

# Simulating snow-covered forest bidirectional reflectance by extending hybrid geometric optical–radiative transfer model

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## ABSTRACT

Accurate simulations of the bidirectional reflectance distribution function (BRDF) of snow-covered forests are crucial for retrieving snow and canopy properties, which affects the analysis of net radiation, radiative forcing, and climate change. The anisotropic reflectance of snow in conifer forests is greatly influenced by the high reflectance of snow and the complex travel pathways of radiation in 3D canopy structures, which complicates BRDF simulations. Although bidirectional reflection models have been widely established for snow-free forests, few studies have attempted to simulate the BRDF in snow-covered forests. Therefore, we propose a new snow-covered forest bidirectional reflectance (SFBR) model by coupling geometric optical and radiative transfer models, which includes a snow anisotropic reflectance model (ART), needle leaf optical properties model (LIBERTY), canopy radiative transfer model (4SAIL), and geometric optical model (GOST2). The SFBR model mainly focuses on conifer forests with snow backgrounds; it can simulate anisotropic reflectance spectra from 400 nm to 2500 nm and is the only model to fully consider discontinuous canopy distribution, topographic effects, and snow anisotropy. The SFBR model was validated by simulating the reflectance over snow-covered forests, the results of which showed good consistency with simulations of 3D scene model and remote sensing observations. The proposed SFBR model has the potential to quantify radiation interactions between the snow background and forest overstory, evaluate the sensitivity of canopy reflectance to snow and forest properties, and retrieve snow-covered forest parameters from satellite-observed reflectance data.

## 1. Introduction

Seasonal snow from mountainous forests is a critical water resource for human survival, crop production, and urban settlement (Barnett et al., 2005; Lievens et al., 2019). In the Northern Hemisphere, the 1/5 of the snow region is composed of boreal conifer forests (Güntner et al., 2007; Molotch et al., 2016), which dominate much of the snow zone in North America and Eurasia (Kostadinov et al., 2019; Reid et al., 2014). The high reflectivity of snow has a strong radiative cooling effect on the global climate (Flanner et al., 2011); however, conifer forests have a strong warming effect in winter (Abe et al., 2017; Li et al., 2015). Moreover, the masking effect of the forest canopy on snow cover creates

strong heterogeneity and has different reflection characteristics to snow-free forests and snow (Loranty et al., 2014; Vepsäläinen et al., 2001). Earth satellites observe the reflected signals of sunlight after interaction with snow and the forest canopy from different directions; therefore, it is important to clarify the radiative transfer process of snow-covered forests for structural parameter retrieval and climate change monitoring.

The bidirectional reflectance distribution function (BRDF) is closely related to the parameter retrieval process for remote sensing images. The snow-covered forest albedo is mainly retrieved by hemispherical integration of the BRDF in all viewing directions; thus, accurate bidirectional reflectance simulation is crucial for albedo retrieval (Ni and Woodcock, 2000), which further affects the analysis of net radiation

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(Seyednasrollah and Kumar, 2014), radiative forcing, and albedo feedback (Flanner et al., 2011). Furthermore, the BRDF model has the potential to reduce errors in snow-covered forest mapping, retrieve the concentration of soot pollution and snow grain size, and analyze the effectiveness of the normalized difference snow index (NDSI) in forest areas under multi-angle observations.

Several physical-based models have been developed for snow-covered forest studies. For example, linear spectral mixing models are often used to retrieve snow properties (Dagrun and Rune, 2003), in which the snow reflectance is simulated by radiative transfer models, and rock, soil, and canopy reflectance are selected from field measurements or spectral laboratories such as MODSCAG (Painter et al., 2009) and SPIReS (Bair et al., 2021). However, multiple scattering, canopy shadows, and sloping terrain are not considered in linear spectral mixing models. Klein et al. (1998) combined a snow radiative transfer model with a discontinuous canopy model (GeoSail; Huemmrich, 2001) to simulate snow-covered forest reflectance for snow mapping. However, snow directional-hemispherical reflectance was simulated by the radiative transfer model without accounting for anisotropic effects (Meador and Weaver, 1980; Wiscombe and Warren, 1980), and GeoSail can only be used to simulate reflectance in nadir views. Manninen and Stenberg (2009) and Jääskeläinen and Manninen (2021) used P-theory (Stenberg et al., 2016) to simulate albedo in snow-covered forests; however, the limited ability of this method to simulate bidirectional reflectance hinders it for snow-covered forest parameter inversion through satellite observations.

The bidirectional reflection characteristics of snow-covered forests were not considered in the aforementioned studies. Rittger et al. (2020) found that the different view zenith angles for canopy effects could lead to significant uncertainty in snow-covered forest maps. Xin et al. (2012) and Wang et al. (2022) combined a snow radiative transfer model (Wiscombe and Warren, 1980; Xiong et al., 2015) and a hybrid geometric optical-radiative transfer (GORT) model (Ni et al., 1999) to analyze the anisotropic characteristics of NDSI in snow-covered forests, and proved that consideration of bidirectional reflection effects could improve snow monitoring in forest areas. However, systematic simulation and verification of snow-covered forest models are still lacking because snow-covered forest bidirectional reflectance simulation faces immense challenges. That is, (1) snow-covered forest reflectance varies greatly in different regions owing to the diversity of canopy cover (Webster and Jonas, 2018), snow reflection (Essery, 2013), and terrain; and (2) a lack of cross-comparison and field measurements makes it difficult to evaluate model effectiveness, which hinders the development of a physical model for BRDF simulation.

For snow-free forests, effective bidirectional reflectance models have been extensively established, including radiative transfer (Verhoef, 1984b; Verhoef and Bach, 2003), geometric optical (Chen and Leblanc, 1997; Li and Strahler, 1992), hybrid GORT (Li et al., 1995; Ni et al., 1999), and 3D scene models (Gastellu Etchegorry et al., 2015; Qi et al., 2019). Among them, hybrid GORT models are particularly suitable for simulating the bidirectional reflectance of discontinuous canopies because they combine the advantages of geometric optical models to describe single scattering and canopy radiative transfer models to describe multiple scattering (Chen and Leblanc, 2001; Kuusk, 2018). Many hybrid GORT models can achieve outstanding simulation results for bidirectional reflectance on flat ground, such as ACTS (Ni-Meister et al., 2010), MGeoSail (Wang et al., 2013), and FRT (Kuusk et al., 2014). However, sloping terrain changes the sun-target-view geometry and path length of the canopy, which results in severe reflectance changes compared with flat ground (Yin et al., 2018; Yin et al., 2017). To apply a geometric optical model to rugged terrain, canopy shape transform and topographic transform can be used to switch the Li-Strahler component areal ratios (Li and Strahler, 1992) from flat ground to sloping terrain (Wu et al., 2018); however, the hypothesis of a spherical canopy restricts the application to conifer forests. Fan et al. (2014b, 2015) built a geometric optical model (GOST2) by extending

the four-scale model (Chen and Leblanc, 1997) to suit sloping terrains, which mainly focused on conifer forest simulation by adopting a “cone + cylinder” tree crown shape and considering the clump distribution. In hybrid GORT models, multiple scattering between the floor and canopy has been widely described by P-theory and the SAIL model (Fan et al., 2014a; Mousivand et al., 2015), the latter of which on the basis of four-stream radiative transfer theory and can couple forest floor bidirectional reflection model flexibility.

Motivated by the need to consider a snow-covered background when simulating bidirectional reflectance of the winter forest, we attempt to extend hybrid GORT models to snow-covered forests. Snow has high reflectance and obvious forward scattering characteristics; thus, the anisotropy of snow cover must be considered in a snow-covered forest reflection model. The asymptotic radiative transfer (ART) model (Kokhanovsky et al., 2005; Kokhanovsky and Zege, 2004) has an excellent ability to simulate snow bidirectional reflection characteristics (Lamare et al., 2020) and has been widely utilized to inverse snow grain size (Kokhanovsky et al., 2011; Zege et al., 2011), concentration of soot pollution (Kokhanovsky et al., 2018), and snow albedo (Qu et al., 2016). Therefore, we combine the snow radiative transfer model and hybrid GORT model for snow-covered forest reflectance simulations.

Eventually, a new snow-covered forest bidirectional reflectance (SFBR) model is proposed to simulate BRDF for a spectra range from 400 nm to 2500 nm, which fully considers the discontinuous canopy distribution, topographic effects, and snow anisotropy. The SFBR model focuses on reflectance simulations for a conifer forest with a snow-covered background by coupling the following four submodels: the robust snow model ART, the needle leaf model LIBERTY (Dawson et al., 1998; Leblanc and Chen, 2000), the canopy radiative transfer model 4SAIL (Verhoef and Bach, 2007), and the geometric optical model GOST2 (Fan et al., 2015). Furthermore, to verify the effectiveness of the SFBR model, we also extend the LESS model, proposed by (Qi et al., 2019) for the radiative transfer modeling of heterogeneous 3D scenes, to suit for bidirectional reflectance simulations of snow-covered forests. We then compare the SFBR simulation results with those of LESS model and remote sensing data to evaluate the model performance for simulating snow-covered forest reflectance.

## 2. Snow-covered forest bidirectional reflectance (SFBR) model

### 2.1. Model structure

The snow-covered forest reflectance is composed of four components within a pixel:

$$R = R_T \cdot K_T + R_G \cdot K_G + R_{ZT} \cdot K_{ZT} + R_{ZG} \cdot K_{ZG} \quad (1)$$

$$\begin{aligned} R_T &= (1-f) \cdot R_T^{\text{dir}} + f \cdot R_T^{\text{dif}} \\ R_G &= (1-f) \cdot R_G^{\text{dir}} + f \cdot R_G^{\text{dif}} \\ R_{ZT} &= (1-f) \cdot R_{ZT}^{\text{dir}} + f \cdot R_{ZT}^{\text{dif}} \\ R_{ZG} &= (1-f) \cdot R_{ZG}^{\text{dir}} + f \cdot R_{ZG}^{\text{dif}} \end{aligned} \quad (2)$$

where  $K_T$ ,  $K_G$ ,  $K_{ZT}$ , and  $K_{ZG}$  are the area ratios of the sunlit canopy, sunlit snow, shaded canopy, and shaded snow in a particular view direction, respectively;  $f$  is the fraction of diffuse skylight, and  $R^{\text{dir}}$  and  $R^{\text{dif}}$  are the reflectance of these four scene components with direct and diffuse radiation, which are wavelength-dependent. For the SFBR model, the GOST2 model was applied to simulate the area ratios, and the 4SAIL model, snow anisotropic model ART, and needle leaf model LIBERTY were coupled to describe multiple scattering within a snow-covered forest scene over sloping terrain. All submodels coupled in the SFBR model are internally connected, and the coupling process and input parameters are described in Fig. 1 and Table 1, respectively.

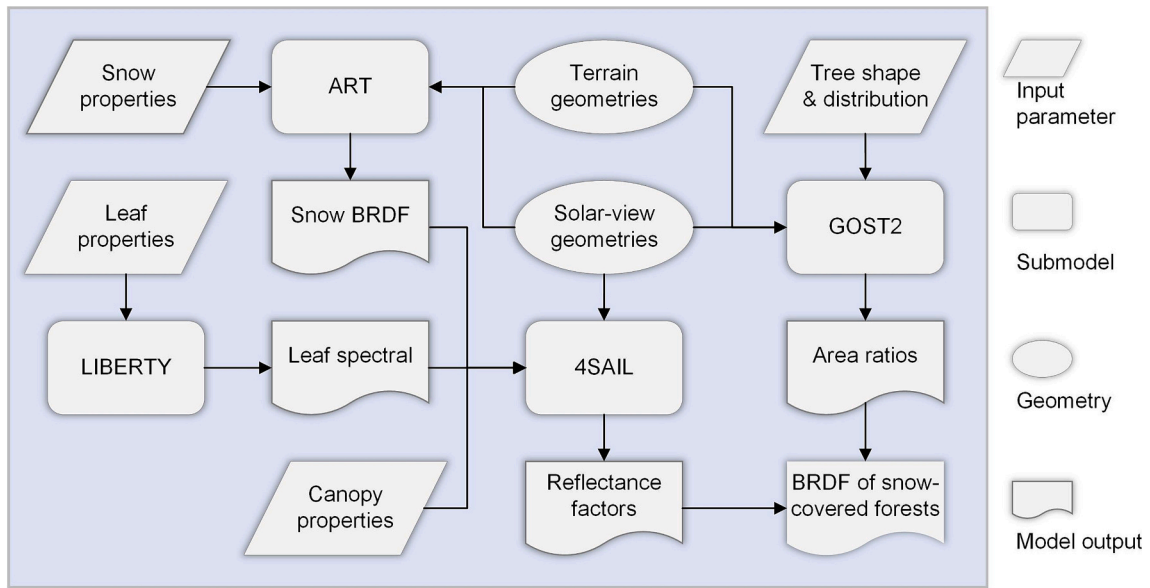


Fig. 1. Flowchart of the proposed snow-covered forest bidirectional reflectance (SFBR) model.

**Table 1**  
Input parameters of the SFBR model.

| Element             | Parameter                                      | Unit                   | Range     | Default value |
|---------------------|------------------------------------------------|------------------------|-----------|---------------|
| Snow                | Snow grain size ( $a_{ef}$ )                   | $\mu\text{m}$          | 50–5000   | 500           |
|                     | Concentration of soot pollution ( $C_{soot}$ ) | ppb                    | 0–5000    | 0             |
|                     | Cell diameter                                  | $\mu\text{m}$          | 20–100    | 40            |
|                     | Leaf thickness                                 | –                      | 1–10      | 1.6           |
|                     | Inter-cellular air space ( $X_{u1}$ )          | –                      | 0.01–0.1  | 0.045         |
| Leaf                | Baseline absorption                            | –                      | –         | 0.0005        |
|                     | Albino absorption                              | –                      | 0–4       | 2             |
|                     | Chlorophyll content ( $C_{ab}$ )               | $\text{mg m}^{-2}$     | 0–600     | 200           |
|                     | Lignin content ( $C_l$ )                       | $\text{g m}^{-2}$      | 10–80     | 40            |
|                     | Nitrogen content ( $C_n$ )                     | $\text{g m}^{-2}$      | 0.3–2     | 1             |
|                     | Water content ( $C_w$ )                        | $\text{g m}^{-2}$      | 0–500     | 100           |
|                     | LIDF <sub>a</sub>                              | –                      | –1–1      | –0.35         |
|                     | LIDF <sub>b</sub>                              | –                      | –1–1      | –0.15         |
|                     | LAI                                            | –                      | 0–7       | 2.4           |
|                     | Tree density ( $\lambda$ )                     | $\text{trees ha}^{-1}$ | 0–4000    | 2000          |
| Canopy              | Grouping ( $m_2$ )                             | –                      | 1–20      | 5             |
|                     | Number of quadrats                             | –                      | –         | 30            |
|                     | Height of trunk ( $H_a$ )                      | m                      | 1–3       | 1             |
|                     | Height of cylinders ( $H_b$ )                  | m                      | 2–20      | 5             |
|                     | Radius of canopy                               | m                      | 0.5–3     | 1             |
|                     | Half apex angle                                | deg                    | 5–30      | 30            |
|                     | Leaf projection function ( $G$ )               | –                      | –         | 0.5           |
|                     | Leaf width ( $W_s$ )                           | m                      | 0.02–0.17 | 0.001         |
|                     | Clumping index ( $\Omega_c$ )                  | –                      | 0–2.1     | 1             |
|                     | Solar zenith angle ( $\theta_s$ )              | deg                    | 0–75      | 40            |
| Geometry and others | Solar azimuth angle ( $\varphi_s$ )            | deg                    | 0–360     | 0             |
|                     | View zenith angle ( $\theta_v$ )               | deg                    | 0–75      | 0             |
|                     | View azimuth angle ( $\varphi_v$ )             | deg                    | 0–360     | 0             |
|                     | Slope ( $\theta$ )                             | deg                    | 0–80      | 0             |
|                     | Aspect ( $\varphi$ )                           | deg                    | 0–360     | 0             |
|                     | Fraction of diffuse skylight (SKYL)            | –                      | 0–1       | 0             |

## 2.2. Component area ratios

The component area ratios were calculated by GOST2, which was developed using geometric optical and ray-tracing theory. GOST2 considers the trees' geotropic growth and sloping terrains. The stand

structure in the SFBR model was parameterized by the canopy shape, internal canopy characteristics, and spatial distribution of trees. The “cone + cylinder” shape was used to describe the geometric characteristics of conifer tree crowns, including the radius, height, and half apex angle. The internal characteristics of the canopy were described using the leaf area index (LAI), clumping index, leaf angle distribution, etc. The pattern of tree positions was considered a clump distribution, and the tree density described the number of trees.

Through the scene description in GOST2, the areas of the forest canopy ( $1 - P_{\text{gap}}$ ) and snow-covered background ( $P_{\text{gap}}$ ) were separated by the directional gap probability, and the gap probability between and within canopy was considered using the Neyman distribution and Lambert–Beer's law. The sunlit snow ( $K_G$ ) was then separated from the snow-covered background using a hotspot function, and the sunlit canopy ( $K_T$ ) was separated from the canopy using a ray-tracing model. Furthermore, the shaded snow was calculated using  $K_{ZG} = P_{\text{gap}} - K_G$ , whereas the shaded canopy was calculated using  $K_{ZT} = 1 - P_{\text{gap}} - K_T$ .

## 2.3. Component reflectance factors

In the SFBR model, we coupled the snow (ART), needle leaf (LIBERTY), and canopy radiative transfer (4SAIL) models to simulate four component reflectance factors, including single and multiple scattering. The component reflectance factors are described by the SAIL model, assuming a Lambert soil surface in a snow-free forest (Wu et al., 2018); however, snow has obvious forward scattering characteristics and strong interaction with the canopy. Therefore, we considered the anisotropic reflection of snow over a sloping terrain in the SFBR model. As described in this section, we first corrected the snow anisotropic radiative transfer model to make it applicable to sloping terrain, then introduced a specific calculation process for the component reflectance factors.

### 2.3.1. Snow anisotropic reflectance simulation for sloping terrain

In sloping terrain, the slope ( $\theta$ ) and aspect ( $\varphi$ ) change the original solar-target-view geometries, which change the snow bidirectional reflectance from that on flat ground. Thus, we corrected the original solar zenith angle ( $\theta_s$ ) and view zenith angle ( $\theta_v$ ) to the relative solar zenith angle ( $\theta'_s$ ) and relative view zenith angle ( $\theta'_v$ ) for sloping surfaces, which can be calculated by  $\cos\theta'_s = \cos\theta_s \cos\theta + \sin\theta_s \sin\theta_s \cos(\varphi - \varphi_s)$  and  $\cos\theta'_v = \cos\theta_v \cos\theta + \sin\theta_v \sin\theta_v \cos(\varphi - \varphi_v)$ , where  $\varphi_s$  and  $\varphi_v$  are the original solar and view azimuth angle, respectively. Note that this correction

focuses only on snow reflectance, and canopy correction is not necessary because the geotropic growth of trees is considered in the geometric optical model.

Ice crystals are the main components of snow that fall from the atmosphere. Most photons incident on the snow surface are reflected by ice crystals. Light reflection and refraction then occur on the crystal surfaces. ART assumes that the crystals are fractal particles and simulates the anisotropic reflectance of snow by parameterizing the concentration of soot pollution and the snow grain size. The snow bidirectional reflectance was simulated as an exponential approximation (Kokhanovsky et al., 2005; Kokhanovsky and Zege, 2004):

$$r_{so} = r_0 \exp\left(\frac{-\alpha K_s K_v}{r_0}\right) \quad (3)$$

where  $K_s = \frac{3}{2}(1 + 2\cos\theta'_s)$  is the escape function for different relative solar zenith angles ( $\theta'_s$ );  $K_v$  has the same form as  $K_s$  for different relative view zenith angles ( $\theta'_v$ ); and  $r_0$  is the reflectance of the zero absorption medium:

$$r_0 = \frac{a + b(\cos\theta'_s + \cos\theta'_v) + c\cos\theta'_s\cos\theta'_v + p}{4(\cos\theta'_s + \cos\theta'_v)} \quad (4)$$

$$p = 11.1\exp(-0.087\Theta) + 1.1\exp(-0.014\Theta) \quad (5)$$

Here,  $a$ ,  $b$ , and  $c$  are equal to 1.247, 1.186, and 5.157, respectively. The scattering angle ( $\Theta$ ) is calculated by  $\cos\Theta = -\cos\theta'_s\cos\theta'_v + \sin\theta'_s\sin\theta'_v\cos(\varphi'_s - \varphi'_v)$ ,  $\varphi'_s$  and  $\varphi'_v$  are the relative solar and view azimuth angle, respectively.

In Eq. (2),  $\alpha$  is expressed by Zege et al. (2008, 2011):

$$\alpha = A\sqrt{\frac{4\pi a_{ef}}{\lambda}}(k + \gamma C_{soot}) \quad (6)$$

$$\begin{aligned} R_4 &= P_{gap}(r_{so}\tau_{oo} + r_{sd}\tau_{do}) + P_{gap}\{r_{sd}\tau_{do}[r_{dd}(1 - K_{open})\rho_{dd}] + r_{so}\rho_{sd}(1 - K_{open})r_{do}\tau_{oo}\} \\ &+ P_{gap}\{r_{sd}\tau_{do}[r_{dd}(1 - K_{open})\rho_{dd}] + r_{so}\rho_{sd}(1 - K_{open})r_{do}\tau_{oo}\}[r_{dd}(1 - K_{open})\rho_{dd}] \\ &+ \dots + P_{gap}[r_{sd}\tau_{do} + r_{so}\rho_{sd}(1 - K_{open})r_{do}\tau_{oo}][r_{dd}(1 - K_{open})\rho_{dd}]^n \\ &= P_{gap}\left\{r_{so}\tau_{oo} + \frac{[r_{sd}\tau_{do} + r_{so}\rho_{sd}(1 - K_{open})r_{do}\tau_{oo}]}{1 - r_{dd}(1 - K_{open})\rho_{dd}}\right\} \end{aligned} \quad (10)$$

where  $A = 5.8$ ;  $\gamma = 0.2$ ;  $\lambda$  is the wavelength;  $a_{ef}$  and  $C_{soot}$  are snow parameters described in Table 1; and  $k$  is related to ice refractive index (Warren and Brandt, 2008).

In this model, the bi-hemispherical reflectance ( $r_{dd}$ ) and directional-hemispherical reflectance ( $r_{sd}$ ) of the snow layer (Kokhanovsky, 2013) can be calculated as

$$r_{dd} = r_0 \exp\left(\frac{-\alpha}{r_0}\right) \quad (7)$$

$$r_{sd} = r_0 \exp\left(\frac{-\alpha K_s}{r_0}\right) \quad (8)$$

Because snow reflectance is reciprocal in the radiative transfer process, the hemispherical-directional reflectance ( $r_{do}$ ) and directional-hemispherical reflectance have the same form; thus, we can acquire  $r_{do} = r_{sd}$  using the relative view zenith angle instead of the relative solar zenith angle.

### 2.3.2. Component reflectance simulation

The component reflectance of the sunlit canopy, shaded canopy, sunlit snow, and shaded snow in the SFBR model was calculated using the snow, leaf, and canopy radiative transfer models. We applied the published version of LIBERTY in a five-scale model (Leblanc and Chen, 2000) and simulated the leaf spectrum by inputting structural and biochemical parameters (Table 1), which are important input parameters for the canopy radiative transfer model. 4SAIL was used to simulate canopy reflectance and transmittance signals by considering multiple scattering between the leaves and the canopy structure. The leaf inclination distribution, LAI, and solar-view geometries were required parameters in the canopy model.

Regarding direct radiation, the incident light is divided into two parts: the photon first collides with the canopy ( $1 - P_{gap}$ ) and first collides with snow passing through the canopy gap ( $P_{gap}$ ). Fig. 2a displays the radiation contributions of the canopy in snow-covered forests. Canopy radiation includes canopy single scattering ( $R_1$ ), multiple scattering between the canopy ( $R_2$ ), and multiple scattering from the interaction between the snow and canopy caused by the first collision from the canopy ( $R_3$ ) and the first collision from the snow ( $R_4$ ). Canopy single scattering and multiple scattering are modeled in 4SAIL (Verhoef and Bach, 2003, 2007) as  $R_1 = \rho_{sos}$  and  $R_2 = \rho_{sod}$ , respectively. The multiple scattering factors between the canopy and snow can be described by  $r_{dd}(1 - K_{open})\rho_{dd}$  (Wu et al., 2018), where  $K_{open}$  is the canopy openness factor  $K_{open} = \int_0^{\pi/2} P_{gap}(\theta)\sin(2\theta)d\theta$ . Because the anisotropic reflectance of snow is considered on the forest floor,  $R_3$  and  $R_4$  are expressed as

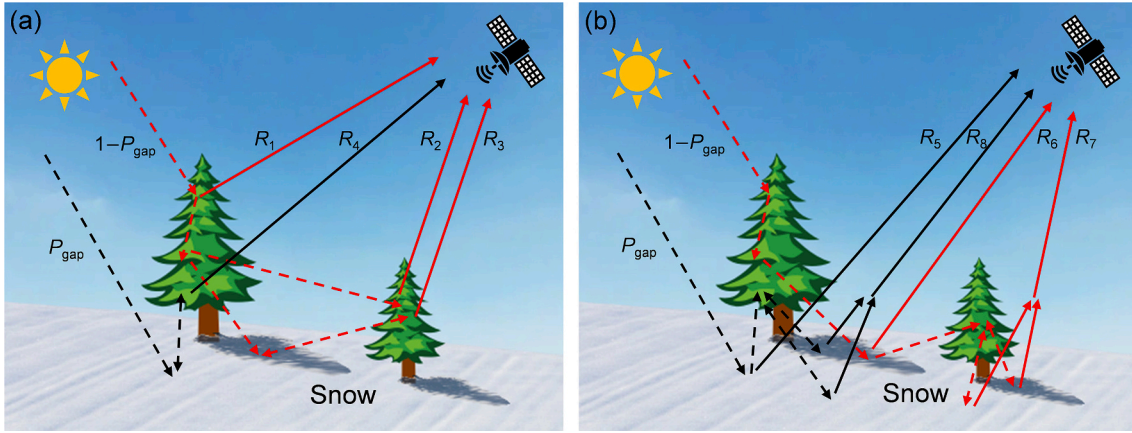
$$R_3 = (1 - P_{gap}) \times \left\{ \tau_{ss}r_{so}\tau_{oo} + \frac{(\tau_{ss}r_{sd} + \tau_{sd}r_{dd})\tau_{do} + [\tau_{sd} + \tau_{ss}r_{sd}(1 - K_{open})\rho_{dd}][r_{do}\tau_{oo}]}{1 - r_{dd}(1 - K_{open})\rho_{dd}} \right\} \quad (9)$$

where  $r$  represents the snow surface reflectance described in Subsection 2.3.1;  $\rho$  and  $\tau$  are the reflection and transmission passing through the canopy, respectively; the three subscript symbols represent the direct solar radiation (s), diffuse hemispherical radiation (d), and observed radiation (o), respectively;  $\rho_{sd}$  represents the directional-hemispherical reflectance of the canopy;  $\rho_{dd}$  represents the bi-hemispherical reflectance of the canopy;  $\tau_{ss}$  represents the canopy direct transmittance in the incident direction;  $\tau_{oo}$  represents the canopy direct transmittance in the observed direction;  $\tau_{sd}$  represents the canopy diffuse transmittance for direct radiation; and  $\tau_{do}$  represents the canopy directional transmittance for diffuse radiation. For definitions of all terminology, refer to Verhoef et al. (2018) and Yang et al. (2020).

The sunlit canopy includes single and multiple scattering, whereas the shaded canopy only includes multiple scattering; thus,  $R_T^{dir}$  and  $R_{ZT}^{dir}$  can be expressed as

$$R_T^{dir} = R_1 + R_2 + R_3 + R_4 \quad (11)$$





**Fig. 2.** Reflectance contributions of the canopy (a) and snow (b) in snow-covered forests under direct radiation.  $R$  and  $P_{\text{gap}}$  substitute for  $R'$  and  $K_{\text{open}}$  under diffuse radiation, respectively.

$$R_{\text{ZT}}^{\text{dir}} = R_2 + R_3 + R_4 \quad (12)$$

The radiation contribution of snow to the snow-covered forests is shown in Fig. 2b. The radiation of the snow includes single scattering from sunlit snow ( $R_5$ ), single scattering from shaded snow ( $R_6$ ), and multiple scattering from the interaction between snow and canopy caused by the first collision from the canopy ( $R_7$ ) and the first collision from the snow ( $R_8$ ). Single scattering of sunlit and shaded snow are simulated using  $R_5 = r_{\text{so}}$  and  $R_6 = (1 - P_{\text{gap}})(\tau_{\text{ss}}r_{\text{so}} + \tau_{\text{sd}}r_{\text{do}})$ , respectively.  $R_7$  and  $R_8$  are expressed as

$$\begin{aligned} R_7 &= (1 - P_{\text{gap}})(\tau_{\text{ss}}r_{\text{sd}} + \tau_{\text{sd}}r_{\text{dd}})[(1 - K_{\text{open}})\rho_{\text{dd}}]r_{\text{do}} \\ &+ (1 - P_{\text{gap}})(\tau_{\text{ss}}r_{\text{sd}} + \tau_{\text{sd}}r_{\text{dd}})[(1 - K_{\text{open}})\rho_{\text{dd}}]r_{\text{do}}[(1 - K_{\text{open}})\rho_{\text{dd}}] \\ &+ \dots + (1 - P_{\text{gap}})(\tau_{\text{ss}}r_{\text{sd}} + \tau_{\text{sd}}r_{\text{dd}})[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]^n \\ &= (1 - P_{\text{gap}})\frac{(\tau_{\text{ss}}r_{\text{sd}} + \tau_{\text{sd}}r_{\text{dd}})[(1 - K_{\text{open}})\rho_{\text{dd}}]r_{\text{do}}}{1 - r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}} \end{aligned} \quad (13)$$

$$\begin{aligned} R_8 &= P_{\text{gap}}[r_{\text{sd}}(1 - K_{\text{open}})\rho_{\text{dd}}]r_{\text{do}} + P_{\text{gap}}[r_{\text{sd}}(1 - K_{\text{open}})\rho_{\text{dd}}][r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]r_{\text{do}} \\ &+ \dots + P_{\text{gap}}[r_{\text{sd}}(1 - K_{\text{open}})\rho_{\text{dd}}][r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]^n r_{\text{do}} \\ &= P_{\text{gap}}\frac{[r_{\text{sd}}(1 - K_{\text{open}})\rho_{\text{dd}}]r_{\text{do}}}{1 - r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}} \end{aligned} \quad (14)$$

$$\begin{aligned} R_4' &= K_{\text{open}}(r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}\tau_{\text{do}}) + K_{\text{open}}\{ (r_{\text{do}}\rho_{\text{sd}}(1 - K_{\text{open}})r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]\tau_{\text{do}} \} \\ &+ K_{\text{open}}\{ (r_{\text{do}}\rho_{\text{sd}}(1 - K_{\text{open}})r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]\tau_{\text{do}} \} \\ &\times [r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}] + \dots + K_{\text{open}}[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]^n \\ &\times \{ (r_{\text{do}}\rho_{\text{sd}}(1 - K_{\text{open}})r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]\tau_{\text{do}} \} \\ &= K_{\text{open}}r_{\text{do}}\tau_{\text{oo}} + K_{\text{open}}\frac{r_{\text{dd}}\tau_{\text{do}} + r_{\text{do}}\rho_{\text{sd}}(1 - K_{\text{open}})r_{\text{do}}\tau_{\text{oo}}}{1 - r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}} \end{aligned} \quad (20)$$

The sunlit and shaded snow include single scattering and multiple scattering; thus,  $R_{\text{G}}^{\text{dir}}$  and  $R_{\text{ZG}}^{\text{dir}}$  can be expressed as

$$R_{\text{G}}^{\text{dir}} = R_5 + R_7 + R_8 \quad (15)$$

$$R_{\text{ZG}}^{\text{dir}} = R_6 + R_7 + R_8 \quad (16)$$

Regarding diffuse radiation, only sunlit canopy ( $1 - K_{\text{open}}$ ) and sunlit

snow ( $K_{\text{open}}$ ) can be viewed in the snow-covered forest because the incident light is commonly assumed isotropic irradiance (Huemmrich, 2001). Canopy radiation includes canopy single scattering ( $R_1'$ ), multiple scattering between the canopy ( $R_2'$ ), and multiple scattering from the interaction between the snow and canopy caused by the first collision from the canopy ( $R_3'$ ) and the first collision from the snow ( $R_4'$ ) (Fig. 2a). In order to maintain the same form as the four factors under direct radiation, the radiation contribution of the diffuse shaded canopy ( $R_{\text{ZT}}^{\text{dif}}$ ) is retained but has the same value as sunlit canopy ( $R_{\text{T}}^{\text{dif}}$ ).

$$R_1' = \rho_{\text{dos}} \quad (17)$$

$$R_2' = \rho_{\text{dod}} \quad (18)$$

$$\begin{aligned} R_3' &= (1 - K_{\text{open}})\tau_{\text{dd}}(r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}\tau_{\text{do}}) \\ &+ (1 - K_{\text{open}})\tau_{\text{dd}}(r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}\tau_{\text{do}})[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}] \\ &+ \dots + (1 - K_{\text{open}})\tau_{\text{dd}}(r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}\tau_{\text{do}})[r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}]^n \\ &= (1 - K_{\text{open}})\frac{\tau_{\text{dd}}(r_{\text{do}}\tau_{\text{oo}} + r_{\text{dd}}\tau_{\text{do}})}{1 - r_{\text{dd}}(1 - K_{\text{open}})\rho_{\text{dd}}} \end{aligned} \quad (19)$$

$$R_{\text{T}}^{\text{dif}} = R_{\text{ZT}}^{\text{dif}} = R_1' + R_2' + R_3' + R_4' \quad (21)$$

The radiation contribution of snow under diffuse skylight includes single scattering from snow with the photons passing through the canopy gap ( $R_5'$ ), single scattering from snow with photons transmitted through the canopy ( $R_6'$ ), and multiple scattering from the interaction

between snow and canopy caused by the first collision from the canopy ( $R'_7$ ) and the first collision from the snow ( $R'_8$ ) (Fig. 2b). Similar to the diffuse sunlit canopy and shaded canopy, the radiation contributions of diffuse sunlit snow ( $R_G^{\text{dif}}$ ) and shaded snow ( $R_{ZG}^{\text{dif}}$ ) also have the same value.

$$\begin{aligned} R'_5 + R'_8 &= K_{\text{open}} r_{\text{do}} + K_{\text{open}} r_{\text{do}} [r_{\text{dd}} (1 - K_{\text{open}}) \rho_{\text{dd}}] \\ &+ \dots + K_{\text{open}} r_{\text{do}} [r_{\text{dd}} (1 - K_{\text{open}}) \rho_{\text{dd}}]^n \\ &= \frac{K_{\text{open}} r_{\text{do}}}{1 - r_{\text{dd}} (1 - K_{\text{open}}) \rho_{\text{dd}}} \end{aligned} \quad (22)$$

$$\begin{aligned} R'_6 + R'_7 &= (1 - K_{\text{open}}) \tau_{\text{dd}} r_{\text{do}} \\ &+ (1 - K_{\text{open}}) \tau_{\text{dd}} r_{\text{do}} [r_{\text{dd}} (1 - K_{\text{open}}) \rho_{\text{dd}}] \\ &+ \dots + (1 - K_{\text{open}}) \tau_{\text{dd}} r_{\text{do}} [r_{\text{dd}} (1 - K_{\text{open}}) \rho_{\text{dd}}]^n \\ &= \frac{(1 - K_{\text{open}}) \tau_{\text{dd}} r_{\text{do}}}{1 - r_{\text{dd}} (1 - K_{\text{open}}) \rho_{\text{dd}}} \end{aligned} \quad (23)$$

$$R_G^{\text{dif}} = R_{ZG}^{\text{dif}} = R'_5 + R'_6 + R'_7 + R'_8 \quad (24)$$

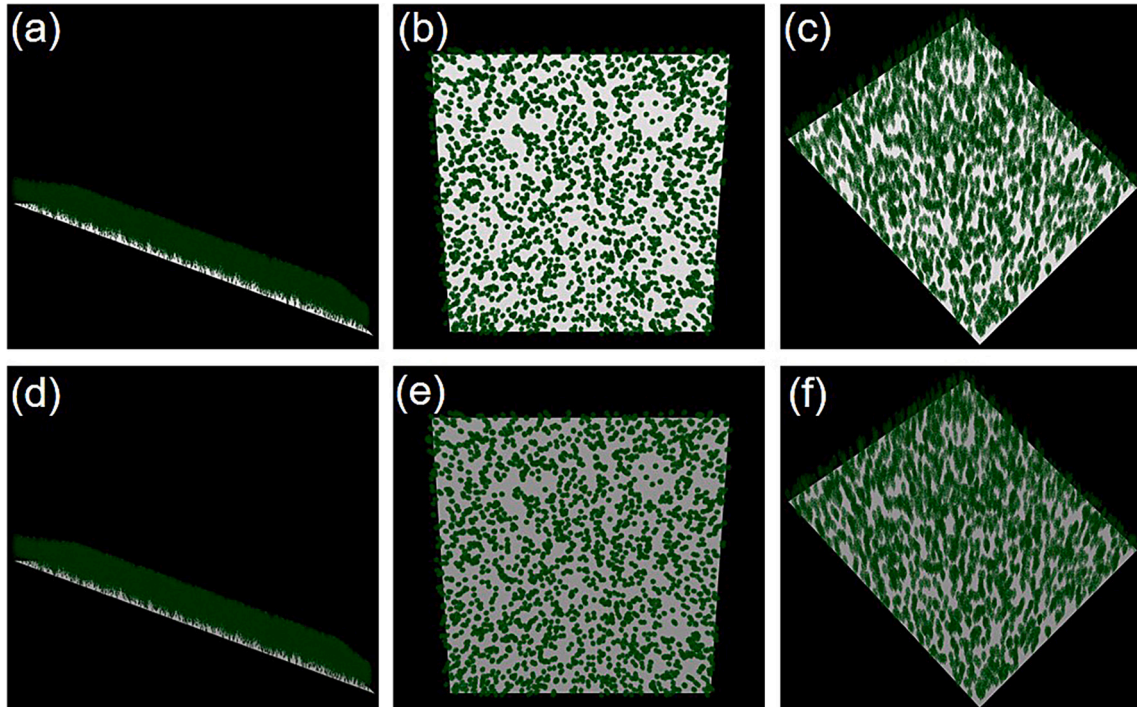
#### 2.4. Validation method

Two methods were adopted to verify the simulation effect of the SFBR model on snow-covered forest reflectance. First, we compared the simulated reflectance with those of the 3D scene model for spectral from 400 nm to 2500 nm. The LESS model, which is based on Monte Carlo ray tracing, can produce multi-angle and multispectral images over a 3D discontinuous canopy (Qi et al., 2019). The LESS model has been used to validate the model of directional forest brightness temperatures (Bian et al., 2022), stochastic radiative transport theory (Yan et al., 2021), and BRDF of forest plantations (Geng et al., 2022). Compared with other 3D scene models, LESS achieved a similar accuracy and faster running speed in the RAMI experiment. At present, LESS and other 3D scene models only focus on snow-free forests.

To validate the SFBR model, we coupled the ART and LIBERTY

models to the LESS model, which results in the same snow and leaf spectral characteristics and similar canopy characteristics for LESS and SFBR, thereby ensuring the effectiveness of the verification results. The simulation steps of LESS model are as follows: first, a 3D landscape with  $100 \times 100$  m scene size and 1 m resolution is constructed for flat or sloping terrain, and virtual cylinder tree crowns are randomly distributed in the scene by input tree density parameters, the leaves are represented by triangular elements within a crown; then, the basic parameters are input including the fraction of diffuse skylight, solar-view geometry, and snow/leaf optical parameters; finally, the multi-angle image of the virtual snow-covered forest are rendered using orthographic observations by changing the view angles of the sensor, and the mean reflectance of the image is regarded as the bidirectional reflectance of LESS simulation. The parameters of the SFBR are used for the LESS model input, and the cross-comparison can be carried effectively between the site of SFBR and the grid of LESS. The multi-angle views of the simulated snow-covered forest with fresh snow and contaminated snow are shown in Fig. 3.

Second, we compared the simulated reflectance with Terra MODIS and Landsat-8 OLI data. Three snow-covered forest locations were selected according to the following criteria: the main vegetation type was conifer forest and the closest meteorological station was covered with snow. The three locations are in Daxinganling, Xiaoxinganling, and Changbai Mountain of Northeast China, which has a widely distributed conifer forest and common snow cover in winter (Che et al., 2016). In MCD43A products, the kernel-driven model assumes that land cover does not change over a period of 16 days (Lucht et al., 2000; Wang et al., 2014). Accordingly, we made the same assumption when using MODIS data to verify the SFBR model during the stable snow period. MOD09GA was used to provide reflectance and solar-view geometry data. The maximum number of cloudless reflectance pixels over 16 days was collected for validation purposes by the cloud mask product in MOD10A1. The locations of the validation sites and China land cover dataset (Yang and Huang, 2021) were shown in Fig. 4a. The NDSI and the normalized difference vegetation index (NDVI) of validation sites have a low positive value and the snow depth of the closest station has a



**Fig. 3.** Multi-angle views of simulated snow-covered forests by LESS with fresh snow (top) and contaminated snow (bottom) over a slope of  $20^\circ$  and tree density of  $2000 \text{ trees ha}^{-1}$ . (a) and (d) side view. (b) and (e) nadir view. (c) and (f) perspective view.

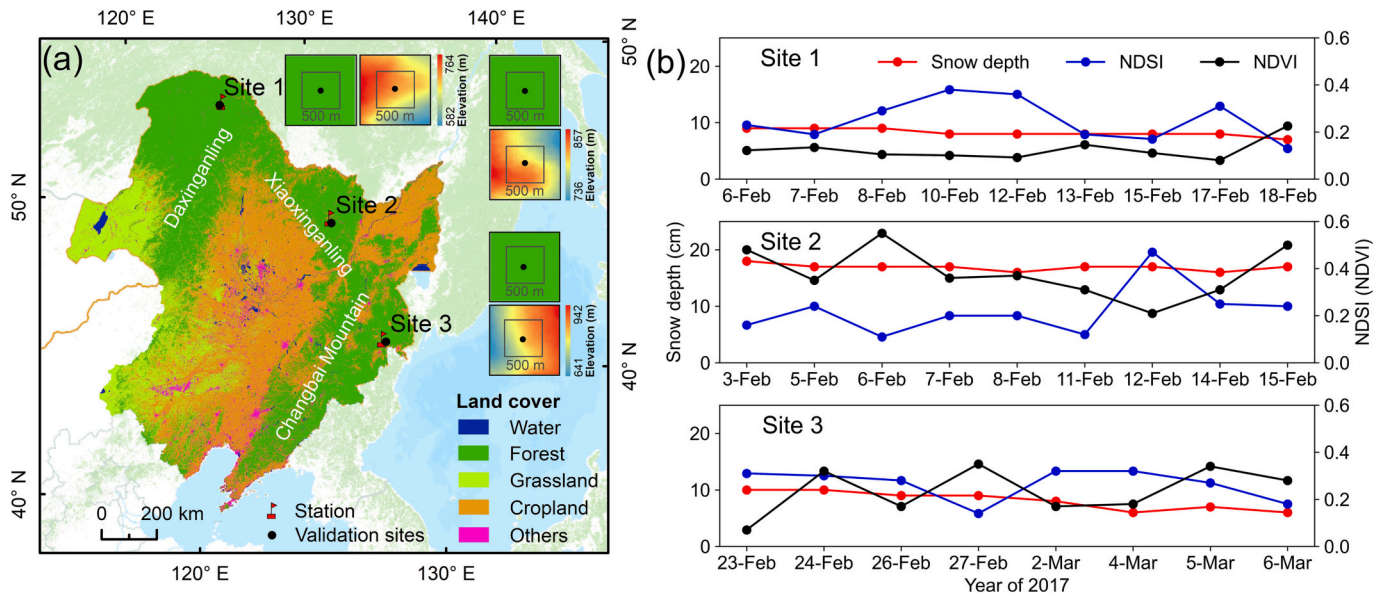


Fig. 4. Location, land cover, and elevation of the validation sites over Northeast China (a), and their time-series snow depth, NDSI, and NDVI over a stable snow period (b).

**Table 2**  
Input parameters for SFBR simulations at three snow-covered forest sites.

| Parameter | Longitude (°) | Latitude (°) | Elevation (m) | $a_{ef}$ ( $\mu\text{m}$ ) | $C_{soot}$ (ppb) | LAI | $\lambda$ (trees $\text{ha}^{-1}$ ) | Slope (°)                   | Aspect (°) |
|-----------|---------------|--------------|---------------|----------------------------|------------------|-----|-------------------------------------|-----------------------------|------------|
| Site 1    | 124.5609      | 52.2444      | 670           | 300                        | 600              | 1.2 | 3000                                | 9.0                         | 112.7      |
| Site 2    | 128.8496      | 47.5275      | 812           | 100                        | 200              | 2.0 | 1000                                | 5.8                         | 58.1       |
| Site 3    | 129.9123      | 43.1799      | 829           | 400                        | 100              | 2.5 | 1400                                | 16.8                        | 263.5      |
|           | $H_a$ : 2 m   | $H_b$ : 10 m | Radius: 1 m   | Half apex angle: 13°       |                  |     | $X_{ii}$ : 0.01                     | $C_w$ : 0 $\text{g m}^{-2}$ |            |

small variation (Fig. 4b), which proved that the selected validation sites have a stable snow-covered forest type. The OLI acquires reflectance in the near-nadir direction and has a low revisit period; thus, only single site can be used for validation. Specifically, the atmospherically corrected surface reflectance of site 1, 2, and 3 were selected from Feb 18, 2017, Mar 03, 2017, and Feb 24, 2017, respectively.

In the retrieval of global land surface parameters, snow models and vegetation models are often used respectively according to land cover

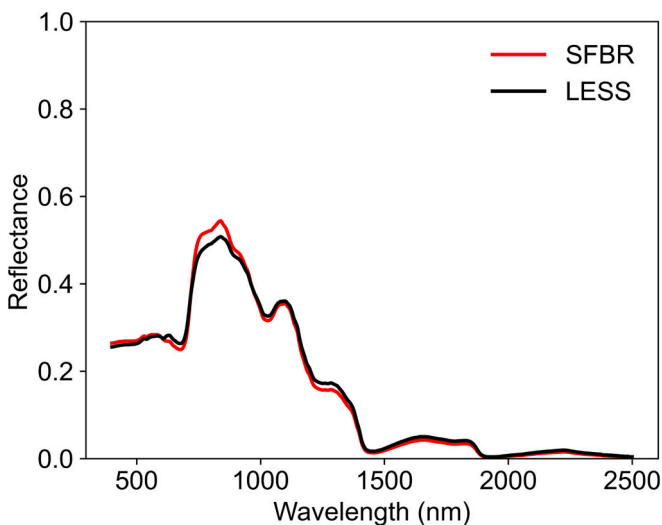


Fig. 5. Comparison of the snow-covered forest nadir HDRF simulated by SFBR and LESS models.

types (Qu et al., 2014), which brings large errors to the retrieval of snow-covered forest parameters. Therefore, we compared the simulated reflectance by snow model ART (Kokhanovsky and Breon, 2012; Kokhanovsky and Zege, 2004), the snow-free forest model PROSAIL (Jacquemoud et al., 2009), the snow and vegetation coupling model of Wang et al. (2022), and SFBR model with MODIS data. It is difficult to measure land surface parameters at MODIS pixels with a resolution of 500 m, we first acquired slope and aspect from SRTM digital elevation data (Farr et al., 2007), the fraction of diffuse skylight derived by an empirical equation under clear-sky  $SYKL = 0.122 + 0.85e^{-4.8\cos(\theta_s)}$  (Stokes and Schwartz, 1994). Then, we trial the snow, leaf, and canopy properties within a reasonable range to acquire the best parameters by comparing the simulated reflectance with MODIS data; this approach has been widely used to validate geometric optical models (Fan et al., 2014b; Geng et al., 2017). The input parameters of the SFBR model for the three sites are listed in Table 2, and other undeclared parameters are assigned to default values in Table 1. When compared with OLI reflectance, the input parameters are determined in the same way as described above.

**Table 3**  
Input parameter settings for different scenarios.

| Parameter                                      | Unit                   | Values           |
|------------------------------------------------|------------------------|------------------|
| Snow grain size ( $a_{ef}$ )                   | $\mu\text{m}$          | 100, 500, 2000   |
| Concentration of soot pollution ( $C_{soot}$ ) | ppb                    | 0, 1000, 2000    |
| LAI                                            | —                      | 1, 3, 5          |
| Tree density ( $\lambda$ )                     | trees $\text{ha}^{-1}$ | 1000, 2000, 3000 |
| FVC                                            | %                      | 27, 47, 61       |
| Slope ( $\theta$ )                             | deg                    | 0, 20, 40        |



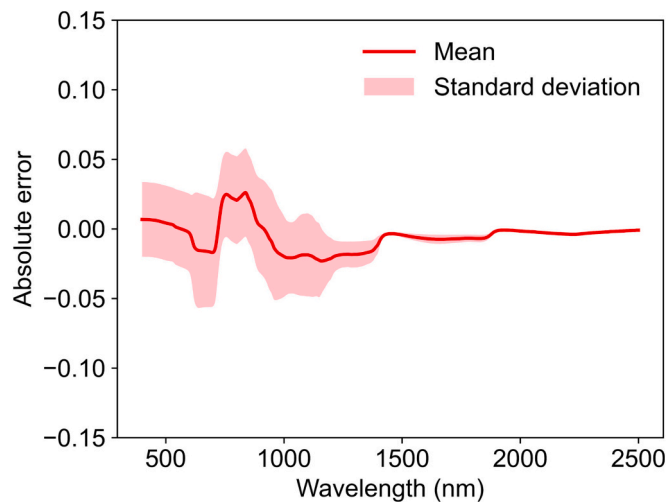


Fig. 6. Absolute error of reflectance simulated by SFBR and LESS models for the different scenarios in Table 3.

### 3. Results and analysis

#### 3.1. Model validation

##### 3.1.1. Cross-evaluation with LESS model

We first compared the simulation results of the SFBR and LESS models using default values (Table 1). The snow-covered forest reflectance spectra simulated by the two models exhibited the same variation trend and similar reflectance values (Fig. 5). To verify the simulation effect under different scenarios, different values of the dominant factors of snow grain size, concentration of soot pollution, LAI, tree density, and slope were used to simulate snow-covered forest reflectance. We used the parameter values in Table 3 to replace each default value and obtain different simulation results, in which, the fractional vegetation cover

(FVC) and tree density can be transformed from each other. The error of snow-covered forest reflectance was  $<0.06$  from 400 nm to 2500 nm (Fig. 6). The visible and near-infrared (NIR) reflectance between the SFBR and LESS models showed greater differences than the shortwave infrared reflectance. Nevertheless, the two models still showed high spectral consistency, and the determination coefficient ( $R^2$ ), root mean square error (RMSE), and mean absolute error (MAE) were 0.985, 0.023, and 0.013, respectively.

Reflectance simulations for wavelengths in the red (645 nm) and NIR (860 nm) bands were shown in the hemispheric space in Fig. 7. The polar plot showed clear hotspot effects and angular variation, and the reflectance value decreases from the hotspot to the edge. There was a small difference between SFBR and LESS reflectance values in the red band, the  $R^2$ , RMSE, and MAE values were 0.963, 0.017, and 0.014, respectively. In the NIR band, the high reflection of snow and canopy increased the complexity of multiple scattering between these surfaces, the simulated reflectance by SFBR showed an overestimation in the NIR band compared with LESS model, especially in the forward direction. Overall, the  $R^2$ , RMSE, and MAE were 0.925, 0.030, and 0.025, respectively.

We further compared the simulated reflectance of SFBR and LESS models for different snow, vegetation, and slope factors, based on the input parameters in Table 3. The reflectance variation with different snow grain sizes (100, 500, and 2000  $\mu\text{m}$ ) in the principal plane (PP) and cross plane (CP) were shown in Fig. 8; the simulated reflectance by SFBR and LESS models exhibited the same hotspot effect and a consistent change trend, and the mean of  $R^2$ , RMSE, and MAE were 0.951, 0.036, and 0.028, respectively. The reflectance values according to different concentrations of soot pollution (0, 1000, and 2000 ppb) (Fig. 9) showed similar accuracies as different snow grain sizes; the mean of  $R^2$ , RMSE, and MAE were 0.967, 0.030, and 0.024, respectively.

The simulated reflectance with different LAI values (1, 3, and 5) in the PP and CP were shown in Fig. 10. As the LAI increased, the reflectance simulated by SFBR gradually converted from overestimation to underestimation in the red and NIR bands compared with LESS model.

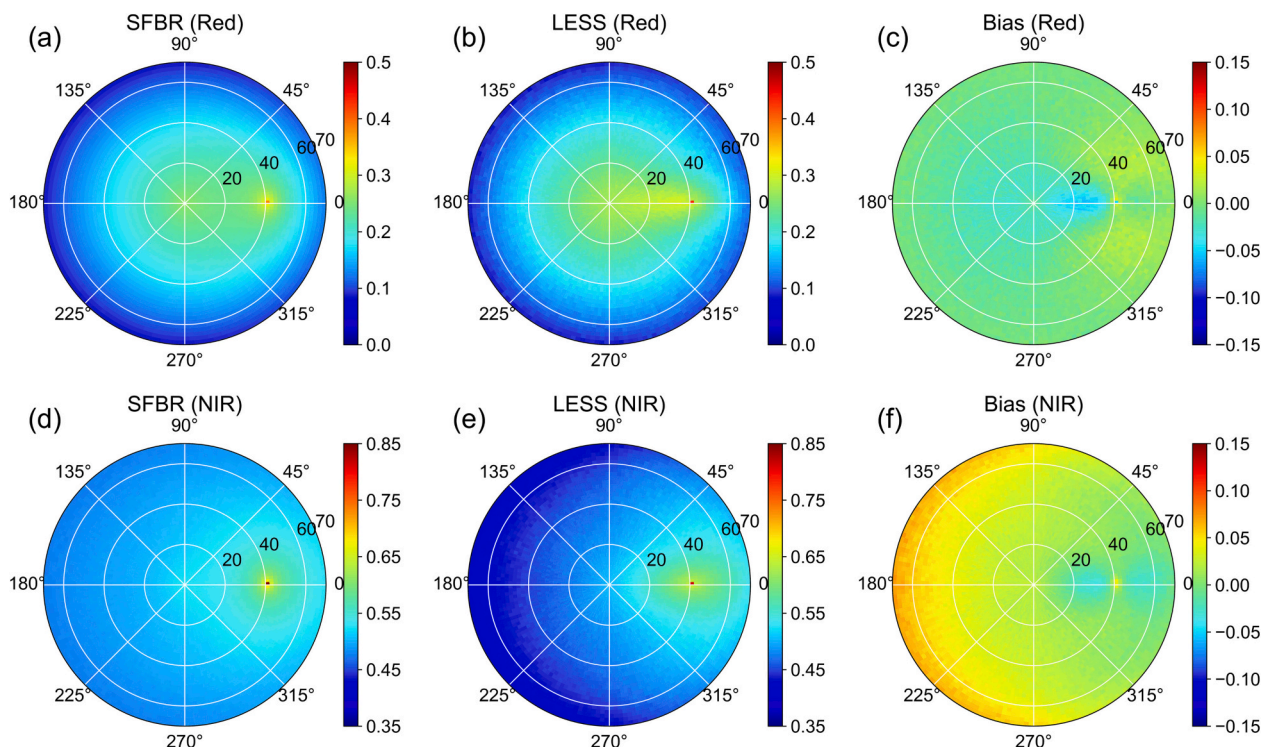
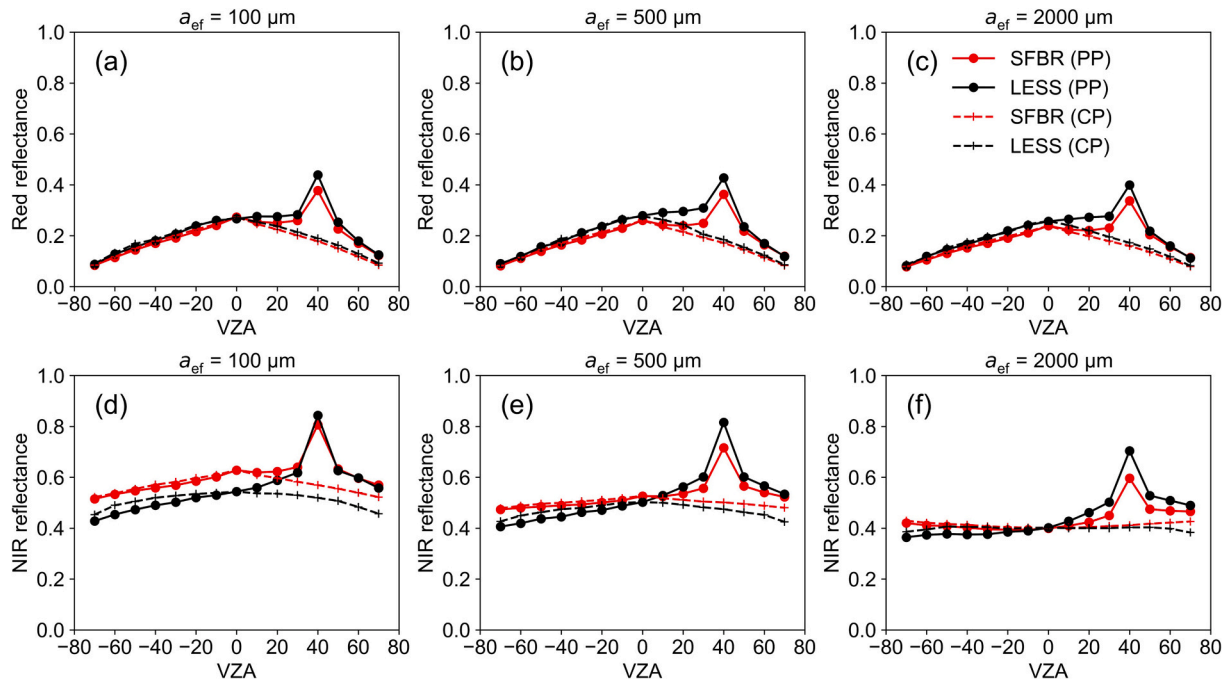
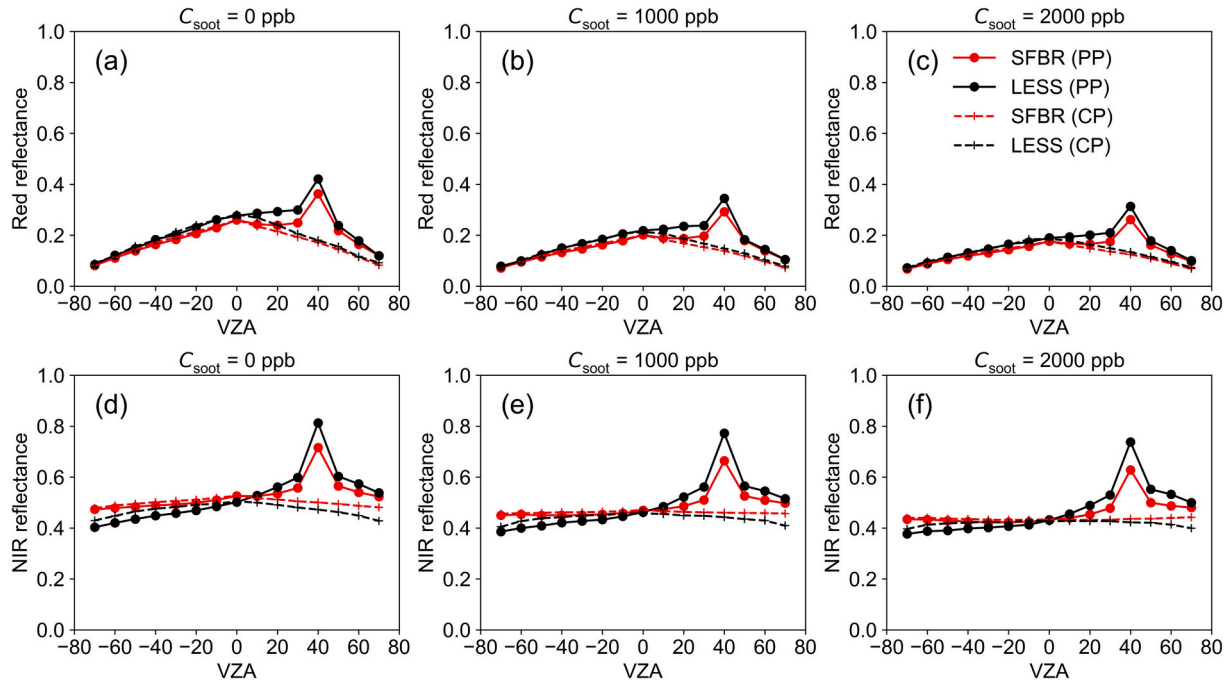


Fig. 7. Polar maps and bias of bidirectional reflectance for red and NIR bands simulated by SFBR and LESS models over snow-covered forests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)





**Fig. 8.** Comparisons of the reflectance simulated by SFBR and LESS models for different snow grain sizes ( $a_{ef}$ ) in the principal plane (PP) and the cross plane (CP). The negative VZA in the PP represents the direction of the relative azimuth angle of  $180^\circ$  (forward scattering direction), and the negative VZA in the CP represents the direction of the relative azimuth angle of  $270^\circ$ .



**Fig. 9.** Comparisons of the reflectance simulated by SFBR and LESS models for different concentrations of soot pollution ( $C_{soot}$ ) in the PP and CP.

However, the differences were not very obvious, and the means of the  $R^2$ , RMSE, and MAE were 0.941, 0.048, and 0.038, respectively. Fig. 11 showed the reflectance variation with different tree densities (1000, 2000, and 3000 trees  $ha^{-1}$ ) in PP and CP. For low tree density (1000 trees  $ha^{-1}$ ), the SFBR underestimated the red reflectance compared with LESS model, but the simulated reflectance for higher tree density (2000 and 3000 trees  $ha^{-1}$ ) had no obvious difference, because the underestimation of the area ratio of sunlit snow leads to an underestimation of

red reflectance for sparse forests. The mean of  $R^2$ , RMSE, and MAE were 0.846, 0.073, and 0.056, respectively.

The simulated reflectance of the SFBR and LESS models on slopes of  $0^\circ$ ,  $20^\circ$ , and  $40^\circ$  were compared in Fig. 12. Different slopes exhibited similar hotspot effects in PP and similar shapes in CP, but variations in magnitude were different. The mean relative variations in snow-covered forest reflectance between  $0^\circ$  and  $40^\circ$  reached 67.05% and 21.82% in the red and NIR bands, respectively. Moreover, the reflectance

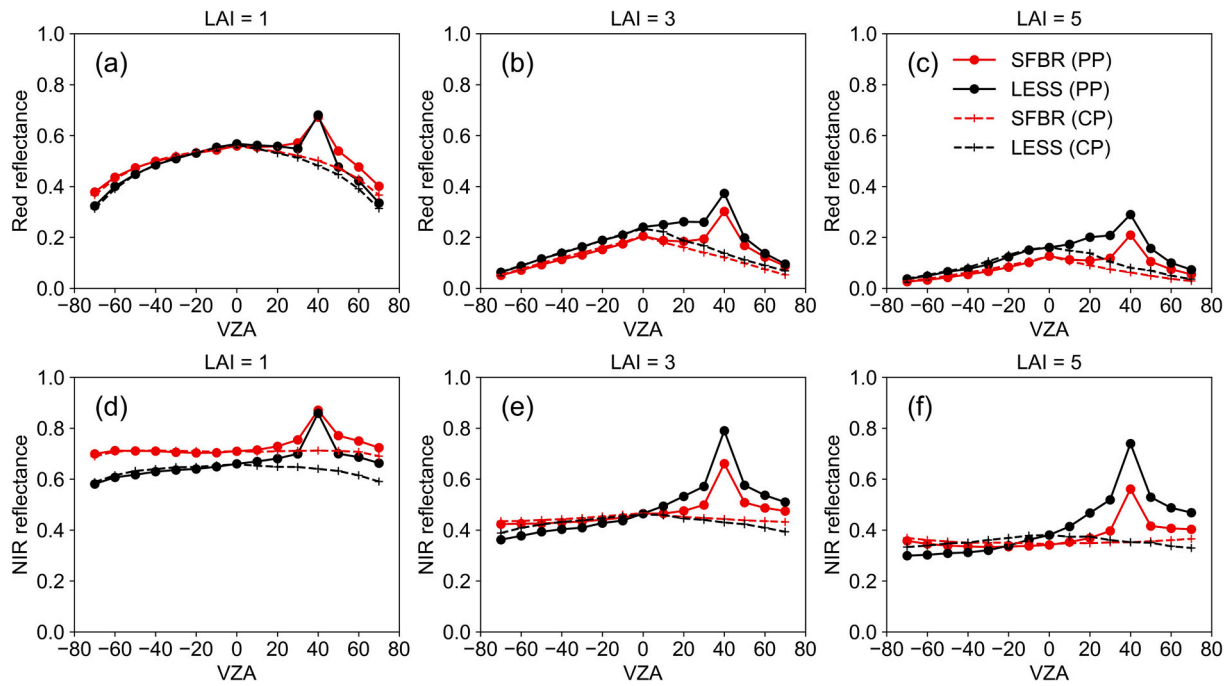


Fig. 10. Comparisons of the reflectance simulated by SFBR and LESS models for different LAI values in the PP and CP.

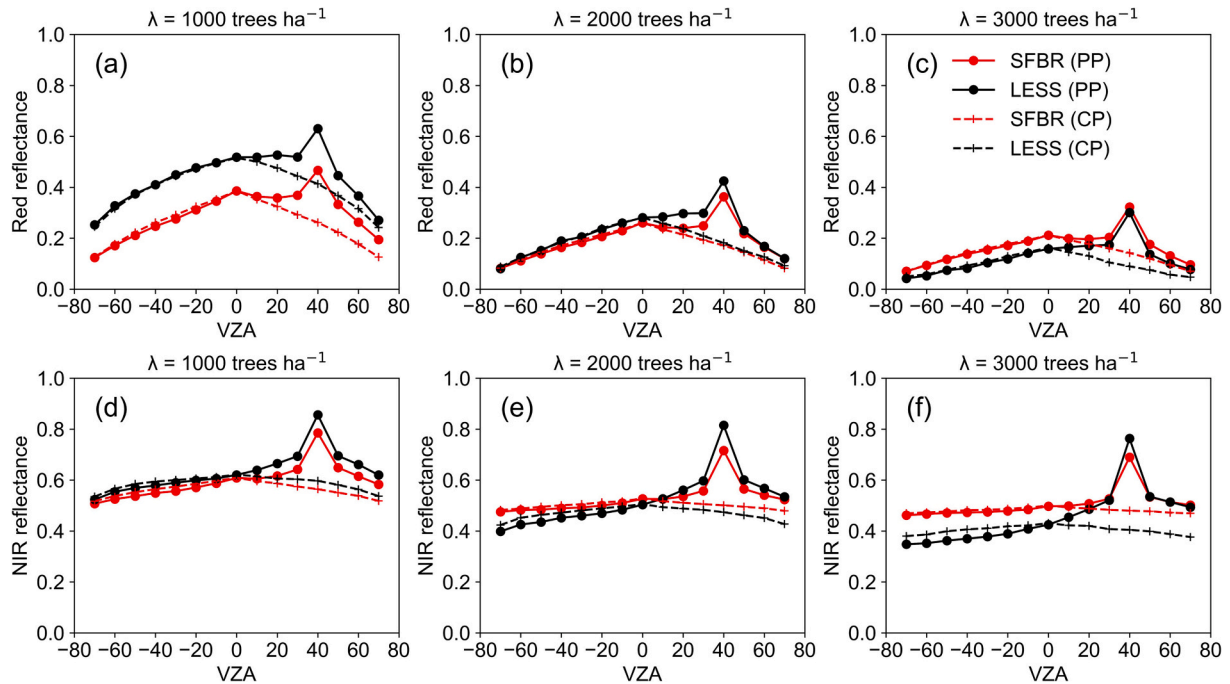


Fig. 11. Comparisons of the reflectance simulated by SFBR and LESS models for different tree densities ( $\lambda$ ) in the PP and CP.

simulated by the SFBR model showed high consistency with that of the LESS model ( $R^2 = 0.973$ ,  $RMSE = 0.033$ , and  $MAE = 0.028$ ). Even when the slope reached  $40^\circ$ , the  $R^2$  values of the two models were as high as 0.829 and 0.807, respectively, in the red and NIR bands.

### 3.1.2. Comparison with remote sensing data

Comparing simulated reflectance with remote sensing data is an important part of model verification. Fig. 13 exhibits the comparisons among ART, PROSAIL, the coupled model of Wang et al. (2022), and the SFBR model using MODIS data in snow-covered forests. The simulated

reflectance by ART has large differences with MODIS data in bands 1–7 because snow and snow-covered forests have different bidirectional reflection and spectral characteristics; in contrast, the PROSAIL model underestimates the reflectance of the visible band (bands 1, 3, and 4), but the simulated reflectance is consistent with MODIS data in the infrared band (bands 2, 5–7), because snow-free forests and snow-covered forests have spectral differences in different wavelength ranges, but they have similar backscattering characteristics.

The coupled model of Wang et al. (2022) has good agreement with MODIS data in Fig. 13c ( $R^2 = 0.589$ ,  $RMSE = 0.064$ , and  $MAE = 0.054$ ).

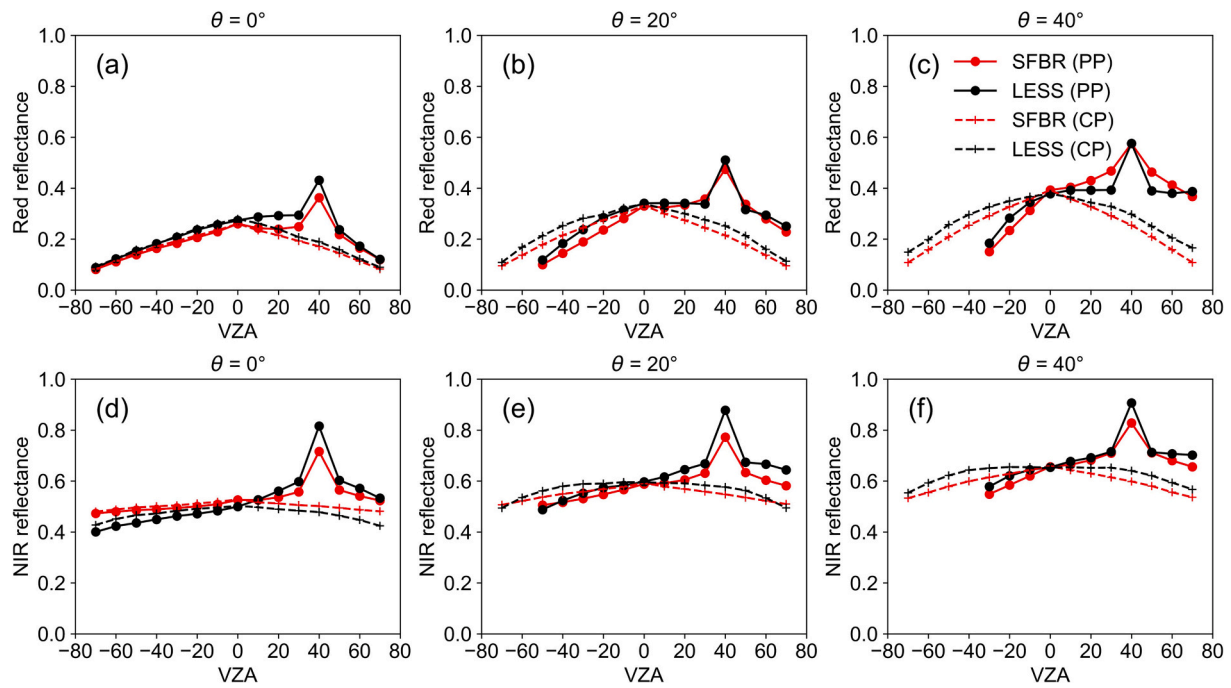


Fig. 12. Comparisons of the reflectance simulated by SFBR and LESS models for different slopes ( $\theta$ ) in the PP and CP.

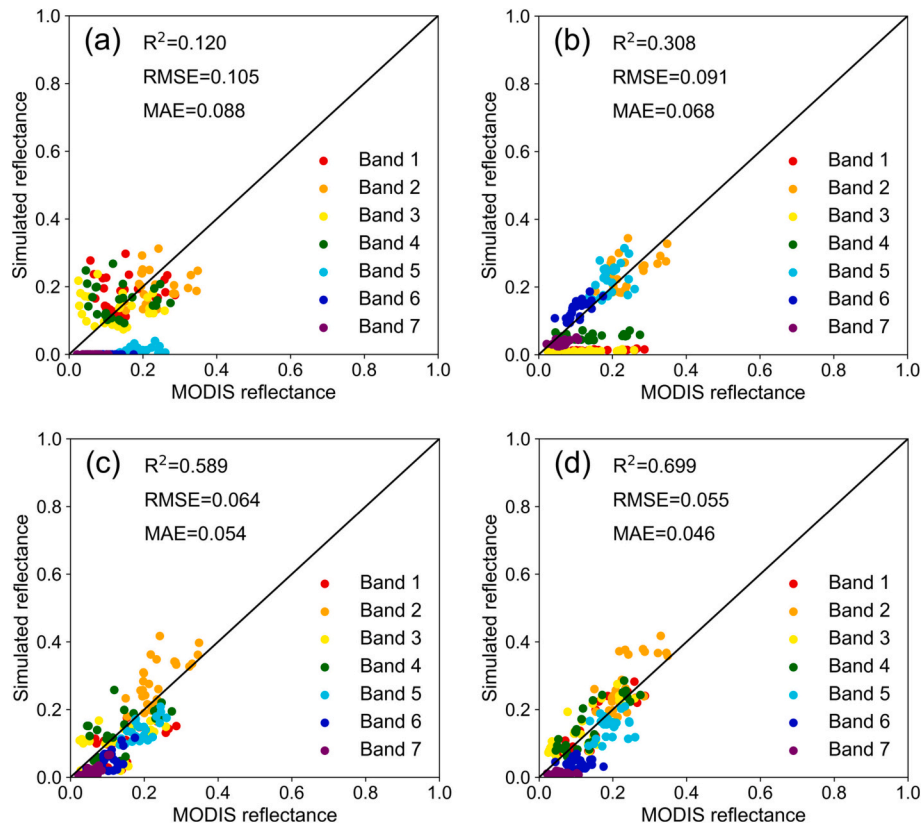
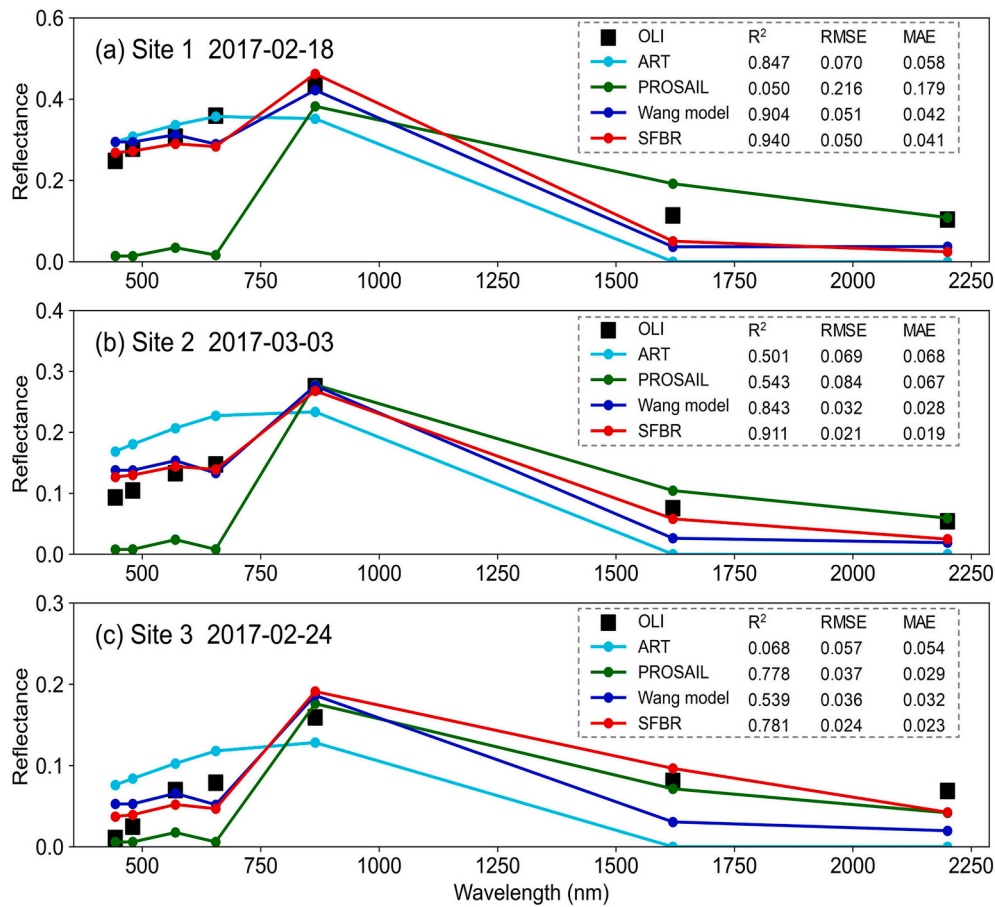


Fig. 13. Comparison of the simulated reflectance by ART (a), PROSAIL (b), the coupled model of Wang et al. (2022) (c), and SFBR model (d) with MODIS reflectance at different bands in snow-covered forests.





**Fig. 14.** Comparison of the simulated reflectance by ART (a), PROSAIL (b), the coupled model of Wang et al. (2022) (c), and SFBR model (d) with OLI reflectance at different bands in snow-covered forests.

However, its accuracy is still lower than the simulation results of SFBR model in Fig. 13d ( $R^2 = 0.699$ ,  $RMSE = 0.055$ , and  $MAE = 0.046$ ), which mainly can be attributed to SFBR considers more of concentration of soot pollution, topography, and coniferous forest characteristics. The simulated reflectance of bands 1–5 are better than bands 6–7 when comparing SFBR with MODIS data, and the underestimation in bands 6–7 exists, but low reflectance of shortwave infrared in snow-covered forests makes the absolute error not obvious.

When compared with OLI reflectance in Fig. 14, the ART model has good accuracy at site 1 but has poor accuracy at sites 2 and 3, and the PROSAIL model exhibits the opposite performance, which is attributed to whether the validation site is dominated by snow or forests. The coupled model of Wang et al. (2022) and SFBR has good agreement with OLI reflectance at all validation sites; meanwhile, the simulated reflectance by SFBR has the best match to the reflectance ( $R^2 \geq 0.781$ ,  $RMSE \leq 0.050$ ,  $MAE \leq 0.041$ ). These comparisons further confirmed that the SFBR model can effectively simulate the reflectance of snow-covered forests.

### 3.2. Sensitivity analysis of the key factors

A sensitivity analysis of the optical signals to some key factors, including two snow factors (snow grain size and concentration of soot pollution), two vegetation factors (LAI and tree density), solar zenith

angle (SZA), and fraction of diffuse skylight (SKYL), was conducted to determine the potential applications of the SFBR model to snow-covered forest monitoring, and the default input variables are used in Table 1.

The effect of snow factors on the snow-covered forest reflectance spectrum and bidirectional reflectance was shown in Fig. 15. In general, snow-covered forest reflectance decreased with increasing snow grain size and the concentration of soot pollution, but the degree of influence differed across the spectrum. The snow grain size strongly affected snow-covered forest reflectance spectrum from 700 nm to 1400 nm and only weakly affected the spectrum from 400 nm to 700 nm. Differently, the concentration of soot pollution had strong effects on snow-covered forest reflectance from 400 nm to 1000 nm but no effects in the spectral region  $>1000$  nm.

Similar to the snow factors, the simulated spectral and bidirectional reflectance also decreased with increasing LAI and tree density (Fig. 16). Furthermore, LAI and tree density had a stronger influence than snow factors on visible reflectance because LAI and tree density directly affect the reflectivity contribution of snow cover. As the LAI varied from 1 to 5, the mean reflectance decreased by 0.43 in the red band and 0.36 in the NIR band. As the tree density varied from 1000 trees  $ha^{-1}$  to 3000 trees  $ha^{-1}$ , the mean reflectance decreased by 0.13 in the red band and 0.09 in the NIR band.

Solar zenith angle and diffuse skylight were external factors that influence snow-covered forest reflectance. With the increase of the solar

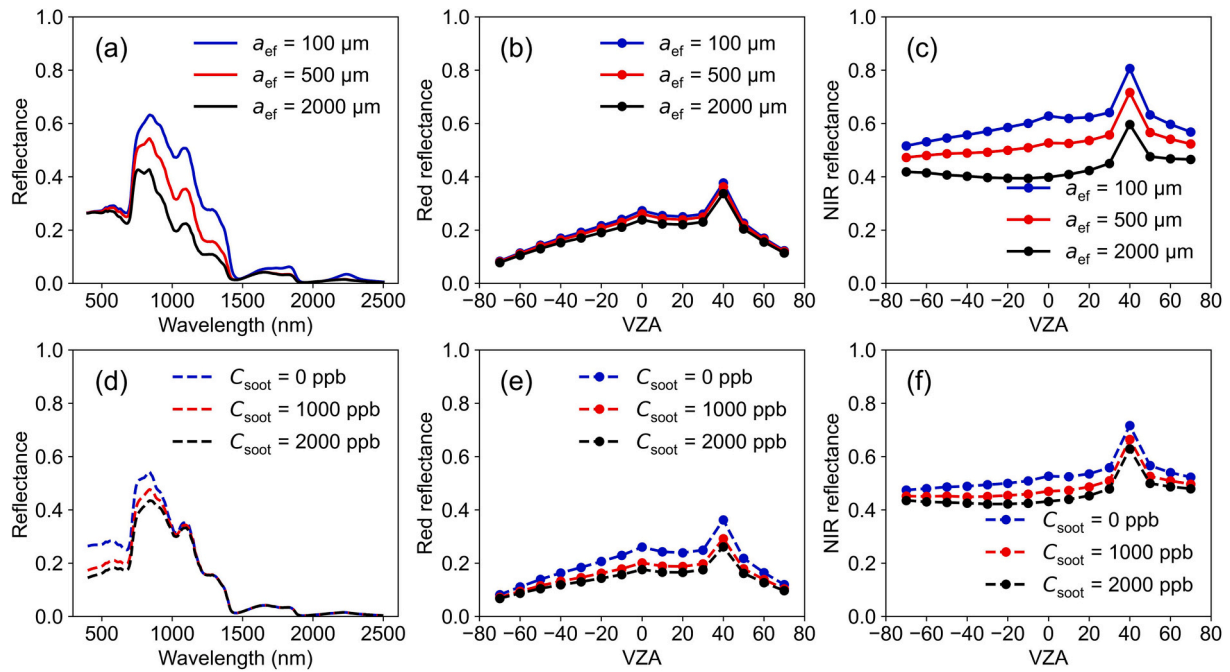


Fig. 15. Effects of snow grain size ( $a_{ef}$ ) and concentration of soot pollution ( $C_{soot}$ ) on snow-covered forest reflectance simulated by the SFBR model.

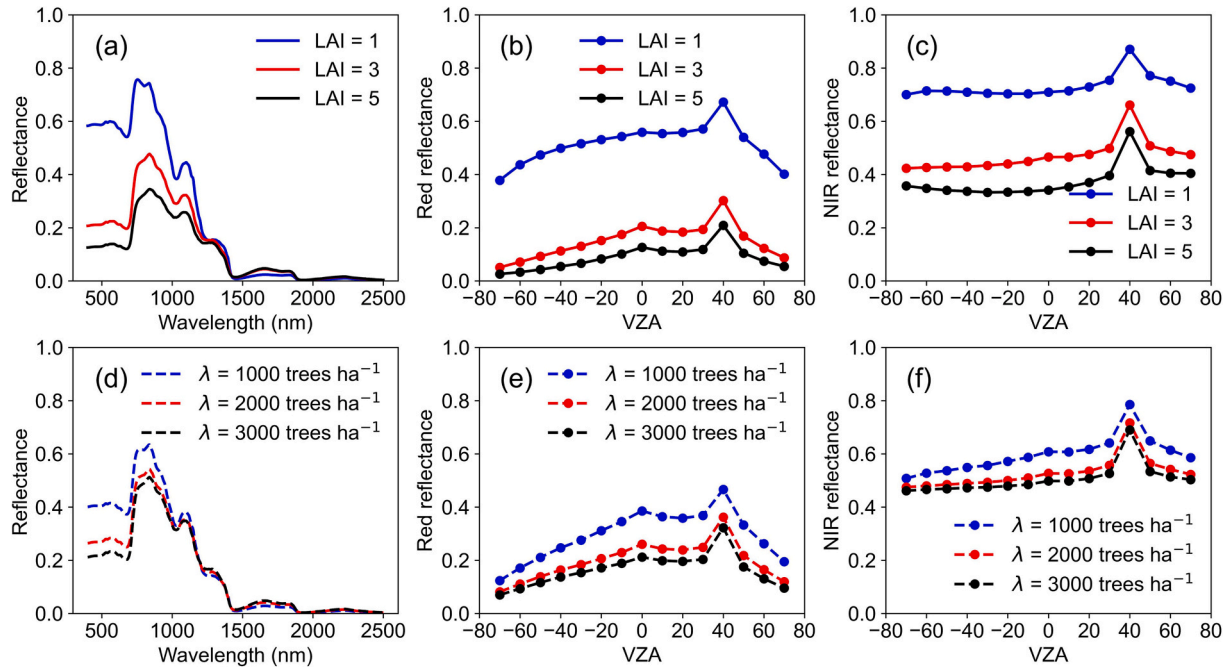


Fig. 16. Effects of LAI and tree density ( $\lambda$ ) on snow-covered forest reflectance simulated by the SFBR model.

zenith angle, the snow-covered forest reflectance shown a decreasing trend (Fig. 17), which was mainly attributed to the path length of direct light propagation in the forest increasing with the increase in the solar zenith angle, and more incident radiation was being absorbed. The increase of the fraction of diffuse skylight also reduces the reflectance of snow-covered forests and weakens the hotspot effect, because diffuse light has an isotropic incident characteristic.

The simulation results were deemed reasonable because the canopy blocked the upward transmission of snow reflections. Snow grain size,

concentration of soot pollution, LAI, tree density, solar zenith angle, and diffuse skylight have an important impact on the spectral and bidirectional reflectance of snow-covered forests. Therefore, the accurate acquisition of snow and canopy parameters is conducive to simulating remote sensing-based reflectance. Furthermore, different solar zenith angles and fraction of diffuse skylight produced the same reflectivity at different observation angles in the reflectance simulation (Fig. 17); thus, multi-angle remote sensing observations can reduce the uncertainties of parameter inversion compared with only one observation.

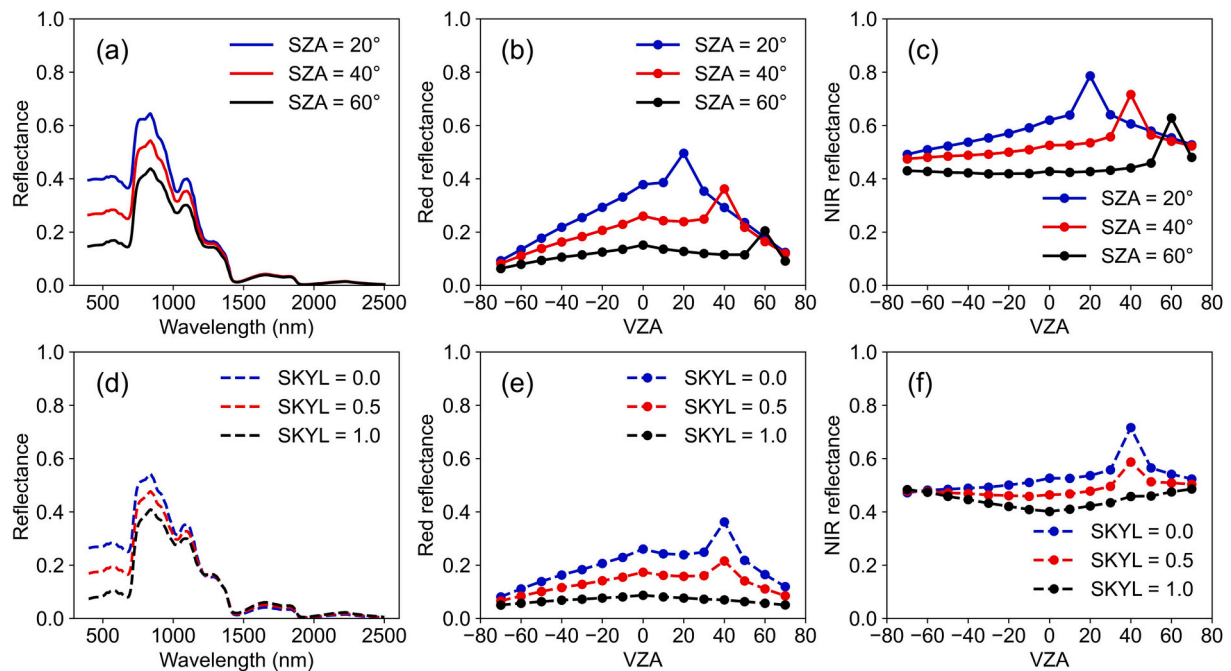


Fig. 17. Effects of solar zenith angle (SA) and fraction of diffuse skylight (SKYL) on snow-covered forest reflectance simulated by the SFBR model.

### 3.3. Comparison of snow-covered forests with snow and snow-free forests

Snow-covered forest dynamics are significantly different from snow areas and snow-free forests (Sun et al., 2018). However, the reflection difference between these scenes has rarely been analyzed because of the lack of an effective snow-covered forest bidirectional reflection model. Using the SFBR model, we analyzed the reflectance variation of snow-covered forests, snow, and snow-free forests in the red and NIR bands. The default parameters listed in Table 1 were used as the model input. In the snow-free forests, the red and NIR reflectance of the soil are set to 0.08 and 0.17, respectively.

Snow-covered forest reflectance exhibited different magnitudes and variation trends in the principal plane compared with snow and snow-free forests (Fig. 18). The reflectance for snow-covered forests was lower than that for snow but higher than that for snow-free forests. The mean difference between snow-covered forests and snow-free forests reached 0.17 and 0.27 in the red and NIR bands, respectively, and the magnitude difference was mainly attributed to the high reflection

characteristics and anisotropy of snow. The shape of snow-covered forest reflectance was different from that of snow but showed a hot-spot effect similar to that of snow-free forests, which because the shadows caused by the canopy were also significant in snow-covered forests.

We then compared the nadir reflectance between snow-covered forests and snow with different snow properties (Fig. 19). The presence of the forest blocks the upward reflection of the snow. The reflectance difference between these surfaces in the red band was 0.29–0.74, which was obviously higher than that in the NIR band (0.09–0.28) because the reflectance of the canopy was significantly lower than that of snow in the visible band but only slightly lower than that in the NIR band. We also compared the nadir reflectance of snow-covered forests and snow-free forests with different vegetation structures (Fig. 20). The LAI and tree density determined the masking effects of the canopy over the background. In the red band, the reflectance of snow-covered forests and snow-free forests had similar change trends, but snow-covered forests had higher reflectance, with differences ranging from 0.06 to

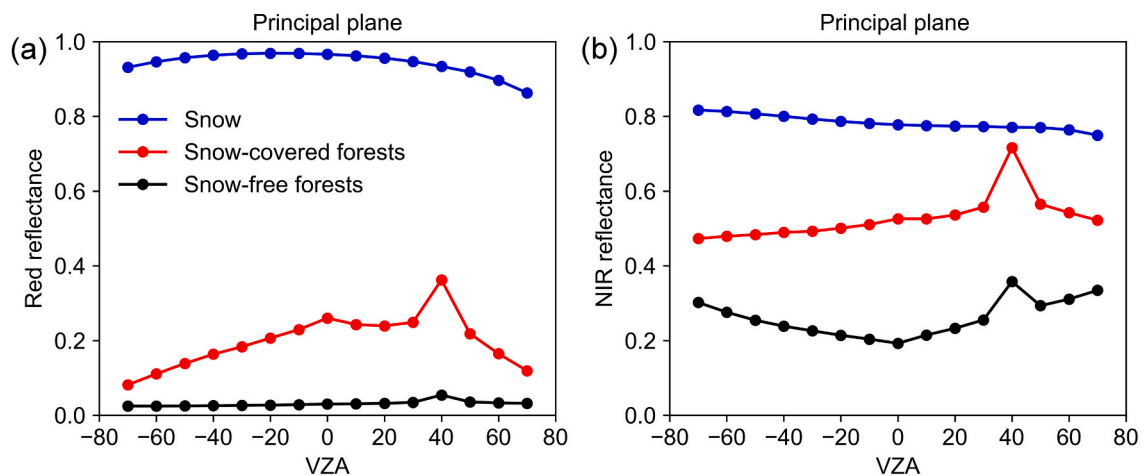


Fig. 18. Reflectance comparison of the red (a) and NIR (b) band over snow, snow-covered forests, and snow-free forests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



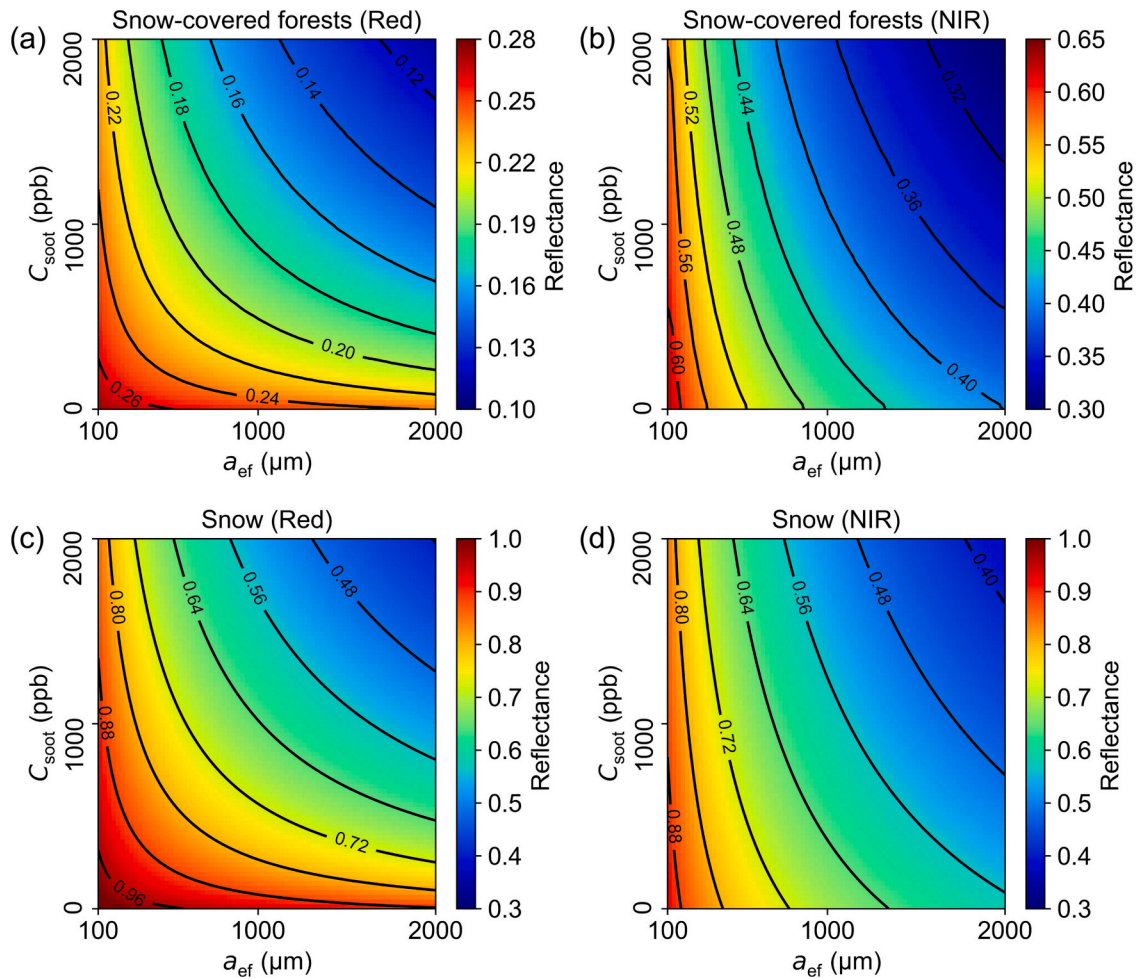


Fig. 19. Reflectance comparison of the snow-covered forests and snow with different snow grain size ( $a_{ef}$ ) and concentration of soot pollution ( $C_{soot}$ ).

0.55. In the NIR band, the reflectance of snow-covered forests decreased with an increase in LAI and tree density, whereas the snow-free forests showed an opposite trend; the reflectance differences between these scenes ranged from 0.10 to 0.56.

#### 4. Discussion

##### 4.1. Advantages and limitations of the SFBR model

Many bidirectional reflection models for snow-free forests and snow areas have been established respectively (Kuusk, 2018; Xiong and Shi, 2018), such as PROSAIL (Jacquemoud et al., 2009), Li-Strahler (Li et al., 1995), and ART (Kokhanovsky and Zege, 2004), which failed in snow-covered forests. GeoSail and P-theory only can be used to simulate the snow-covered forest nadir reflectance (Klein et al., 1998; Manninen and Stenberg, 2009). Meanwhile, the snow-covered forest bidirectional reflectance has been simulated by coupled snow model (Wiscombe and Warren, 1980; Xiong et al., 2015) and GORT vegetation model (Ni et al., 1999) in previous studies by Xin et al. (2012) and Wang et al. (2022), which does not consider concentration of soot pollution, topography, and coniferous forest characteristics.

The SFBR fully considers the characteristics of the discontinuous distribution of forests, conifer crown shapes, snow properties, multiple scattering, sloping terrain, and diffuse skylight. After considering the anisotropy of snow on the conifer forest background, the four-stream theory and the adding method (Verhoef, 1984a; Verhoef and Bach, 2003) were used to couple the snow model ART and canopy model 4SAIL, the high reflectance of snow increases the multiple scattering

between snow background and canopy, thus, an isotropic background can lead to significant uncertainty (Ma et al., 2022). In order to simulate the real natural conditions, the terrain and fraction of diffuse skylight are parameterized in a geometric optical framework, the BRDF of snow-covered forests as the sum of direct and diffuse components, the component area ratios are calculated by the canopy projection areas on the slope of snow background, and the spectra of reflectance components are simulated by single and multiple scattering with entering snow/leaf optical properties. Therefore, SFBR model has better accuracy for snow-covered forests than ART, PROSAIL, and the coupled model of Wang et al. (2022) (Figs. 13 and 14). Meanwhile, compared to 3D scene models, which have higher accuracy but complex computational steps and detailed scene structure, SFBR achieves simpler analytical expression and consistent accuracy with LESS model enabling convenient parameter retrieval.

However, the SFBR model framework also has limitations: (1) woody elements in the tree crown are not considered, and the reflectivity of wood elements in shortwave infrared is relatively high, which may explain why the simulated reflectance is underestimated compared with bands 6 and 7 of MODIS data (Fig. 13d); (2) the forest floor is fully snow cover in SFBR model, this in line with the actual situation of the stable snow period; however, the situation of fractional snow cover also exists in the ground truth and is not considered in our model; (3) the SFBR model assumes that snow is only distributed under the canopy, which is the basis of many snow-covered forest identification algorithms such as MODSCAG (Painter et al., 2009) and SPIRES (Bair et al., 2021). This assumption is reasonable in most cases, but does not consider snow interception on the canopy (Webster and Jonas, 2018), which is worthy



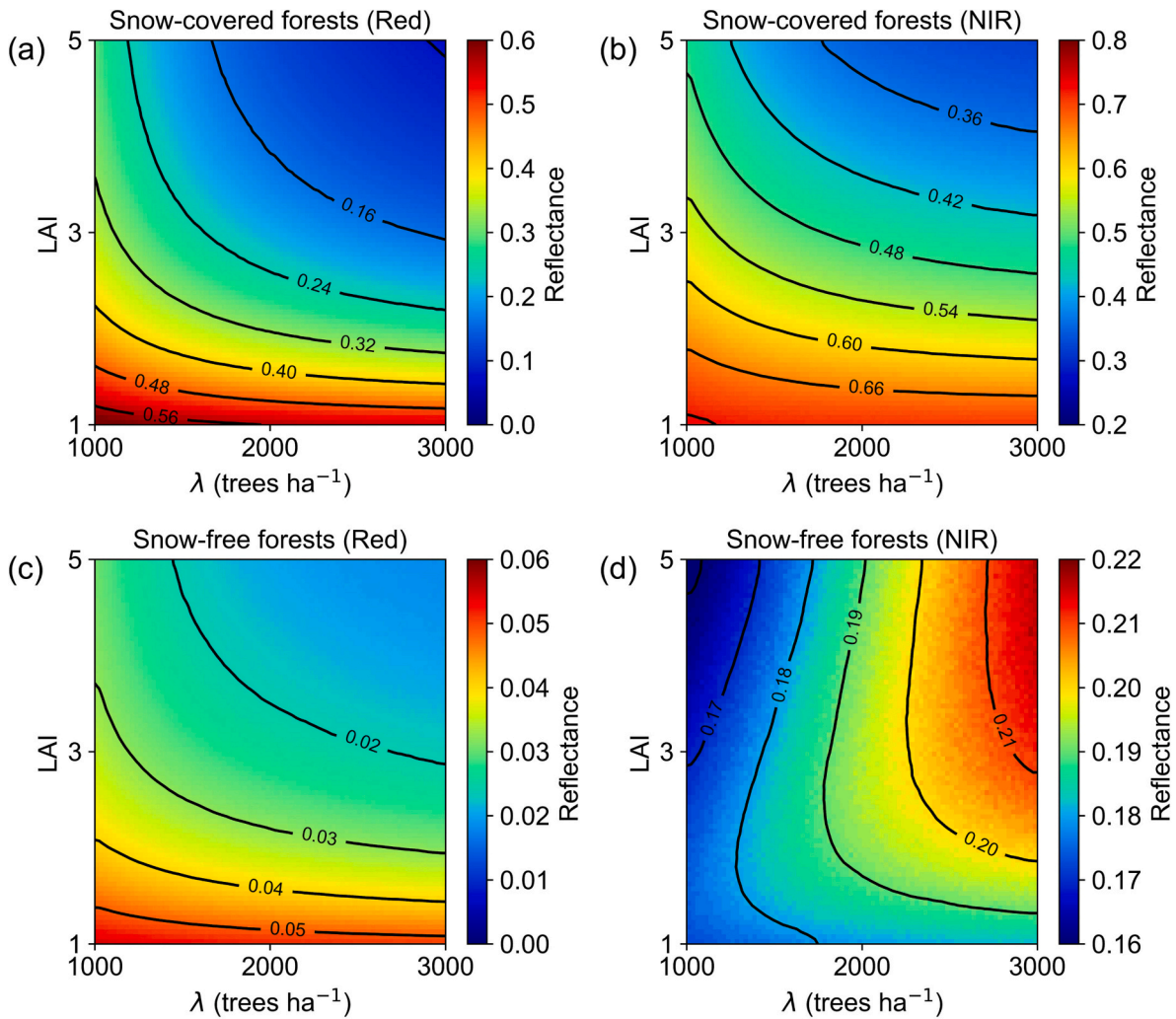


Fig. 20. Reflectance comparison of the snow-covered forests and snow-free forests with different LAI and tree density ( $\lambda$ ).

of further study.

Model validation through comparisons with the LESS model and MODIS data indicated that the SFBR model is effective. However, a more comprehensive evaluation remains very challenging because observations of multi-angle reflectance and the structural properties of snow-covered forests are extremely deficient. Therefore, obtaining accurate land surface parameters and conducting multi-angle observations using LiDAR measurements (Kostadinov et al., 2019) and UAV technology (Webster and Jonas, 2018) can further verify the applicability of the model.

#### 4.2. Potential applications of the SFBR model

The complex snow-covered forest process causes many difficulties in remote sensing applications. By simulating snow-covered forest reflectance using parameterized snow characteristics and canopy structures, the SFBR model achieves significant theoretical and technical progress.

(1) The SFBR model can be applied to spectra simulation and mechanism analysis of snow-covered forests. The sensitivity analysis of spectra includes a wide range of input parameters: geometries, fraction of diffuse skylight, snow/canopy parameters, etc. The effects of snow, leaves, and canopy properties on bidirectional reflectance (Figs. 15 and 16), and the difference of radiation effects before and after the appearance of snow in forest areas (Fig. 18) can be effectively quantified through the SFBR model. Meanwhile, the radiative transfer process could be analyzed to promote our understanding of the interactions

between radiation and snow-covered forests. Furthermore, snow has different characteristics during periods of accumulation, stabilization, and ablation. The SFBR simulations of the interaction between snow and canopy in different periods can help reveal the internal mechanism of snow-covered forest changes.

(2) The SFBR model has the potential to quantitatively retrieve and dynamically monitor snow-covered forest parameters. Simulation of the shortwave radiation budget requires accurate surface albedo data (Seyedsnasrollah and Kumar, 2014; Seyedsnasrollah et al., 2013). MODIS global albedo products are produced by kernel-driven models, which are mainly suitable for simulating the backscattering characteristics of vegetation (Lucht et al., 2000). However, snow has obvious forward scattering characteristics, and the kernel-driven model has some limitations in snow-covered forests. In contrast, the SFBR model established for snow-covered forests is conducive to improving the inversion accuracy of the snow-covered forest albedo. In addition, snow-covered forest mapping faces a major challenge regarding snow identification from remote sensing data because snow in forested areas has a low NDSI value (Luo et al., 2022; Wang et al., 2020). The SFBR model can attempt to theoretically analyze the effectiveness of the NDSI and thus improve the accuracy of snow-covered forest mapping.

#### 5. Conclusions

A new snow-covered forest bidirectional reflectance (SFBR) model is proposed to simulate the effects of snow-leaf-canopy properties, sloping

terrain, and solar-view geometries on spectra and bidirectional reflectance from 400 nm to 2500 nm. The shape and magnitude of BRDF in snow-covered forests are different from snow-free forests and snow, the hotspot caused by dense forests under direct radiation is clearly in the principal plane. Comparison and validation of SFBR generally exhibit close consistencies with that of the 3D scene model LESS ( $R^2 \geq 0.807$ ,  $RMSE \leq 0.073$ , and  $MAE \leq 0.056$ ) and remote sensing observations ( $R^2 \geq 0.699$ ,  $RMSE \leq 0.055$ , and  $MAE \leq 0.046$ ), which is mainly attributed to reasonably considering the anisotropic reflection of snow and the multiple scattering characteristics between snow and canopy. Meanwhile, the results are not satisfactory under certain conditions such as a large number of woody elements, fractional snow cover, and canopy-intercepted snow. Nevertheless, the reflectance modeling of snow-covered forests based on geometric optical and radiative transfer is effective and feasible. Therefore, we present the SFBR model as a promising approach for snow-covered forest reflectance simulation, analysis, and parameter retrieval.

### CRedit authorship contribution statement

**Siyong Chen:** Conceptualization, Methodology, Writing – original draft. **Pengfeng Xiao:** Conceptualization, Methodology, Funding acquisition. **Xueliang Zhang:** Resources, Investigation, Supervision. **Jianbo Qi:** Software, Validation. **Gaofei Yin:** Writing – review & editing. **Wei Ma:** Writing – review & editing. **Hao Liu:** Writing – review & editing.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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