

Title: Estimating 10-m land surface albedo from Sentinel-2 satellite observations using a direct estimation approach with Google Earth Engine

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Abstract

Land surface albedo plays an important role in controlling the surface energy budget and regulating the biophysical processes of natural dynamics and anthropogenic activities. Satellite remote sensing is the only practical approach to estimate surface albedo at regional and global scales. It nevertheless remains challenging for current satellites to capture fine-scale albedo variations due to their coarse spatial resolutions from tens to hundreds of meters. The emerging Sentinel-2 satellites, with a high spatial resolution of 10 m and an ~5-day revisiting cycle, provide a promising solution to address these observational limitations, yet their potential remains underexplored. In this study, we integrated the Sentinel-2 observations with an updated direct estimation approach to improve the estimation and monitoring of fine-scale surface albedo. To enable the capability of the direct estimation approach at a 10-m scale, we combined the 10-m resolution European Space Agency (ESA) WorldCover land cover data and the 500-m resolution MODIS Bidirectional Reflectance Distribution Function (BRDF)/albedo product to build a high-quality and representative BRDF training database. To evaluate our approach, we proposed an integrated evaluation framework leveraging 3-D physical model simulations, ground measurements, and satellite observations. Specifically, we first simulated a comprehensive dataset of Sentinel-2-like surface reflectance and broadband albedo across a variety of geometric configurations using the MODIS BRDF training samples. With this dataset, we built the Look-Up-Tables (LUTs) that connect surface broadband albedo and Sentinel-2 reflectance through a direct angular bin-based linear regression approach and coupled these LUTs with the Google Earth Engine (GEE) cloud-computing platform. We next evaluated the proposed algorithm at two levels: 1) 10-m scale for absolute accuracy assessment using the references from the Discrete Anisotropic Radiative Transfer (DART) simulations and flux-site observations, and 2) 500-m scale for large-scale mapping assessment by comparing the estimated albedo with the MODIS albedo product. Finally, we presented four examples of the Sentinel-2 albedo in detecting the fine-scale characteristics of vegetation and urban covers. Results show that: (1) the proposed algorithm accurately estimates surface albedo from Sentinel-2-like reflectance across different landscape configurations (overall root-mean-square-error (RMSE) = 0.018, bias = 0.005, and coefficient of determination (R^2) = 0.88); (2) the Sentinel-2-derived surface albedo agrees very well with the ground measurements (overall RMSE = 0.030, bias = -0.004, and R^2 = 0.94) and the MODIS

products (overall RMSE = 0.030, bias = 0.021, and $R^2 = 0.97$); and (3) Sentinel-2-derived albedo captures the long-period leaf phenology and short-period snow events, and detects the interspecific (or interclass) variations of tree species and colorful urban rooftops. These results demonstrate the capability of the proposed approach to map high-resolution surface albedo from Sentinel-2 satellites over large spatial and temporal contexts, suggesting the potential of using such fine-scale datasets to improve the understanding of albedo-related biophysical processes in the coupled human-environment ecosystem.

Keywords: Direct estimation approach; Flux network; High-resolution satellite; Sentinel-2 reflectance; MODIS BRDF/albedo; Spatial heterogeneity; Temporal dynamics

1. Introduction

Land surface albedo—the fraction of radiative flux reflected by a surface to the atmosphere—is a critical variable in estimating the global surface energy budget (Dickinson, 1983; Liang et al. 2019; Schaaf et al. 2002). It is one of the essential climate variables that reflect the variations, patterns, and drivers of the Earth's climate by regulating the biophysical effects of natural events or human activities (Shuai et al. 2014; Zeng et al. 2021). It is also tightly connected with several biogeochemical and hydrological cycles as the absorbed radiant flux (e.g. absorbed photosynthetically active radiation, APAR) drives the processes of plant photosynthesis, vegetation growth, and evapotranspiration (Chen and Liu, 2020; Marshall et al. 2018; Zhang et al. 2020a). Therefore, an accurate estimation of surface albedo helps quantify the global surface energy budget and understand the biogeochemical and hydrological processes for improving predictions of future climate change within the context of increasing anthropogenic impacts.

Increasing interest has particularly focused on the accurate mapping of fine-scale surface albedo, especially for the spatial resolution varying from a few to tens of meters (Li et al. 2018; Shuai et al. 2014). Fine-scale land surface presents spatially detailed characteristics of the landscape. Thus, the fine-scale variability in surface albedo reflects multiple relevant local- and landscape-scale biophysical processes of natural events and anthropogenic activities, such as land surface energy budget and radiative forcing, canopy photosynthesis and transpiration, wildfire burning, snowfall and snowmelt, urban expansion, and heat island effect (Baldinelli et al. 2015; Hu et al. 1999; Mihailovic et al. 2012; Potter et al. 2020; Schwerdtfeger, 2002; Trlica et al. 2017;

Wang et al. 2011). An increasing number of recent studies have proven the great potential of fine-scale surface albedo for many other practical applications, such as forestry management (Kuusinen et al. 2014; Vanderhoof et al. 2014), agricultural monitoring (Gao et al. 2014; Li and Fang, 2015), and accuracy assessments of satellite products (Lin et al. 2018; Román et al. 2013; Wu et al. 2016). Therefore, an improved estimation and monitoring of fine-scale surface albedo are essential for understanding multiple albedo-driven biophysical processes and facilitating albedo-related practical applications.

Multi-source remote sensing approaches have paved the way for monitoring surface albedo across different spatial and temporal scales. Tower-based flux network is the most accurate way to record surface albedo but is constrained to local spatial samples with an effective footprint of several hundred to thousands of meters (Baldocchi et al. 2001; Cescatti et al. 2012; Chu et al. 2021). Drone flights are an alternative to flux-site observations for quantifying surface albedo with broader spatial coverage in a cost-effective way. However, this approach is also restricted to a limited spatial extent of several hectares (Cao et al. 2018; Levy et al. 2018). Satellite remote sensing is widely recognized as the only practical method for mapping surface albedo at regional and global scales owing to its global spatial coverage and short revisiting cycle (Liang et al. 2013; Schaaf et al. 2002). With rapidly increasing satellite launches over the past few decades, a variety of global-scale surface albedo products have become available across different spatial and temporal resolutions, such as the Advanced Very High Resolution Radiometer (AVHRR, 5-km spatial resolution and daily temporal resolution; Csizar and Gutman, 1999), POLarization and Directionality of the Earth's Reflectances (POLDER, 6-km spatial resolution and 10-day temporal resolution; Breon and Maignan, 2017), Multi-angle Imaging SpectroRadiometer (MISR, 1.1-km spatial resolution and 9-day temporal resolution; Diner et al. 1998), Moderate-Resolution Imaging Spectroradiometer (MODIS, 500-m spatial resolution and daily temporal resolution; Schaaf et al. 2002), Global LAnd Surface Satellite (GLASS, 1-km spatial resolution and 8-day temporal resolution; Liang et al. 2013), and Visible Infrared Imaging Radiometer Suite (VIIRS, 500-m spatial resolution and daily temporal resolution; Wang et al. 2013). However, these global products are limited to coarse spatial resolutions that cannot accurately capture the fine-scale dynamics of surface albedo caused by natural disturbances (Wang et al. 2016b) and anthropogenic disturbances (Trlica et al. 2017).

High-resolution satellites, especially Sentinel-2 with a 10-m spatial resolution and Landsat with a 30-m spatial resolution, offer an essential alternative to address the observational limitations of traditional coarse-resolution satellite sensors. However, insufficient multi-angular observations preclude using physical BRDF models to directly retrieve surface albedo from high-resolution satellites. Several recent studies have demonstrated the feasibility of integrating such high-resolution satellite reflectance data and the coarse-resolution satellite BRDF product for monitoring fine-scale surface albedo. For example, Shuai et al. (2011) proposed a MODIS-concurrent approach by integrating the paired surface reflectance of Landsat and MODIS observations of Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR) and albedo for mapping surface albedo with a 30-m spatial resolution. Li et al. (2018) recently extended this approach to the Sentinel-2 satellite for generating surface albedo with a 20-m spatial resolution. These studies have two model assumptions: (1) an equal ratio of reflectance and albedo between the high-resolution satellites (i.e. Landsat and Sentinel-2) and MODIS within the same land cover, and (2) high-quality MODIS data that is concurrent with the high-resolution satellite for providing BRDF parameters across different land covers. However, this type of approach relies on the concurrent high-resolution land cover classification map that limits its practicability to map surface albedo over large spatial areas.

Alternatively, the direct estimation approach provides another method to map surface albedo from the top of atmosphere (TOA) or surface reflectance by using the linear relationships between surface albedo and reflectance (Liang et al. 1999). This approach avoids the real-time data processing of directional reflectance normalization, spectral albedo calculation, and narrowband-to-broadband albedo conversion. He et al. (2018) used this approach to estimate surface albedo from the 30-m Landsat satellites. Zhang et al. (2020b) independently proposed a similar framework with flux-tower measurements to demonstrate the feasibility of using the direct estimation approach to monitor surface albedo from Landsat data. All these studies collectively suggest the great potential of using the direct estimation approach for mapping fine-scale surface albedo. However, the application of this approach remains unexplored for the Sentinel-2 satellites with much higher spatial and temporal resolutions and fewer spectral bands (only four 10-m resolution spectral bands) due to the lack of high-quality BRDF training samples and reliable evaluation datasets at the 10-m scale. Additionally, previous studies have successfully applied the direct estimation approach to other alternative satellites (e.g. Landsat) across individual sites, while the

potential of mapping fine-scale surface albedo from the Sentinel-2 satellites over regional and global scales remains poorly investigated.

In this study, our main goal is to develop a direct estimation approach that allows for mapping fine-scale surface albedo from the 10-m Sentinel-2 satellites, with three sub-objectives: 1) building a 10-m scale high-quality and representative dataset of BRDF samples for algorithm training and proposing a comprehensive albedo evaluation framework; 2) providing a feasible way for large-scale albedo mapping; and 3) exploring the practical implications of the Sentinel-2 albedo. To this end, we first integrated the 10-m resolution European Space Agency (ESA) land cover data and 500-m resolution MODIS BRDF/albedo product to select the representative BRDF training samples, simulated the pairs of surface albedo and Sentinel-2-like surface reflectance under different illumination and viewing geometry using MODIS BRDF training samples, generated Look-Up-Tables (LUTs) that connect these two quantities, and then fused these LUTs with the Google Earth Engine (GEE) cloud-computing platform. With this algorithm, we next estimated surface albedo from Sentinel-2 and validated the derived albedo with the references from the 3-D Discrete Anisotropic Radiative Transfer (DART) simulations, tower-mounted flux measurements, and MODIS satellite albedo products. Finally, we investigated the practical applications of the Sentinel-2 albedo in detecting the fine-scale characteristics of vegetation cover and urban area.

2. Materials

Two kinds of datasets were used in this study and described in detail as follows.

2.1. Training and calibration datasets

2.1.1. MODIS collection 6 BRDF/albedo product

The 21-year (2000-2020) MCD43A1 and MCD43A3 products with 500-m spatial resolution were used. The MCD43A1 product provides three weighting parameters (isotropic, volumetric, and geometric) for seven narrow bands and three broad bands, allowing to simulate surface reflectance at the specific illumination and viewing geometry. The MCD43A3 product offers daily narrowband and broadband albedo for both direct (black-sky albedo, BSA) and diffuse (white-sky albedo, WSA) illumination conditions. The MODIS BRDF/albedo product is accessible at <https://modis.gsfc.nasa.gov/data/dataproduct/mod43.php>. In this study, we downloaded and used MODIS BRDF/albedo for two distinct purposes. First, the MCD43A1 BRDF products

of individual samples were used to generate the simulated datasets of broadband albedo and Sentinel-2-like spectral surface reflectance for building up the reflectance-to-albedo LUTs with an angular bin-based linear regression, according to He et al. (2018), Qu et al. (2014), and Wang et al. (2015). Second, the MCD43A3 albedo data was selected as the benchmark data to assess the accuracy of Sentinel-2-derived surface albedo across regional and global scales.

To collect reliable and representative BRDF data of individual samples, we filtered and downloaded the MODIS observations following four criteria: 1) high quality, using the quality assurance (QA) layer to extract the high-quality MODIS pixels (i.e. quality bit index = 0); 2) homogenous coverage, firstly screening out the candidate MODIS pixels that themselves and their surrounding area of 3×3 pixels have remained as unchanged land cover (indicated by the MCD12Q1 land cover product) during the last 21 years (2000-2020) and then selecting those pure homogeneous MODIS pixels with one dominant land cover (with the pixel-scale fraction of dominant land cover larger than 95% as indicated by the 10-m resolution ESA WorldCover data); 3) coverage of a variety of land cover types, selecting MODIS data covering 16 land covers except for water body following the IGBP classification scheme; and 4) reasonable data range, ensuring the pair values of spectral reflectance and albedo calculated from the MCD43A1 BRDF kernel parameters within the physical range of $[0, 1]$. According to our sensitivity analysis of the impacts of BRDF training samples on algorithm accuracy (see Section 3.1.2 below), a total of 7200 individual MODIS samples with 450 samples for each land cover type were finally selected and used (Fig. 1).

To assess the accuracy of the proposed algorithm over regional scale, we also downloaded and used the gridded tiles of MCD43A3 albedo products across 16 land cover types covering a global area distribution (i.e. sites #a – #p in Fig. 2) during the four seasons of spring, summer, fall, and winter (i.e. one gridded tile per land cover per season) in 2019 for the purpose of albedo comparisons (see Section 3.3 below). Each MCD43A3 gridded tile included one dominant land cover (i.e. fraction of dominant land cover larger than 50% as indicated by the 500-m MCD12Q1 product) and was quality controlled using the QA layer (i.e. quality bit index = 0).

2.1.2 Sentinel-2 surface reflectance product

The Sentinel-2 constellations with two identical polar-orbiting satellites (Sentinel-2A and Sentinel-2B) were launched by the European Space Agency (ESA) in 2015 and 2017 with the aim

to provide high-resolution observations to support the monitoring of the Earth's surface dynamics (Drusch et al. 2012). Both are equipped with the Multi Spectral Instrument (MSI) to help collect optical imagery with global coverage from 56° S to 84° N in a wide swath width of 290 km and a frequent revisit cycle of 5 days at the equator. The Sentinel-2 satellite has 13 spectral bands spanning from visible and near-infrared (NIR) to shortwave infrared (SWIR) at different spatial resolutions ranging from 10 to 60 m on the ground with distinct purposes. Specifically, three visible (blue, green, red) and NIR bands at 10-m resolution were designed to ensure continuity mission with the other high-resolution satellites (e.g. Landsat-8) to improve the land cover classification. Six infrared (four red edges, SWIR-1, and SWIR-2) bands at 20-m spatial resolution are used to enhance land-cover classification and improve the retrieval of geophysical parameters. The other three spectral bands at 60 m are dedicated mainly for atmospheric corrections and cirrus-cloud screening (Drusch et al. 2012; Li et al. 2018). Moreover, the high-quality radiometric performance of the Sentinel-2 satellite with a 12-bit radiometric resolution and radiometric error within 5% allows to feasibly acquire surface signals without saturation (Sentinel-2 Team, 2021). Thus, the high spatial resolution, frequent revisits, wide swath, multispectral features, and high radiometric quality of Sentinel-2 enable the global monitoring of surface dynamics.

The 10-m resolution Level-2A Sentinel-2 surface reflectance products of three visible (blue, green, and red) bands and one NIR spectral band were used herein, which are freely available from the GEE platform at https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR. To test the proposed algorithm, we used the three-year (2018-2020) Sentinel-2 surface reflectance data and the associated cloud probability product together with default cloud masking parameters (<https://developers.google.com/earth-engine/tutorials/community/sentinel-2-s2cloudless>). In the main text, we primarily focused on the 2019 Sentinel-2 data, with the results of 2018 and 2020 shown in the supplementary material. The results were overall comparable with those shown in 2019. In this study, we used Sentinel-2 data to estimate fine-scale surface albedo, which was later validated against ground measurements and MODIS satellite product (see Section 3.2 below) and next assessed for practical applications (see Section 3.3 below).

2.1.3. Land cover product

To help select pure-pixel BRDF training samples, we used two types of land cover products, including the 10-m resolution ESA land cover mapping data in 2020 and the 21-year (2000-2020) 500-m resolution MCD12Q1 land cover product. These two datasets were downloaded from the GEE platform and used with quality control from the default QA layer.

The MCD12Q1 product was used for two purposes. First, to help select high-quality MODIS training BRDF samples, we used MCD12Q1 to screen out the pure MODIS pixels along with their 3×3 pixel surrounding areas that have shown homogeneous coverages and static land covers during the past 21 years. Second, to assess the accuracy and uncertainty of the proposed algorithm over regions scale, we employed MCD12Q1 to select the homogeneous gridded tiles of MCD43A3 albedo products across different land cover types as the validation benchmark. The ESA land cover mapping data were used to select the 10-m resolution representative BRDF samples from the candidate MODIS pixels filtered by the MCD12Q1 product.

2.2. Validation datasets

2.2.1. Flux network observations

The tower measurements of downward and upward solar radiation from five flux networks in 2018-2020 were used. These flux networks include four globally distributed flux networks: Baseline Surface Radiation Network (BSRN), Surface Radiation (SURFRAD), AmeriFlux, European Fluxes Database (EuroFlux), and one regionally distributed Heihe Watershed Allied Telemetry Experimental Research (HiWATER) wireless sensor network (HiWaterWSN) with details as follows.

BSRN: managed by the World Radiation Monitoring Center (WRMC) with the aim of providing high-quality observations of shortwave and longwave surface radiation fluxes, together with meteorological and other supportive measurements for validating and evaluating satellite-based estimates of the surface radiative fluxes since 1992. It measures downward and upward shortwave radiation with both direct and diffuse components at 1-min intervals of sampling time. The flux datasets are available at <https://dataportals.pangaea.de/bsrn/>.

SURFRAD: part of BSRN and supported by the National Oceanic and Atmospheric Administration (NOAA) office of global programs with the primary objective of collecting accurate, continuous, and long-term measurements of surface radiation budget over the United States for supporting climate-related research since 1995. It measures downward and upward

shortwave radiation with total, direct, and diffuse components at 1-min recording time intervals through the broadband pyranometers mounted on 10-m flux towers. The SURFRAD network data contained in the BSRN network has been excluded in the main text below to avoid any duplications. The flux datasets are available at <http://www.esrl.noaa.gov/gmd/grad/surfrad/>.

AmeriFlux: launched in 1996 and it has become one of the most highly regarded networks in climate and ecological research, focusing on climate-relevant responses and terrestrial ecosystem processes. It is now supported by the AmeriFlux Management Project (AMP) of Lawrence Berkeley National Laboratory (LBNL) and offers half-hourly observations of downward and upward shortwave solar radiation together with tower height and other meteorological variables. The flux datasets are available at <https://ameriflux.lbl.gov/>.

EuroFlux: mainly funded by the European Union since 1996 and jointly supported by several research projects (i.e. CarboAfrica, Carbo-Extreme, GHG-Europe, ICOS, and InGOS) with the primary objective of providing standard and high-quality observations to better understand the carbon and water cycles of terrestrial ecosystems. The European network currently manages over 400 flux sites and records downward and upward shortwave radiation at a sampling interval of 30 min, with flux data available at <http://www.europe-fluxdata.eu/>.

HiWaterWSN: launched during the HiWATER campaign that was conducted over the Chinese Hehei river basin in 2012 with the scientific goal of using integrated, distributed, and multi-scale observations to improve the understanding of hydrological processes and ecosystem functioning of arid and semi-arid regions. A wireless sensor network (WSN) with 40 nodes was installed across seven meteorological stations to measure upward and downward shortwave radiation with a 10-min sampling interval (Che et al. 2019). The datasets are freely available from the National Tibetan Plateau/Third Pole Environment Data Center at <http://data.tpdc.ac.cn/en/special/heihe/>.

Tower height is the key parameter for the effective footprint of flux sites, according to Román et al. (2013). We thus formulated the flux sites that do not provide auxiliary information on tower heights based on two assumptions: 1) for the high-tower flux sites (e.g. forest), we assumed the flux cameras could be installed at 3 m above the vegetation (Rojas-Robles et al. 2020) and extracted vegetation heights from the Global Ecosystem Dynamics Investigation (GEDI) database (Dubayah et al. 2020); and 2) for the low-tower flux sites (e.g. grassland and shrubland), we assumed installing flux cameras at a standard 10-m height similar to the SURFRAD network.

Considering that the footprints of flux towers are larger than the Sentinel-2 pixel resolution, we assessed the representativeness of available flux sites using two Sentinel-2 albedo images across the leaf development and leaf senescence stages at each site, and selected only those homogeneous sites with the coefficient of variation (CV) metric less than 10% as the validation sites. Therefore, a total of 108 flux sites (with 91 site-years in 2018, 97 site-years in 2019, and 68 site-years in 2020) across different land cover types were downloaded and used, including 5 sites from BSRN, 4 sites from SURFRAD, 76 sites from AmeriFlux, 19 sites from EuroFlux, and 4 sites from HiWaterWSN (Fig. 2 and Table 1). In this study, the flux observations were first used to calculate site-level surface albedo, and then used as ground truth to validate surface albedo derived from the Sentinel-2 satellites (see Section 3.2 below).

2.2.2. 3-D DART simulations

3-D DART simulations of different landscape configurations were used. With the DART model, we first created eight sets of 100-m $\times$ 100-m archetype scenarios with a 10-m spatial resolution (Fig. 3), covering one homogenous grassland, three-category (i.e. sparse, medium, and dense) heterogeneous forests, two types of built-ups (i.e. one unevenly distributed and one uniformly distributed), and two types of topography (i.e. one sloping surface with solo slope gradient and one rugged terrain that composited with a variety of individual sloping surfaces). We then generated a variety of synthetic scenarios from the archetype scenarios using different canopy structures, solar-viewing geometry, and illumination radiation configurations, with the leaf area index (LAI) ranging from 1 to 7 with an interval of 2, the solar zenith angle ranging from 0° to 60° with an interval of 10°, the viewing zenith angle ranging from 0° to 20° with an interval of 10°, the relative azimuth angle ranging from 0° to 180° with an interval of 45°, and two diffuse skylight ratios of 0 and 1. We specifically built a set of sloping surfaces (Fig.3g) with the slope gradient ranging from 0° to 60° with an interval of 10° and the aspect gradient ranging from 0° to 180° with an interval of 45°. Consequently, a total of 35,280 scenarios were generated, covering all possible combinations of configuration parameters. With the typical leaf (deciduous leaf), ground (brown sandy loam), building (red cement), and road (gray concrete) properties, we finally simulated a synthetic dataset of Sentinel-2-like surface reflectance and shortwave albedo across different landscape configurations.

3. Methodology

We divided the methodology into the following three major steps: 1) building up the direct estimation approach of angular bin-based regression by using the simulated datasets of surface reflectance and albedo; 2) validating the proposed algorithm with references from the 3-D DART simulations, ground-based measurements, and MODIS albedo product; and 3) exploring the practical applications of Sentinel-2-derived albedo in detecting fine-scale characteristics of surface dynamics. A flowchart that summarizes these major steps is shown in Fig. 4.

3.1. Developing the direct estimation approach

We divided this task into the following two sub-steps.

3.1.1. Generating simulated datasets of surface reflectance and albedo from MODIS BRDF data

The MODIS BRDF data of individual samples across different land cover types were primarily used to simulate datasets of Sentinel-2-like surface reflectance and surface shortwave albedo under different illumination and viewing geometry conditions.

We simulated Sentinel-2-like surface reflectance with several steps. First, we split the complete datasets of 7200 MODIS BRDF data of 16 land cover types into training and validating components, with 400 and 50 samples (Fig. 1) for each land cover type, respectively. Second, we divided the illumination and geometry into small angular bins and simulated MODIS-like surface reflectance across seven spectral bands for each angular bin using the MODIS BRDF data together with the linear RossThick-LiSparseR BRDF model as follows (Lucht et al. 2000):

$$\rho(\theta_s, \theta_v, \varphi, \lambda) = f_{iso}(\lambda) + f_{geo}(\lambda) k_{geo}(\theta_s, \theta_v, \varphi) + f_{vol}(\lambda) k_{vol}(\theta_s, \theta_v, \varphi) \quad (1)$$

where $\rho(\theta_s, \theta_v, \varphi, \lambda)$ is surface reflectance under the solar zenith angle of θ_s , viewing zenith angle of θ_v , and relative azimuth angle of φ at the wavelength of λ ; k_{geo} and k_{vol} are the geometric optical and volumetric scattering kernels characterized by the functions of the illumination and viewing geometry, respectively; f_{geo} and f_{vol} are the weights of these two kernel functions; and f_{iso} is the isotropic weight.

Finally, we converted the simulated MODIS-like surface reflectance into the Sentinel-2-like surface reflectance with the band conversion coefficients between these two satellites (Eq. 2 and Fig. S1), which were derived from a linear regression approach using the relative spectral response (RSR) function profiles of Sentinel-2 and MODIS, together with 2394 samples of high-quality spectra data. These spectra include 815 samples from the Ground Object Background Spectral Library for Surveying and Mapping (GOSPEL) (Zhong et al. 2020), 119 samples from the book of quantitative remote sensing for land surfaces (Liang et al. 2004), 221 samples from the spectral library of typical objects in China (Wang et al. 2009), 47 samples from the snow spectral datasets in Greenland (Qu et al. 2014), and 1192 samples from the USGS digital spectral library (Clark et al. 2007). Because the Sentinel-2 twin satellites have very similar spectral response curves (Fig. 5), we used the same band conversion coefficients for these two sensors as follows:

$$\rho_{S2}(\lambda_i) = a_0 + \sum_{j=1}^7 a_j \times \rho_{MODIS}(\lambda_j) \quad (2)$$

where $\rho_{S2}(\lambda_i)$ is the Sentinel-2-like surface reflectance at spectral band λ_i ($i = 1, 2, 3, 4$); $\rho_{MODIS}(\lambda_j)$ is the MODIS-like surface reflectance at spectral band λ_j ($j = 1, 2, 3, 4, 5, 6, 7$); a_j ($j = 1, 2, 3, 4, 5, 6, 7$) is the band conversion coefficient from MODIS spectral band λ_j to Sentinel-2 spectral band λ_i ; and a_0 is the constant coefficient (Table 2). The close agreement between the converted Sentinel-2-like reflectance from MODIS-like reflectance and the directly simulated Sentinel-2-like reflectance suggests high accuracy of the proposed band conversion coefficients (Fig. S1).

We simulated datasets of shortwave albedo from the MODIS BRDF data with three steps: 1) generating the narrowband albedo of seven MODIS spectral bands by integrating the BRDF data over the illumination or viewing geometry (Lucht et al. 2000; Schaaf et al. 2002). Specifically, we integrated MODOS BRDF data over the viewing hemisphere and the illumination and viewing hemispheres to simulate the BSA and WSA datasets, respectively; 2) converting the narrowband albedo to shortwave albedo with the regression coefficients suggested by Liang et al. (2002).

3.1.2. Building LUTs from the simulated datasets

With the simulated Sentinel-2-like spectral reflectance for one angular bin and the associated shortwave albedo, we used the linear regression approach to build the LUTs (i.e.

reflectance-albedo relationship) that connect shortwave albedo (both BSA and WSA) and spectral reflectance (He et al. 2018; Qu et al. 2014):

$$\alpha = C_0(\theta_s, \theta_v, \varphi) + \sum_{j=1}^4 C_j(\theta_s, \theta_v, \varphi) \times \rho_{S2}(\lambda_j) \quad (3)$$

where α is the surface shortwave albedo; $\rho_{S2}(\lambda_j)$ is the Sentinel-2-like surface reflectance at spectral band λ_j ($j = 1, 2, 3, 4$); and $C_j(\theta_s, \theta_v, \varphi)$ denotes the regression coefficient at spectral band λ_j .

We built up the LUTs with three steps. First, we fine-tuned the optimal sizes of BRDF training sample and angular bin on the LUT building with two sensitivity analyses: 1) with the validating component of the MODIS data, we selected different angular bin sizes for algorithm training and validation and found that the angular bin sizes of 2° , 2° , 2° , and 5° for solar zenith angle, viewing zenith angle, solar zenith angle at local solar noon, and relative azimuth angle, respectively, could generate surface albedo with reasonable accuracy (Fig. 6 and Fig. S2) and then used these optimal angular bin sizes in our algorithm; and 2) with the optimal angular bin size, we selected different BRDF training samples for algorithm training and validation and found that the total sample size of 6000 could make the proposed algorithm stable with high accuracy (Fig. S3).

Second, we considered the topographic effects in generating reflectance-albedo LUTs with two assumptions. First, we assumed that the MODIS BRDF parameter product is stable regardless of topography so that it can be used for generating BRDF over slopes. Second, we assumed that the topographic effects on 10-m Sentinel-2 surface reflectance are more dominated by the distortions of illumination and viewing geometry than the vegetation's geotropic nature and the multiple-scattering among slopes (Wen et al. 2018). With these two assumptions, we used the local solar-viewing geometry (i.e. relative geometry between slope and solar or viewing sensor) as algorithm inputs to drive the LUTs. Thus, with the training component of MODIS data, we generated two types of LUTs for the BSA and WSA retrievals, respectively.

Finally, we coupled the two LUTs of BSA and WSA with the GEE platform by using the default remap function to search regression coefficients and retrieve surface albedo. It's noteworthy that since regional- and global-scale 10-m digital elevation model (DEM) datasets that match Sentinel-2 resolution are very limited and have not yet been indigested by the GEE platform, we thus set the slope gradients as zero by default in our following regional and global albedo estimation and analysis that were conducted on the GEE platform, but we considered topographic

impacts in the accuracy assessment with 3-D model simulations and tower-based flux measurements.

3.2. Validating the direct estimation algorithm

The 3-D DART simulations, ground measurements, and MODIS observations were used to evaluate the accuracy of Sentinel-2-derived surface albedo across three spatial levels ranging from the site, regional, to global scale. We first applied the developed algorithm to the DART simulated Sentinel-2-like reflectance to estimate surface albedo and compared the derived albedo with the DART simulated albedo. We then further used this algorithm to estimate surface albedo from Sentinel-2 satellite surface reflectance and conducted evaluations with the tower-based flux measurements and MODIS data. Three commonly used metrics, including the bias, root-mean-square-error (RMSE), and coefficient of determination (R^2), were used for accuracy assessments.

3.2.1. Estimating surface albedo using the developed LUTs

Pre-built LUTs were used to estimate surface albedo from the DART simulated Sentinel-2-like reflectance data and Sentinel-2 satellite surface reflectance.

(1) Retrieval of surface albedo from the DART simulated reflectance. With the DART simulated Sentinel-2-like surface reflectance and solar-viewing geometry, we retrieved surface albedo using the pre-built LUTs in Eq. 3 to estimate BSA and WSA, respectively.

(2) Retrieval of surface albedo from Sentinel-2 reflectance. We first used the cloud probability product with the s2cloudless algorithm provided by GEE to remove cloudy and shady Sentinel-2 pixels. With the cloud-free Sentinel-2 reflectance and solar-viewing geometry, we then used them as inputs for the pre-built LUTs in Eq. 3 to estimate both BSA and WSA, respectively.

3.2.2. Assessing the proposed algorithm at a 10 m scale

The absolute accuracy and uncertainty of the Sentinel-2-derived albedo were evaluated at a 10-m scale using the DART simulations and flux observations. We first compared the estimated pairs of BSA and WSA using our algorithm with the DART simulation pairs of BSA and WSA (Fig. 7 and Figs. S4-S5), respectively. We then compared the blue-sky albedo derived from the Sentinel-2 observations with the flux measurements, with three considerations: 1) given that flux measurements are a mix of direct and diffuse illuminations, we integrated the derived BSA and

WSA to calculate blue-sky albedo using the fraction of diffuse skylight in two cases: (i) if the flux site has recorded both direct and diffuse fluxes, ground-measured diffuse skylight fraction was used, and (ii) otherwise, a default value of 0.2 was used, according to He et al. (2018); 2) to minimize the potential impacts of unstable illuminations on the flux measurements, we selected tower flux measurements between 11: 00 a.m. and 13 : 00 p.m. local time to calculate ground albedo of local solar noon; and 3) since most tower flux footprints are larger than one Sentinel-2 pixel size, we selected the Sentinel-2 pixels that centered on the tower flux footprint, and conducted the "point-to-pixel" evaluation by comparing ground albedo with the Sentinel-2 centered-pixel albedo (Fig. 8 and Fig. S6), together with a sensitivity analysis of geometric mismatch effects with 100-time repeated comparisons between ground albedo and the random Sentinel-2 pixel observations within the tower flux footprints (Fig. S7). Third, we assessed the accuracy of the proposed algorithm across different snow cover conditions (Fig. S8), topographic slopes (Fig. S9), flux site networks (Fig. S10), and cross-year variations (Fig. 9, Figs. S11 and S12). We also compared our algorithm with other alternatives, including the narrow-to-broadband (NTB) conversion method (Bonafoni and Sekertekin, 2020) and the MODIS-concurrent approach (Li et al. 2018, Fig. S13).

3.2.3. Assessing the proposed algorithm at a 500 m scale

Subsequently, we assessed the large-scale mapping capability of the proposed algorithm by comparing the Sentinel-2-derived pairs of BSA and WSA with the MODIS BSA and WSA products at the 500-m scale using two steps. First, we estimated surface albedos from Sentinel-2 in gridded tiles across 16 land cover types and four seasons (Fig. 2) and compared them with the corresponding MODIS albedo product with strict quality control (quality bit index = 0) for regional-scale assessment (Figs.10, 11 and Figs.S14-S16). Second, we generated monthly means of global BSA and WSA from Sentinel-2 in June 2019 and compared them with the corresponding monthly means of global MODIS BSA and WSA for global-scale assessment. Specifically, the derived Sentinel-2 albedos were upscaled from their original resolution of 10 m to 500 m to match MODIS data resolution using an area-weighted averaging approach for regional- and global-scale assessments (Fig. 12 and Fig. S17).

3.3. Exploring practical applications of Sentinel-2 albedo

We explored the potential of 10-m Sentinel-2 albedo in capturing fine-scale spatial and

temporal characteristics of surface dynamics, including two examples of detecting interspecific variations across temperate trees and discriminating interclass differences across urban rooftops, and two examples of monitoring leaf phenology and snow events. Because BSA is very close to WSA, we used the Sentinel-2-derived BSA as examples to demonstrate the practical applications of Sentinel-2 albedo.

3.3.1. Detecting fine-scale spatial dynamics of surface

(1) Capturing interspecific variations across temperate trees. The high resolution of Sentinel-2 improves the capability of mapping tree species and assessing interspecific variations. We used the Sentinel-2-derived albedo to detect interspecific variations of one mixed temperate forest stand in Brandenburg, Germany. This forest stand (53°00'00" - 53°00'32"N, 13°46'48" - 13°49'19"E, site #q in Fig. 2) spans an area of 3 km × 0.7 km and contains 8 dominant tree species, including *Common red alder*, *Common sessile oak*, *Douglas fir*, *European ash*, *European beech*, *European Japanese larch*, *Norway spruce*, and *Scots pine* (Fig. 13). More details on the forest compositions of this site can be found in Hemmerling et al. (2021). With the vector maps of dominant tree species from the forest inventory data, we extracted the time series of vegetation albedo across tree species by cropping the estimated Sentinel-2 albedo time series in 2019, and then assessed the interspecific variations (Fig. 13). We also presented the results of the 30-m resolution Landsat satellite for comparison.

(2) Capturing interclass variations across urban roofs. The ability of high-resolution Sentinel-2 albedo to capture fine-scale characteristics of built-ups was evaluated at one urban site in Beijing, China. This site is located south of Beijing (39°47'35" - 39°48'04"N, 116°23'56" - 116°24' 50"E, site #r in Fig. 2) and occupies an approximate 1-km × 1-km area displaying a variety of colorful rooftops. With the high-resolution Google Earth imagery, we first visually identified each building roof and manually drew the rooftop map with the region of interest (ROI) of different colors. We then overlapped the manual ROIs with the Sentinel-2 albedo time series in 2019 and extracted the time series of rooftop albedos. We lastly compared the extracted albedos across different urban rooftops (Fig. 14) and extracted the Landsat satellite results of rooftop albedos for comparison (Fig. S18).

3.3.2. Monitoring fine-scale temporal dynamics of surface

Two phenocam sites of the National Ecological Observatory Network (NEON) were

selected to demonstrate the advantage of Sentinel-2 albedo in monitoring fine-scale temporal variations, including one forest site and the one agricultural site.

(1) Capturing leaf phenology of temperate trees. We evaluated the capability of Sentinel-2 albedo in capturing leaf phenology using the phenocam observations of the Casey Tree Farm in the Blandy Experimental Farm (BLAN) site in Virginia, USA. This forest site ($39^{\circ}02'01''\text{N}$, $78^{\circ}02'30''\text{W}$, site #s in Fig. 2) includes a mix of land-use types, including woodland, tree nurseries, and hay fields. The tower-top RGB (i.e. red, green, and blue) camera observations of an 8-m flux tower were used to measure leaf phenology dynamics. Using the Sentinel-2 imagery collection in 2019, we first extracted and analyzed the albedo and enhanced vegetation index (EVI) time series of the Sentinel-2 pixel centered on the flux footprint, then compared them with the RGB camera observations (Fig. 15a). We also compared our results with the albedo time series of the Landsat pixel located at the same site.

(2) Capturing snowfall and snowmelt events. We assessed the ability of Sentinel-2 albedo to monitor rapid snowfall and snowmelt events using the phenocam observations of the North Sterling (STER) site in Colorado, USA. This agricultural site ($40^{\circ}27'43''\text{N}$, $103^{\circ}01'45''\text{W}$, site #t in Fig. 2) cultivates a variety of crops, including winter wheat, millet, and maize. We used the tower-top RGB camera observations of an 8-m flux tower to measure cropland dynamics and compared them with the albedo and EVI time series of the central Sentinel-2 pixel within the flux footprint (Fig. 15b). We also compared our results with the albedo time series of the Landsat satellite.

4. Results

4.1. Uncertainties of the direct estimation approach from simulated datasets

We assessed the theoretical accuracy and uncertainty of the proposed direct estimation approach using the validating component of the MODIS sampling data. As shown in Fig. 6, the mean of fitted RMSE in simulating shortwave albedo increased from 0.017 to 0.050, with the local solar zenith angle increasing from 0° to 80° . Particularly, the mean RMSE was less than 0.020 when the local solar zenith angle was lower than 60° , indicating the high accuracy of the proposed approach for estimating surface albedo from Sentinel-2 satellites. Our results showed that the direct estimation approach is relatively insensitive to the changes in angular bin size of

illumination and viewing geometry (Fig. S2), with slight increases in the maximum RMSEs of 0.035, 0.025, and 0.019 for an increasing bin size from 0° to 40° for the local solar zenith angle, solar zenith angle, and relative azimuth angle, respectively. Our results also showed that algorithm accuracy increased with the size of BRDF training samples (Fig. S3), with the mean RMSE ranging from 0.056 to 0.017 for an increasing sample size from 500 to 6000 and remaining stable when the sample size was larger than 6000.

4.2. 10-m scale accuracy assessment of the direct estimation approach

The absolute accuracy of the proposed direct estimation approach in estimating surface albedo from Sentinel-2 were evaluated against the 3-D DART simulations and ground measurements from local flux sites. When compared with the DART simulations, the direct estimation approach presented high theoretical accuracy across different landscape configurations (bias = -0.010 - 0.012, RMSE = 0.015 - 0.020, $R^2 = 0.73 - 0.98$ for BSA; bias = -0.010 - 0.010, RMSE = 0.014 - 0.022, $R^2 = 0.70 - 0.97$ for WSA; overall RMSE = 0.018, overall bias = 0.005, overall $R^2 = 0.88$; Fig.7 and Fig. S4). The low pixel-scale RMSE map also suggests the high accuracy of the direct estimation approach (Fig. S5). When compared with ground measurements, as shown in Fig. 8, ground flux towers detected significant variations in surface albedo with ranges from 0.065 to 0.907 across different land cover types. Our results demonstrated that the Sentinel-2 satellite accurately captures variations in surface albedo, showing an overall high agreement with ground measurements across all flux sites (bias = -0.004, RMSE = 0.030, $R^2 = 0.94$) and different land cover types (bias = -0.023 - 0.011, RMSE = 0.015 - 0.042, $R^2 = 0.40 - 0.99$; Fig. 8, Figs. S6 and S7). Our results also showed that the Sentinel-2 satellite closely tracked albedo variations of snow-free and snow-covered surfaces (bias = -0.003, RMSE = 0.027, and $R^2 = 0.62$ for snow-free surface; bias = -0.009, RMSE = 0.060, $R^2 = 0.84$ for snow-covered surface; Fig. S8), flat and rugged topography (bias = -0.004, RMSE = 0.029, $R^2 = 0.94$ for slope < 5°; bias = -0.006, RMSE = 0.031, $R^2 = 0.96$ for 5° < slope < 10°; and bias = 0.003, RMSE = 0.040, $R^2 = 0.97$ for slope > 10°; Fig. S9), flux networks (Fig. S10), and cross-year variations (Figs. S11-S12). Our sensitivity analysis results of the geometric match effects between flux footprint and Sentinel-2 pixel show the feasibility of the proposed evaluation strategy for selecting representative flux sites and conducting direct comparisons (bias = -0.005 - 0.006, RMSE = 0.028 - 0.035, $R^2 = 0.82 - 0.98$;

Fig. S7). The sensitivity analysis of the model selection showed a better performance of the proposed direct estimation approach compared with the other similar alternatives (i.e. the NTB conversion method and MODIS-concurrent approach; Fig. S13).

Our evaluations show that Sentinel-2 and flux tower observations detected significant seasonality in surface albedo caused by leaf phenology or surface changes across different land cover types (Fig. 9). Deciduous broadleaf forest (DBF) exhibited a leaf phenology-driven seasonality with increasing albedo for the green-up stage and decreasing albedo for the leaf senescence stage, respectively (Fig. 9b). Evergreen forest (ENF) showed a relatively stable albedo pattern across seasons except for the increasing pattern in spring and winter due to snowfall events (Fig. 9c). In contrast, cropland (CRO) displayed a human-driven seasonality with many variabilities in albedo that might have been disturbed by management activities (e.g. increasing albedo patterns in the growing phase augmented by the decreasing soil moisture and abrupt drops in albedo magnitude caused by irrigation practices; Fig. 9a). Wetland presented an increasing albedo seasonality likely due to the decreasing seasonal soil moisture (Fig. 9f). Compared with the other land covers, grassland (GRA) and open shrubland (OSH) showed much fewer albedo variations across seasons (Fig. 9d-e). Our results also showed that the surface albedos derived from Sentinel-2 have similar seasonality patterns with the ground measurements across different land cover types (Fig. 9) and inter-annual cycles (Figs. S12).

4.3. 500-m scale accuracy assessment of the direct estimation approach

We evaluated the capability of the proposed direct estimation approach in large-scale albedo mapping by comparing the Sentinel-2-derived surface albedo with MODIS albedo product across both individual gridded tile and global coverage. As shown in Fig. 10a-a2 and Fig. 10c-c2, and Fig. S14, both the Sentinel-2 and MODIS gridded tiles showed large variations in the extracted surface albedo across spatial regions and different land cover types. Compared with the MODIS albedo with a relatively coarse resolution of 500 m, our local zoom-in results show that Sentinel-2 detected many more details on the spatial variations of surface albedo in specific regions, such as the heterogeneous agricultural mosaics of cropland (Fig. 10b-b2) and disturbance patches of evergreen forest (Fig. 10d-d2). The 500-m scale assessment results show that the surface albedos derived from Sentinel-2 were overall comparable with the albedos derived from MODIS across gridded tiles (bias = 0.021, RMSE = 0.030, $R^2 = 0.97$; Fig. 11a) and different land cover types

(bias = 0.008 - 0.048, RMSE = 0.011 - 0.060, R^2 = 0.47 - 0.98; Figs. 11b-c and Fig. S15). Our results also showed the high consistency between Sentinel-2- and MODIS-derived BSA and WAS (bias = 0.008, RMSE = 0.013, R^2 = 0.81 for BSA; bias = 0.010, RMSE = 0.16, R^2 = 0.77 for WSA; Fig. S16).

Our global-scale comparison maps of two satellites presented similar spatial variations in surface albedo, with large albedos at the North Pole covered by permanent snow (e.g. Greenland), African regions and Australia characterized by desert or dryland, and mountainous areas of the North American Cordillera, Andes, Appalachians, Alps, and Himalayas (Fig. 12a-12b and Fig.S17a-S17b). Our results also show close spatial consistency between pixel-level Sentinel-2 and MODIS albedos, with a maximum bias of less than 0.02 across 45.9% of the global areas (Fig. 12c and Fig. S17c). Overall, the Sentinel-2-derived surface albedos were highly comparable with those from MODIS at the global scale (bias = 0.031, RMSE = 0.048, R^2 = 0.93 for BSA; bias = 0.032, RMSE = 0.048, R^2 = 0.93 for WSA; Fig.12 and Fig.S17).

4.4. Fine-scale surface dynamics from Sentinel-2-derived albedo

We assessed the potential of the Sentinel-2 albedo for monitoring tree albedo variations, discriminating built-ups, and capturing leaf phenology and snow events. We first mapped the pixel-scale albedos of Sentinel-2 and Landsat over the forest stand (Fig. 13). These maps showed that there were large spatial variabilities in the estimated albedo across the entire landscape, with observed higher values in the north and east regions and lower values in the south and west regions (Fig. 13c-d). Due to higher spatial resolution, Sentinel-2 albedo showed many more spatial heterogenous characteristics than Landsat albedo (Fig. 13c vs. Fig. 13d). When overlapping these albedo maps with the dominant tree species map (Fig. 13b), we quantified the albedo variations at the interspecific and intraspecific levels and found large seasonal variations within and across tree species (Fig. 13e-13g). At the interspecific level, our results showed that *European ash* has the largest species-level mean albedo, followed by *Common sessile oak*, *European beech*, *Common red alder*, *Douglas fir*, *European Japanese larch*, *Scots pine*, and *Norway spruce*. At the intraspecific level, our results showed that *European beech* has the largest variability (indicated by the standard deviation of albedo within the same species), followed by the *Norway spruce*, *Common red alder*, *Common sessile oak*, *Douglas fir*, *European Japanese larch*, *Scots pine*, and *European ash*. Our comparative results between the two satellites demonstrated that Sentinel-2

has many more frequent observations than Landsat (observation number of 43 vs. 13 within a one-year cycle) and can detect both the interspecific and intraspecific albedo variations, while Landsat shows less capability in detecting intraspecific albedo variations (Fig. 13e vs. Fig. 13f).

We then mapped the pixel-scale albedos of Sentinel-2 over the built-up area (Fig. 14). The resulting map showed large spatial variabilities of the estimated albedo across the entire urban area, with observed higher values over the light-colored rooftops and lower values over the dark-colored rooftops. By overlapping the albedo results with the manual rooftop map, we quantified the albedo variations within and across color classes and found that light-colored rooftops showed larger class-level mean albedo and within-class albedo variations (indicated by the standard deviation of albedo within the same color class) than the dark-colored rooftops (Fig. 14b vs. Fig. 14j). Our results also showed a greater potential of Sentinel-2 than Landsat in discriminating different colorful urban roofs due to the larger interclass Sentinel-2-derived albedo variability (Fig. 14 vs. Fig. S18).

Lastly, we extracted and analyzed the albedo and EVI time series over the forest and agricultural sites. As shown in Fig. 15, phenocam RGB images clearly illustrated the key stages in the leaf phenology and snowfall and snowmelt events. The extracted Sentinel-2 EVI showed two different seasonality patterns between forest and cropland. The value of forest EVI remained low during the dormant period (i.e. timing T_1 to T_2), increased with leaf green-up (i.e. timing T_2 to T_4) previous to the stable leaf peak stage (i.e. timing T_4 to T_5), decreased with the leaf senescence (i.e. timing T_5 to T_7), and reverted back to the dormant stage (i.e. timing T_7 to T_8 , Fig. 15a). By contrast, cropland EVI presented a more rapid leaf green-up and senescence stages with a double-cropping cycle within one year (Fig. 15b). When comparing the temporal dynamics between EVI and albedo, as shown in Fig. 15a, Sentinel-2 albedo closely tracked EVI seasonality with an increasing pattern during the leaf green-up stage and a decreasing pattern during the leaf senescence stage, suggesting the potential of using Sentinel-2 in monitoring phenology-related biophysical processes. Additionally, Sentinel-2 albedo showed its capability of capturing the rapid temporal trajectory of snow events with different snowfall magnitudes. For example, as shown in Fig. 15b, Sentinel-2 albedo detected a total of three snowfall and snowmelt events (i.e. timing T_1 - T_2 - T_3 , T_3 - T_4 - T_5 , and T_6 - T_7 - T_8). Due to the relatively lower temporal resolutions, Landsat albedo has fewer informative observations on the leaf phenology and snow events.

5. Discussion

The accurate monitoring of fine-scale surface albedo over large spatial coverage has fostered increasing research interests. However, large uncertainties remain in regards to current satellites with coarse spatial and temporal resolutions (Li et al. 2018; Qu et al. 2014; Shuai et al. 2014; Wang et al. 2018). We addressed this challenge by integrating the high resolution of Sentinel-2 satellites with an improved direct estimation approach, which allows for estimating albedo from the surface reflectance of Sentinel-2 without the comprehensive retrieval from physical BRDF models that requires multi-angular observations within a short time period. Using this approach, we found that Sentinel-2 strongly agreed well with the DART simulations, ground measurements, and MODIS satellite product, and accurately detected the fine-scale spatial and temporal characteristics of surface albedo dynamics in vegetation and urban cover. These results demonstrate the great feasibility of using Sentinel-2 data for mapping fine-scale surface albedo to advance the characterization and understanding of multiple biophysical and biogeochemical processes.

Our approach for extracting fine-scale surface albedo was also comprehensively evaluated across different spatial levels, including 1) 10-m scale assessments with comparisons between the Sentinel-2 simulations/observations and the DART simulations and ground measurements, and 2) 500-m scale assessments with comparisons between the Sentinel-2 data and MODIS products across gridded tiles and global coverage. Overall, we found those surface albedos extracted from Sentinel-2 were highly comparable with the DART simulations, ground measurements, and MODIS satellite product across different land cover types (Figs. 7, 8, 11, S4, S6, and S15). The accuracy of Sentinel-2-derived albedo is consistent with previous assessments of surface albedo from Sentinel-2 or Landsat (Franch et al. 2014; He et al. 2018; Li et al. 2018; Shuai et al. 2014; Wang et al. 2016a). We also found that Sentinel-2 accurately detected the albedo seasonality within and across years, indicating the potential of using Sentinel-2 to capture natural dynamics and anthropogenic activities. In addition, we observed better performance of the albedo of snow-free surface extracted from Sentinel-2 than the albedo of snow-cover surface (Fig. S8a vs. Fig. S8b), which might be explained by the relatively higher uncertainty in the MODIS snow BRDF/albedo data (Schaaf et al. 2011; Wang et al. 2012) due to the lack of snow kernels in the current RossThick-LiSparseR kernel-driven models. Despite the relative greater uncertainty in the snow-covered albedo, we observed that the retrieval accuracy of the snow-covered surface was close to

the other satellite data (e.g. MOD10A1, MCD43A3, VIIRS, and Landsat; He et al. 2018; Stroeve et al. 2006; Wang et al. 2018; Zhou et al. 2016). We also noted that the overall accuracy of our algorithm was highly comparable with other state-of-the-art methods (e.g. the NTB conversion method and MODIS-concurrent approach; Fig. S13). Our results showed the reasonable accuracy of Sentinel-2 albedo over rugged terrain (Figs. 7, S4, and S8), which is very comparable with the results of previous studies using physical BRDF models (Wen et al. 2022). The results also showed close agreement between the Sentinel-2-derived BSA and WSA data and the benchmark of the MODIS product (Fig. S16), which have also been previously reported (Manninen et al. 2019). These multifaceted evaluations and comparisons collectively demonstrate the effectiveness of the proposed direct estimation approach for estimating albedo from Sentinel-2 or other similar satellites with four spectral bands.

The fine-scale characteristic examples of Sentinel-2 albedo demonstrate the great potential of using the proposed approach or data to advance albedo-related fields. First, it can aid multiple practical applications across the agricultural, forestry, and urban sectors, including detecting leaf phenology in forests (Figs. 9b-c, 15a, and S12b; Alibakhshi et al. 2020; Berbet and Costa, 2003; Wang et al. 2018; Williamson et al. 2016), management practices in croplands (Figs. 9a, 15b and S12a; Davin et al. 2014; Lobell et al. 2006; Miller et al. 2016; Singarayer et al. 2009) and grasslands (Figs. 9d and S12d; Abraha et al. 2021; Sciusco et al. 2020; Wang et al. 2007; Zheng et al. 2021), urban built-up infrastructure (Fig.14), and snowfall events (Fig. 15b). Second, it further allows the monitoring of fine-scale biophysical or physical processes from Sentinel-2 albedo. These include, but are not limited to, studies of inferring forest growth from the close connections between land surface albedo and structural properties of individual trees (e.g. leaf area, stem area, and canopy height), tree species, forest age, and species composition (Alibakhshi et al. 2020; Bright et al. 2018; Hovi et al. 2019; Kuusinen et al. 2014, 2016), as well as studies of assessing urbanization by relating surface albedo to the urban metrics of impervious cover fraction, tree coverage, population density, and land surface temperature (Kaplan et al. 2016; Trlica et al. 2017). More importantly, since the spatial resolution of Sentinel-2 is finer than or almost equal to most tree-crown diameters (Bush et al. 2020; Wu et al. 2021), it also offers a promising way to monitor individual tree albedo and help understand the individual-to-ecosystem scaling mechanisms of albedo-related ecological processes plus other local disturbances (e.g. wildfires, drought, and snow melting) that might impact regional- and global-scale surface vulnerability and

feedback to global climate change (Diffenbaugh, 2005; Levy et al. 2018; Sciusco et al. 2020). Second, this approach could produce a unique high-resolution albedo dataset across multiple years (2018-present), which is critical for constraining the parameterization of Earth System Models in simulating the surface energy budget (Bonan and Doney, 2018; Brovkin et al. 2021), thus clarifying the impacts of human activity on global warming by changing biophysical processes (Wohlfahrt et al. 2021; Zeng et al. 2021) and improving the future projection of changing climate (Li et al. 2016; Wang et al. 2016a). Such a dataset would also serve as a benchmark to enable some advancements in refining algorithm development for generating the albedo product from satellites (Li et al. 2018) and improving validation efforts in accuracy assessments of satellite products (Lin et al. 2018; Wu et al. 2017). Third, the proposed integrated evaluation framework provides a multi-scale strategy for assessing the accuracy and uncertainty of high-resolution satellite albedo. The use of 3-D radiative transfer model simulation, in particular, can offer valuable benchmarks when fine-scale ground measurements of surface albedo are lacking. This evaluation framework is also transferable and applicable to other satellite sensors (e.g. Gaofen-2 and PlanetScope; Houborg and McCabe, 2018; Vos et al., 2019) with equivalent or superior spatial resolution than Sentinel-2.

The success of our approach for Monitoring fine-scale surface albedo relies on three premises. First, to compensate for the lack of 10-m surface BRDF data, our algorithm integrates the high-quality MODIS BRDF/albedo product and high-resolution ESA WorldCover data to build a 10-m resolution BRDF database for training, validating, and testing the semi-empirical statistic relationships between surface reflectance and albedo (Fig. 1). Second, to address the challenge of missing 10-m scale validation datasets, our approach provides an integrated evaluation framework of the 3-D radiative transfer model simulations, flux measurements, and satellite observations for generating 10-m scale simulations and representative flux measurements, and satellite albedo for the rigorous cross-scale accuracy and uncertainty assessments. Third, the Sentinel-2 twin satellites with a 10-m spatial resolution and ~5-day revisiting cycle (usually with tens to hundreds of cloud-free observations per local site in a 1-year cycle) allow to capture spatially explicit information (Figs. 10, 12, S14, and S17) and the seasonality of surface albedo (Figs. 9, 15, and S12). Consequently, our algorithm shows that the integration of Sentinel-2 reflectance data and MODIS BRDF/albedo product enables the monitoring of fine-scale surface albedo with high confidence and accuracy.

Compared with previous studies, our study presents at least the following three advancements. First, it is one of the few studies that estimate surface albedo from optical satellites at such a high spatial resolution. Previous studies monitoring surface albedo have primarily focused on satellites with coarse spatial resolution from a distance of several hundred meters (e.g. MODIS and VIIRS; Liu et al. 2017; Wang et al. 2018) to tens of meters (e.g. Landsat; Baldinelli et al. 2017; Franch et al. 2014; He et al. 2018; Shuai et al. 2011). Although Sentinel-2 alone, or together with the Landsat, has been previously used for estimating surface albedo in agriculture and grassland (Li et al. 2018), urban environments (Baldinelli et al. 2017; Guo et al. 2022), and tropical forests (Franch et al. 2018), the integration of the direct estimation approach and 10-m Sentinel-2 twin satellites with rigorous algorithm development and comprehensive validation strategy has rarely been explored. Comparing the results with the other alternatives suggests that our algorithm is the most accurate among all comparative methods. Second, topography significantly impacts surface albedo (Hao et al. 2018; Ma et al. 2022; Wu et al. 2018), but has rarely been considered in the albedo retrieval algorithm for satellite observations. In our approach, we accounted for the topographic effects and assessed these effects using both DART simulations and ground measurements. Third, to the best of our knowledge, this study is the first to enable mapping surface albedo from Sentinel-2 at regional and global scales. The integration of the direct estimation approach with the GEE cloud-computing platform provides a promising possibility to map surface albedo over large spatial coverages. Our experiments show that estimating the surface albedo of one Sentinel-2 gridded tile ($110 \text{ km} \times 110 \text{ km}$) with the GEE service takes only a few minutes (i.e. 3-10 minutes), demonstrating the great potential of generating a global, high-quality, 10-m surface albedo product.

Despite the successful implementations of algorithm development, evaluation, and practical usage, there are still several limitations that might bring some uncertainty to our results and should be considered and improved in future efforts. Firstly, our approach for estimating fine-scale surface albedo reveals a degree of uncertainty in the snow-cover surface compared with the snow-free surface given the poor quality of snow-cover BRDF data from MODIS and the rapid changes in snowfall events. Therefore, an integration of improved physical BRDF models of the snow surface, which could generate more accurate training samples of snow reflectance and albedo (Jiao et al. 2019; Qu et al. 2014), and very high-resolution satellites (e.g. PlanetScope with 3-m spatial resolution and daily global coverage), which could allow for capturing rapid snowfall and

snowmelt events with a higher spatial and temporal frequency (Cannistra et al. 2021; Planet, 2021; Roy et al. 2017, 2021; Wu et al. 2021), would improve the accuracy of our approach in mapping albedo over snow surfaces. Moreover, considering the spatial resolution differences between the MODIS BRDF training samples and Sentinel-2 reflectance, the physical BRDF models or their associate kernel-driven functions accounting for fine-scale surface characteristics (e.g. building morphology and topography relief) could provide 10-m resolution and high-quality BRDF datasets to improve the algorithm training and albedo estimation. Secondly, regarding the evaluation aspect, the lack of ground reference makes the pixel-scale albedo evaluation difficult. More ground measurements with flux footprints that strictly match the Sentinel-2 pixel resolution are thus suggested to be conducted to provide reliable evaluation benchmarks. The integration of unmanned aerial vehicles (UAVs) and hyperspectral imaging technology could also generate valuable albedo references for evaluating satellite-estimated albedo. The area-weighted aggregation approach used in this study without accounting for surface heterogeneity might also involve some uncertainties in comparing Sentinel-2 and MODIS albedo. The multi-scale aggregation strategy that accounts for surface heterogeneity (e.g. rugged topography, Lin et al. 2018, 2021) is suggested to be developed for cross-scale albedo comparisons and assessments. Lastly, cloud cover and shadow result in significant data discontinuity in surface albedo and limit albedo data applicability. Therefore, gap-filling approaches should be developed to fill data gaps and generate high-quality, global-scale 10-m surface products for large-scale albedo analysis (e.g. albedo changes due to vegetation greening and urbanization; Guo et al. 2022; Li et al. 2016).

6. Conclusions

The accurate mapping and monitoring of fine-scale surface albedo are essential to quantify the biophysical processes of natural dynamics and anthropogenic activities. In this study, we proposed a direct estimation approach to advance our capability of estimating high-quality and high-resolution surface albedo from 10-m Sentinel-2 satellites. Our results demonstrate that Sentinel-2 can accurately capture surface albedo and strongly agree with the 3-D DART simulations, ground measurements, and the MODIS satellite product across the site, regional, and global scale. The pilot study demonstrates the promise of integrating the proposed approach with Sentinel-2 to map large-scale surface albedo at a 10-m spatial resolution and capture fine-scale characteristics of surface dynamics. This will enhance Sentinel-2 data science, facilitate higher

resolution surface energy balance mapping, monitoring, and modeling, and contribute to global change research.

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