atmospheric emulation (Brodrick et al., 2021; Thompson et al., 2018, 2020). Ten flight lines were mosaicked together, and three sites were selected in areas with relatively low vegetation cover (less than 5%), as determined by spectral mixture analysis.

Unlike the laboratory spectra, AVIRIS data were acquired under natural conditions, which will have included the effects of soil surface crusts/seals and soil roughness and shadows. These factors can significantly influence the reflectance spectra of soils, especially in the shortwave infrared region (Boardman et al., 1995; Goetz et al., 1985; Roberts et al., 1998). Therefore, the AVIRIS reflectance spectra are expected to be more realistic than the laboratory spectra and more representative of the actual soil conditions in the study area.

The NASA Soil Moisture Active Passive (SMAP) mission Level-4 Soil Moisture product provides global, 3-hourly, 9-km resolution estimates of top soil (0–5 cm) soil moisture assimilating SMAP L-band (1.4 GHz) daily microwave brightness temperature into the NASA Catchment land surface model (Ducharme et al., 2000; Koster et al., 2000). Reflectance estimates were averaged from AVIRIS-C data to match the resolution of corresponding SMAP footprints (Figure 2c).

## 2.5. CliMA-Land Model

The CliMA-Land model includes a hyperspectral canopy radiative transfer, soil water movement, plant water transport, stomatal regulation, and simulates water, carbon, and energy fluxes in a modular manner being part of a new ESM developed by the Climate Modeling Alliance (CliMA). The CliMA-Land radiative transfer scheme



**Figure 2.** (a) Soil color map at 0.23° resolution over the continental USA from the Community Land Model version 5 (CLM5). Locations of soil samples and AVIRIS + Soil Moisture Active Passive (SMAP) data are indicated (see Methodology for a description of sites and data). (b) Scatter plot of photosynthetically active radiation band and near infra-red band soil albedos for the default soil moisture scheme in CLM5 (left) versus the updated soil moisture scheme version (right). Different colors indicate different sites, while shading indicates different levels of soil moisture. (c) Diagram showing the soil color map resolution from CLM5 in two-band with the AVIRIS + SMAP data coverage indicated (left). The observed shortwave hyperspectral soil albedo is shown (black dotted line) with the two-band albedo from CLM5 for soil color 15 (blue line), and the fitted curve using Four Bands Fitting Hybrid method (4H, brown line). See methodology for a complete description of the fitting methods. (d) RMSE of soil albedo for the CLM5 two-band method and all the other fitting methods (2P: Two Bands Fitting Point; 2C: Two Bands Fitting Curve; 2H: Two Bands Fitting Hybrid; and 4C: Four Bands Fitting Curve). All the other experiments carried out the 4H method due to smaller associated errors.

is based on the vertically heterogeneous mSCOPE (Yang et al., 2017), which makes use of Fluspect (Vilfan et al., 2016) to simulate leaf reflectance, transmittance, and fluorescence at leaf level, and a SAIL based formulation (Verhoef, 1984) to compute spectrally resolved radiative transfer, as well as emitted fluorescence (van der Tol et al., 2016). However, some important changes were incorporated into the new CliMA-Land radiative transfer scheme including: (a) accounting for carotenoid light absorption as part of absorbed photosynthetically active radiation (Wang & Frankenberg, 2022; Wang et al., 2021, 2023) and (b) accounting for horizontal canopy structure with the inclusion of a clumping index (Braghiere et al., 2021a).

We used the gridded Moderate Resolution Imaging Spectroradiometer (MODIS) LAI product at 0.5° spatial resolution and 8-day temporal resolution (Yuan et al., 2011), weekly mean leaf chlorophyll content to represent seasonality of canopy greenness (Croft et al., 2020), and assumed leaf carotenoid content being 1/7 of the chlorophyll content, specific leaf area as the inverse of leaf mass per area (Butler et al., 2017), leaf photosynthetic capacity represented by the maximum carboxylation rate at a reference temperature of 25°C ( $V_{max25}$ ) from a machine learning based product (Luo et al., 2021), the maximum electron transport rate at a reference temperature of 25°C ( $J_{max25}$ ), and respiration rate at a reference temperature of 25°C ( $R_{d25}$ ) scaled from  $V_{max25}$  as  $J_{max25} = 1.67 \cdot V_{max25}$  and  $R_{d25} = 0.015 \cdot V_{max25}$ , a canopy height map was used to initialize plant hydraulic architecture within each simulation (Simard et al., 2011), and MODIS clumping index was used to represent canopy horizontal structure (Braghiere et al., 2019; He et al., 2012). Gridding Machine (Wang et al., 2022) is a tool developed for CliMA-Land that simplifies the replacement of plant trait maps. These maps contain important information about vegetation characteristics and are crucial for accurately representing vegetation processes in the model. With Gridding Machine, researchers can easily incorporate new or improved plant trait maps into

CliMA-Land, allowing for the integration of the latest scientific advancements and data sources. This flexibility enhances the model's capabilities in capturing the complexities of vegetation processes and improves predictions of ecosystem dynamics.

## 2.6. Climate Simulation

We ran simulations using National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM) 6, coupled with CLM5 and prescribed surface ocean temperatures, a river transport model (MOSART) and the Los Alamos Sea Ice Model (CICE). Simulations were run at a 30-min time step with a resolution of  $1.9^\circ$  by  $2.5^\circ$  for 50 years. We specifically ran the model using compset F\_2000\_SP, which uses the models described above. We ran the model with no dynamic vegetation response; atmospheric CO<sub>2</sub> was held constant at 367 ppm for one set of runs and 700 ppm for the other set. Present-day prescribed surface ocean temperatures were used in both CO<sub>2</sub> scenarios.

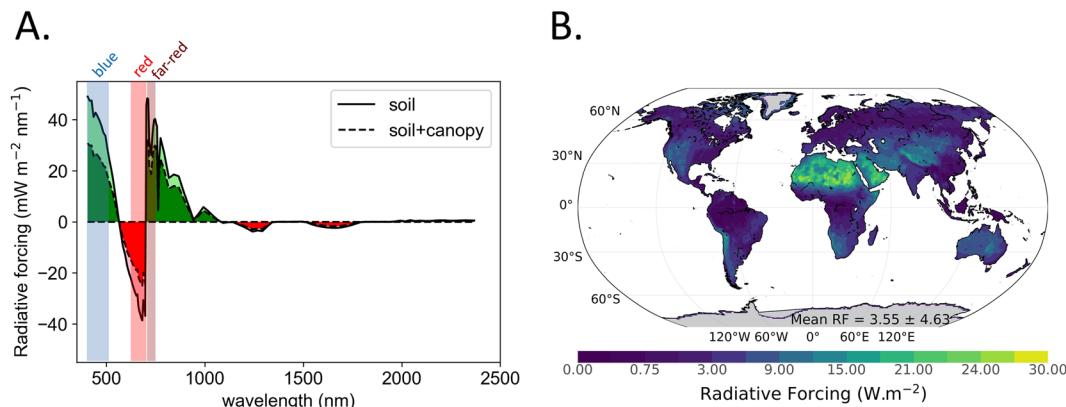
We simulate global climate for scenarios where the background soil albedo behaves as if the diffuse incident PAR was completely blue (Figure 1c), and the incident direct PAR was completely red (Figure 1d), but only for sun zenith angles over  $60^\circ$ . The justification for the general representation of the extreme sun zenith angles ( $>60^\circ$ ) used in these climate simulations comes from radiative transfer model results under clear sky conditions that indicate most of the direct photosynthetically active irradiance is skewed to red, while most of the diffuse photosynthetically active irradiance is skewed to blue (Kravitz et al., 2012; Mayer & Kylling, 2005). Supplementary runs were performed assuming the background soil albedo acted as: (a) global PAR radiation was blue, (b) global PAR radiation was red, and (c) global NIR radiation was far-red. These large changes to soil albedo were chosen to clearly demonstrate the extremes of change. Similarly, analysis considering all sun zenith angles is presented in Supporting Information (Table S3 in Supporting Information S1). The canopy albedo in CLM was calculated using the two-stream radiative transfer scheme, which is a function of LAI and SAI, leaf albedo and transmittance, soil albedo, and the cosine of the zenith angle of the incident beam radiation, among other parameters (Sellers, 1985). We averaged the final 30 years of the following variables (collected monthly) from the modified CLM5 with new soil background albedos: net shortwave radiation flux at TOA (W m<sup>-2</sup>); latent heat flux (W m<sup>-2</sup>); maximum daily 2 m air temperature (K); photosynthesis (μmol m<sup>-2</sup> s<sup>-1</sup>); precipitation (mm day<sup>-1</sup>); and cloud cover (%) from CAM6.

## 3. Results

In this study, we represent the effects of soil color and soil water volumetric content globally using a combination of the CLM5 soil color scheme (P. J. Lawrence & Chase, 2007; D. M. Lawrence et al., 2019) and the GSV soil albedo model (Jiang & Fang, 2019). First, we updated the impact of top layer (0–5 cm) soil moisture content in CLM5 by linearly averaging the soil albedos for saturated and dry soil color classes (Equation 1). Figure 2 shows a validation of the updated method for calculating the impact of soil moisture on PAR and NIR soil background albedos.

Figure 2a shows the CLM5 soil color map over the continental USA with five locations where soil samples were collected (Lobell & Asner, 2002) and one location in California where hyperspectral data was collected with AVIRIS-C (hereafter “AVIRIS”) (Green et al., 1998, 2020). Soil color was combined with measurements of soil moisture collected with NASA’s SMAP mission (Reichle et al., 2019) and validated with AVIRIS data (Figure 2c). The updated soil moisture scheme increased the predictive skill of top soil layer impact on soil albedo (from  $R^2 = 0.29$  to  $R^2 = 0.54$ ). The data points show in Figure 2a are independent spectral soil measurements, either from ground data or a combination of AVIRIS and SMAP, and therefore, they were not used in the training processes of the GSV model. Likewise, in Figures 2b and 2d, the updated CLM5 soil moisture scheme is validated with independent data, as well as the fitting methods.

The two-band soil albedo in CLM5 with the updated soil moisture scheme was then used with the GSV vectors to upscale the broadband version into a hyperspectral curve using the different methodologies described in Note S1 in Supporting Information S1. The different fitting methodologies minimize the sum of the square error between the average values for each part of the spectrum separately. A complete description of the method can be found in Methods, and a visual diagram can be found in Figure S3 in Supporting Information S1. Figure 2d shows the RMSE of soil background albedo for the CLM5 two-band method and all the other fitting methods. The method 4H presented the lowest associated RMSE and it was used in all the experiments that followed.



**Figure 3.** (a) Global average spectral radiative forcing ( $\text{mW m}^{-2} \text{ nm}^{-1}$ ) caused by the difference between a hyperspectral and broadband background soil albedo over soil only (continuous line) and for soil + canopy (dashed line) from CliMA-Land using yearly climatological values for 2020 (see Methodology). (b) The spectrally integrated radiative forcing between the continuous hyperspectral soil albedo and the discontinuous broadband albedo for soil + vegetation canopy from CliMA-Land. The global mean radiative forcing with standard deviation is also shown.

Figure 1 shows the global average broadband soil albedo following the “soil color” scheme at  $1^\circ$  resolution (P. J. Lawrence & Chase, 2007) and the hyperspectral soil albedo calculated using the GSV model (Jiang & Fang, 2019). Averaged across the shortwave radiation spectrum (400–2,500 nm), the difference between the hyperspectral curve and the broadband curve are negative and less than 1% ( $\Delta\alpha_s = -0.007 \pm 0.005$ ), indicating that overall, the solar spectrum reflectance is slightly greater when assuming a broadband soil albedo. In some places on Earth, especially over deserts with sandy soils, these averaged spectral differences can reach  $|\Delta\alpha_s| > 0.02$  (Figure S1 in Supporting Information S1). However, for particular wavelengths (e.g., blue and far-red), the differences in spectral albedo can be substantial ( $|\Delta\alpha_s| > 0.2$ ). The largest differences between the hyperspectral and broadband soil background albedos are found in three distinct bands of the shortwave radiation spectrum, that is, far-red (702–747 nm with average  $\Delta\alpha_s = -0.046 \pm 0.033$ , blue (404–504 nm) with average  $\Delta\alpha_s = -0.038 \pm 0.033$ , and red (624–697 nm) with average  $\Delta\alpha_s = 0.035 \pm 0.029$  (Figures 1b–1d).

The net shortwave surface radiation budget and thus surface temperature are directly affected by changes in surface albedo. The shortwave radiative forcing has been used to estimate the global impact of regional changes in surface albedo (Kramer et al., 2021; Loew et al., 2014). In this study, the shortwave radiative forcing is interpreted as a disturbance of the reflected radiances caused by variations in soil and surface albedos. Therefore, the soil albedo-induced radiative forcing as presented here should not be interpreted as estimates of radiative forcing from different climate forcing agents (Bright & Lund, 2021), but rather as a proxy of the surface shortwave energy imbalance caused by assuming a broadband background soil albedo representation versus a hyperspectral one. The albedo-induced radiative forcing ( $\text{RF}_{\alpha_s}$ ) is given by

$$\text{RF}_{\alpha_s} = -R_{\text{TOA}}^{\downarrow} \Gamma_a^{\uparrow} \Delta\alpha_s = \int_{400\text{nm}}^{2500\text{nm}} -R_{\text{TOA}}^{\downarrow}(\lambda) \Gamma_a^{\uparrow}(\lambda) \Delta\alpha_s(\lambda) d\lambda \quad (2)$$

where  $R_{\text{TOA}}^{\downarrow}(\lambda)$  ( $\text{mW m}^{-2} \text{ nm}^{-1}$ ) is the TOA spectral incoming solar radiation flux following Kurucz (Kurucz, 1992) (Figure S2 in Supporting Information S1),  $\Gamma_a^{\uparrow}(\lambda)$  is the two-way spectral atmospheric transmissivity that is given as the product of the downward and upward spectral atmospheric transmissivities, assumed to be equal to one another, and  $\Delta\alpha_s(\lambda)$  is the difference in spectral soil albedo between the hyperspectral and the broadband cases.

We calculate radiative forcing for barren soils and for soils with vegetation using the CliMA-Land model (Figure 3a). The mean yearly climatological values for 2020 from ERA5 of: (a) direct and diffuse incident shortwave irradiance, (b) volumetric soil moisture at the first soil layer, and (c) incident shortwave radiation at the TOA were used. Yearly means of all the canopy related variables (LAI, clumping index, chlorophyll content, soil colors) were also used in these calculations. For barren soils globally, the absolute soil albedo-induced radiative forcing is greater than the case when vegetation canopies and soils are considered together. Over areas with dense vegetation (i.e., tropical and boreal forests), the difference between a hyperspectral soil representation and a

broadband one is attenuated because solar radiation interacts less with the background soil in the presence of an optically active vegetation (Figure 3b).

The spectral discontinuity in 700 nm, also known as the “red edge,” is more applicable to vegetated surfaces, as it reflects the transition from PAR to NIR. This feature is often used to determine the two-band spectral curve of soil background albedo in ESMs, but for barren soils or areas with low vegetation cover, the spectral discontinuity becomes less relevant in determining surface reflectance. This can lead to inaccuracies in shortwave radiation simulations in ESMs that assume a spectral discontinuity in the soil background albedo at 700 nm. Additionally, the high variability in LAI throughout the year can lead to significant seasonal biases in shortwave radiation simulations based on this assumption.

Over desert areas, the integrated radiative forcing can be as high as  $30 \text{ W m}^{-2}$ , mostly due to blue and far-red wavelengths. In the PAR spectral region, although the blue radiative forcing and the red one have opposite signs, the blue radiative forcing is at least 50% higher than the red one, causing a positive bias over the entire PAR region. In the NIR spectral region, most of the radiative forcing is positive and associated with the spectral region 700–1,000 nm. The global-mean integrated radiative forcing bias including soil and vegetation canopy is therefore positive and it is equal to  $3.55 \text{ W m}^{-2}$ . We conducted an additional analysis to compute the global-mean radiative forcing bias including ocean points set to zero, to further our initial analysis that used only land-based reference values. The results show a smaller value ( $1.20 \text{ W m}^{-2}$ ) but still positive (see Figure S6 in Supporting Information S1).

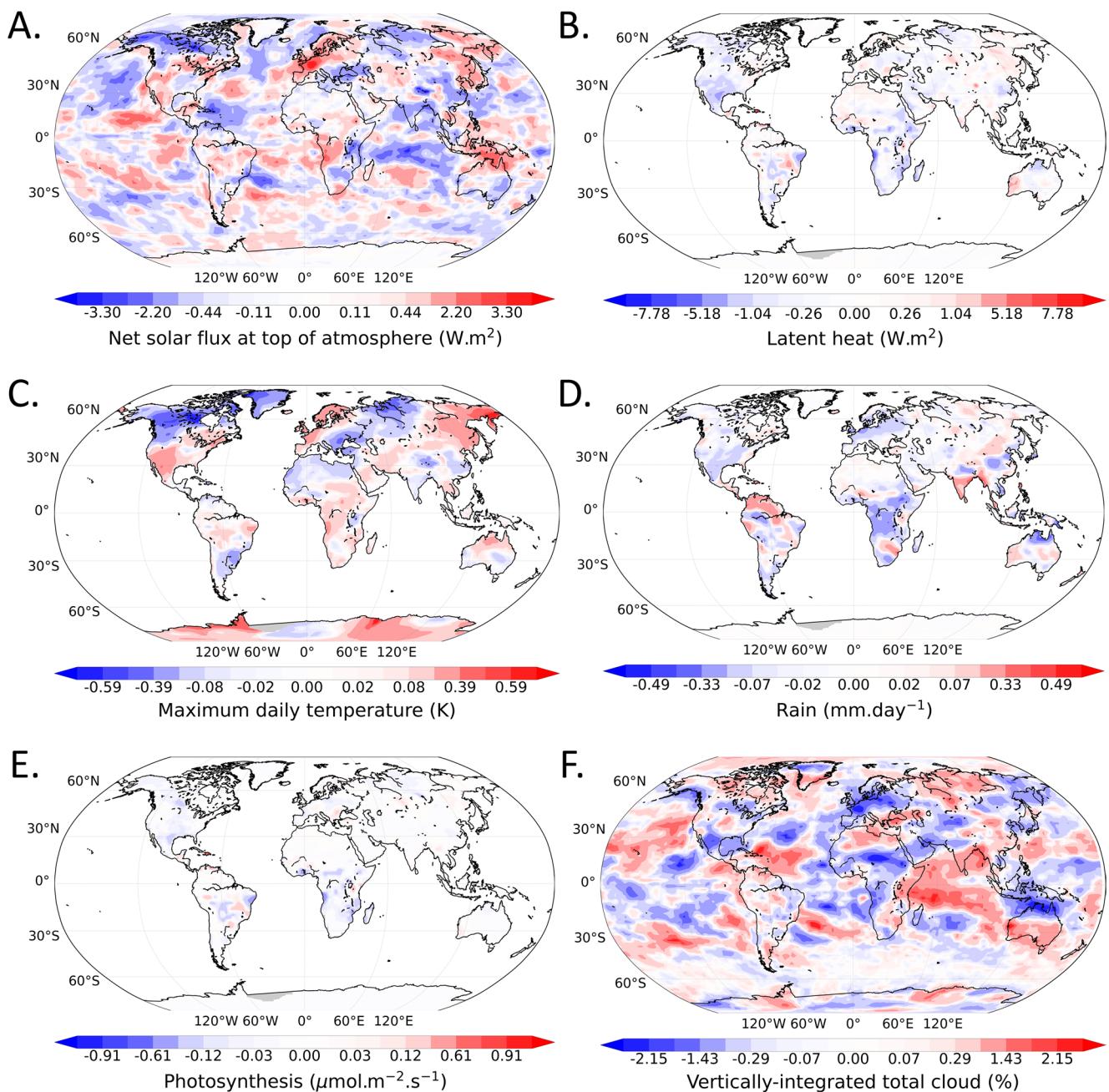
This difference in soil albedo-induced global radiative forcing propagates into other ESM components, presenting further impacts on climate simulations. For instance, at  $\text{CO}_2$  concentrations for the year 2000 (367 ppm), accounting for the different spectral characteristics of direct (red) versus diffuse (blue) light for sun zenith angles over  $60^\circ$  decreases average latent heat fluxes (Figure 4b and Table 1), cloud cover (Figure 4g), and rainfall (Figure 4d). At current and future  $\text{CO}_2$  concentrations, maximum daily temperature (Figure 4c) increases when considering the spectral effect of direct red versus diffuse blue light on soil reflectance. Photosynthesis decreases for current  $\text{CO}_2$  concentrations (Figure 4e) but increases in the future relative to biases in blue/red ratio. The same analysis is presented in Supporting Information S1 considering all sun zenith angles (Table S3 in Supporting Information S1).

The maps (Figure 4) show a significant decrease in net solar flux at TOA over Alaska and northern/western Canada, as well as parts of central Siberia. By contrast, over Europe and eastern Asia, we find an increase in net solar flux at TOA. Over most tropical forests, there is an increase in net solar flux at TOA, although parts of northern Amazon, eastern Africa, and southern/central Australia present a decrease in net solar flux at TOA. Spatial patterns of maximum daily temperature tend to follow changes in net solar flux at TOA, with cloud cover and rainfall patterns showing the opposite behavior.

A validation with observation-based products is shown in Figures S4 and S5 in Supporting Information S1. The bias, RMSE, correlation coefficient, and overall score (the weighted average between bias and RMSE, given double weight to RMSE) for the control global run of CLM 5.0 coupled to CAM 6.0 (control), the modified version of the model considering diffuse light as blue and direct light as red for sun zenith angles larger than  $60^\circ$  (color) and observation products for precipitation in  $\text{mm d}^{-1}$  from Willmott-Matsuura (Willmott & Matsuura, 2018), all-sky albedo from MODIS (2001–2003) (Schaaf et al., 2002), latent heat in  $\text{W m}^{-2}$  and photosynthesis in  $\text{gC m}^{-2} \text{ d}^{-1}$  from FLUXNET (1982–2008) (Jung et al., 2011) are shown in Table S4 in Supporting Information S1. A validation for atmospheric variables is shown Table S5 in Supporting Information S1, including the Clouds and Earth's Radiant Energy Systems (CERES) Energy Balanced and Filled (EBAF) shortwave Cloud Forcing product at  $1^\circ$  resolution globally from March 2000 to February 2017 (Kato et al., 2018) showing a slight improvement in the space-time correlation coefficient between the hyperspectral version of the model and observations.

#### 4. Discussion

ESMs can propagate errors into several parts of the climate system by making simplistic assumptions about the hyperspectral nature of the shortwave radiation. Understanding how global changes affect the composition of solar radiation reaching the Earth's surface is integral to accurate modeling of the global carbon cycle (Schneider, Lan, et al., 2017). For instance, global changes in cloudiness and pollution may be affecting the sunlight received



**Figure 4.** Climate simulations with blue diffuse versus red direct soil background albedos for present-day  $\text{CO}_2$  concentrations. Simulations of CLM-5.0 coupled with CAM-6.0 for 30 years, for which we assumed photosynthetically active radiation (PAR) band background soil albedo acted as the diffuse incident PAR was blue and the incident direct PAR was red for sun zenith angles greater than  $60^\circ$ . (a) Change in net shortwave radiation flux at the TOA ( $\text{W m}^{-2}$ ). (b) Change in latent heat flux ( $\text{W m}^{-2}$ ). (c) Change in maximum daily 2 m air temperature (K). (d) Change in precipitation ( $\text{mm day}^{-1}$ ). (e) Change in photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ). (f) Change in cloud cover percentage (%).

by plants (Braghieri et al., 2020b; Durand et al., 2021). Local seasonal and diurnal changes in the spectral composition of surface incident shortwave radiation are related to atmospheric water vapor, which are predicted to increase given higher average global temperatures (Kotilainen et al., 2020). Therefore, it is desired that state-of-art ESMs become able to represent the hyperspectral nature of the radiation in order to allow different hypothesis testing and more accurate uncertainty quantification. In our simulations, we observed a global integrated radiative forcing divergence of  $3.55 \text{ W m}^{-2}$  between the two-band and the hyperspectral representations of soil background albedo.

**Table 1**  
*Change in Latent Heat ( $\text{W m}^{-2}$ ), Sensible Heat ( $\text{W m}^{-2}$ ), Cloud Cover (%), Rainfall ( $\text{mm d}^{-1}$ ), Air Temperature (K), Photosynthesis ( $\text{PgC yr}^{-1}$ ), and Net Solar Flux at the Top of the Atmosphere ( $\text{W m}^{-2}$ ) When Considering Diffuse Light as Blue and Direct Light as Red for Sun Zenith Angles Over  $60^\circ$  Using CLM 5.0 Coupled to CAM 6.0 for the Entire Globe*

		Latent heat ( $\text{W m}^{-2}$ )		Sensible heat ( $\text{W m}^{-2}$ )		Cloudiness (%)		Rainfall ( $\text{mm d}^{-1}$ )		Temperature (K)		Photosynthesis ( $\text{PgC yr}^{-1}$ )		Net solar flux TOA ( $\text{W m}^{-2}$ )	
		367 ppm	700 ppm	367 ppm	700 ppm	367 ppm	700 ppm	367 ppm	700 ppm	367 ppm	700 ppm	367 ppm	700 ppm	367 ppm	700 ppm
Mean variable control	40.46	<b>38.34</b>	31.94	<b>33.83</b>	67.38	<b>67.16</b>	2.39	<b>2.36</b>	282.06	<b>282.24</b>	140.03	<b>175.28</b>	239.53	<b>239.86</b>	
Explicit color change	40.30	<b>38.37</b>	32.07	<b>33.80</b>	67.35	<b>67.22</b>	2.38	<b>2.36</b>	282.09	<b>282.26</b>	139.29	<b>175.36</b>	239.48	<b>239.76</b>	
Difference (%)	-0.38	<b>0.07</b>	0.41	<b>-0.07</b>	-0.05	<b>0.08</b>	-0.54	<b>-0.04</b>	0.01	<b>0.01</b>	-0.53	<b>0.04</b>	-0.02	<b>-0.04</b>	

Note. We show mean value at standard assumption (no difference between blue vs. red, mean variable control), the explicit differentiation between blue versus red (Explicit color), and the change between the control run and the color run. Values are shown for 367 (left) and 700 ppm (right).

When performing land-atmosphere coupled runs while considering the more red nature of direct light at sunsets/sunrises globally, we estimate a significant difference in net solar flux at TOA ( $>3.3 \text{ W m}^{-2}$ ) and further impacts on latent and sensible heat fluxes, cloudiness, rainfall, surface temperature, and photosynthesis (Figure 4). These results highlight the importance of incorporating hyperspectral information in current ESMs. Doing so in the coming years will also enable direct assimilation of in-situ and satellite observations of hyperspectral surface reflectance (Schimel et al., 2019; Schneider, Teixeira, et al., 2017), linking intrinsic surface properties with processes, such as leaf pigments (Féret et al., 2019), vegetation and soils chemical composition (Meacham-Hensold et al., 2019; Serbin et al., 2014), as well as rhizospheric processes (Braghiere et al., 2021b; Sousa et al., 2021).

Figure 4 includes variables that were evaluated over both land and ocean, such as net solar flux at TOA ( $\text{W m}^{-2}$ ) and vertically integrated total cloud (%), which may be influenced over the ocean through changes in land-sea temperature contrasts or circulation patterns. However, for the remaining variables, we intentionally concentrated our analysis on the impacts of changes in soil albedo specifically over the land surface. We did this because these variables are more immediately affected by alterations in soil albedo treatment on land, and have significant implications for human societies. This focused approach enables us to more accurately evaluate the potential impacts of soil albedo changes on key land-based climate variables, such as precipitation, temperature, and latent heat flux. By doing so, we hope to provide valuable insights into the potential regional impacts of soil albedo changes.

Our results also indicate that the diffuse blue versus direct red sunset/sunrise phenomenon in climate models may change precipitation and temperature patterns by simply considering the soil background albedo bias between two distinct treatments of the problem. However, further studies are needed where hyperspectral vegetation albedo biases are also included in the analyses. To do so, more hyperspectral models of vegetation, such as the GSV model for soils, are required. Yet to date, there are no real globally comprehensive observations of hyperspectral soil spectra—only models constructed from sparse data sets. Nevertheless, the general argument of this study is that two-band surface radiative transfer schemes are insufficient to completely characterize shortwave radiation-surface interactions, and that the development of atmosphere and surface hyperspectral radiative transfer schemes within ESMs is highly desirable.

It is important to consider the broader context of climate change and to compare the magnitudes of the changes in our study to the changes that would be expected in a current versus elevated- $\text{CO}_2$  climate. To address this concern, we have provided a comparison between the two scenarios as shown in Table 1. Through our analysis, we have determined that the changes in latent heat flux resulting from different soil albedo treatments are on the order of  $0.16 \text{ W m}^{-2}$ , while those resulting from increased  $\text{CO}_2$  concentrations are on the order of  $2.12 \text{ W m}^{-2}$ . By comparing all the evaluated variables shown in Table 1, we are able to better contextualize the significance of these changes within the broader context of climate change.

The global-mean changes due to explicit color are only fractions of a percent. However, we believe that these changes are still important to consider, particularly in light of the potential regional impacts that we have highlighted in our study. For example, regional changes in latent heat can be higher than  $5 \text{ W m}^{-2}$  (Figure 4b). This indicates the importance of the spatial heterogeneity of the impacts of soil albedo changes on climate and the potential implications for regional climate variability and predictions of extreme events.

We acknowledge the limitations of this analysis and the uncertainties associated with the magnitude and direction of the changes in the evaluated climate variables caused by these two different treatments of soil albedo. For example, the analysis of the changes in soil albedo could be subject to uncertainties associated with the measurement or estimation of the optical properties of soils. Different methods or models may produce different estimates of the spectral reflectance of soils, and these differences may affect the calculation of the changes in soil albedo and the subsequent effects on climate variables. Also, there may be potential feedbacks between climate variables and vegetation dynamics that were not fully accounted for in the analysis. The analysis may need to consider the interactions between soil albedo, vegetation dynamics, and other biophysical and biogeochemical processes that affect climate variables (Chakraborty et al., 2022; Luo et al., 2018).

To account for the influence of other factors that may affect soil spectral reflectance, we acknowledge that our study has focused on only two variables, soil color and moisture, and that there are other factors

that could be confounding. For example, soil roughness has been shown to significantly impact soil reflectance, as well as other compositional characteristics such as soil organic matter content and iron-oxides (Cierniewski et al., 2004; Coulson & Reynolds, 1971; Hapke, 2012; Jacquemoud et al., 1992). While the spectral vectors used to simulate hyperspectral soil reflectance were derived from dry and humid observed soil reflectance data, it should be noted that laboratory soil spectra are typically measured on soils treated in standardized methods, which removes intrinsic soil aggregates that create shadow and does not represent the spatiotemporal variability in soil surface dynamics, such as soil surface crusts/seals that occur preferentially at the soil surface (Rodríguez-Caballero et al., 2022).

Likewise, vegetation canopy structure can significantly impact the magnitude of surface albedo, especially in sparsely vegetated surfaces (Braghiere et al., 2019, 2020a, 2021a). We have taken this into consideration when comparing land model runs with a clumping index, accounting for vegetation canopy horizontal heterogeneity in both setups (broadband and hyperspectral). Nevertheless, we acknowledge that improvements can be made to the soil color map if a clumping index is also taken into account when running the two-stream scheme with climatological values of soil moisture and LAI. We recognize that the omission of these factors in our methodology may increase uncertainty of our results and should be considered in future studies.

The launching of global missions to comprehensively collect hyperspectral data and further inform the mineral composition of Earth's soils, such as the NASA Earth Surface Mineral Dust Source Investigation (EMIT), will support future modeling endeavors to help close this gap. Likewise, NASA's Surface Biology and Geology mission will enable acquisition of high spatial resolution (~30 m pixels) hyperspectral data globally with sub-monthly temporal revisits over terrestrial, freshwater, and coastal marine habitats (Cawse-Nicholson et al., 2021), allowing ESMs to finally shift radiative transfer paradigms from broadband to hyperspectral unlocking a new era in climate modeling.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

The scripts to generate the global hyperspectral soil albedo map used in this study can be found in soil.jl (<https://doi.org/10.5281/zenodo.7662527>). Code and documentation of the in-development CliMA-Land model are publicly available at <https://github.com/CliMA/Land> and Zenodo (<https://doi.org/10.5281/zenodo.7662527>). Simulations using NCAR's Community Atmosphere Model (CAM-6.0, <http://www.cesm.ucar.edu/models/cam>), coupled with the Community Land Model (CLM 5.0, <http://www.cgd.ucar.edu/tss/clm/>) with prescribed surface ocean temperatures, a river transport model (MOSART, <https://www.cesm.ucar.edu/models/cesm2/river>) and the Los Alamos Sea Ice Model (CICE, <https://www.cesm.ucar.edu/models/cice>). The global reflectance maps and diagnostics plots of CAM and CLM are available in <https://doi.org/10.5281/zenodo.7996096>.

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