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The mSCOPE model: A simple adaptation to the SCOPE model to describe reflectance, fluorescence and photosynthesis of vertically heterogeneous canopies

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ABSTRACT

The vertical heterogeneity of leaf biophysical and biochemical properties may have a large effect on the bi-directional reflectance and fluorescence of vegetation canopies. This has implications for the interpretation of remote sensing data. We developed a model for light interaction and energy balance in vegetation canopies in which leaf biophysical and biochemical properties vary in the vertical. The model mSCOPE is an extension of the Soil-Canopy Observation of Photosynthesis and Energy fluxes (SCOPE) model, which simulates spectral and bidirectional reflectance, fluorescence, and photosynthesis of vertically heterogeneous vegetation canopies. The modelling of radiative transfer in mSCOPE is based on the classical SAIL theory. A solution to the radiative transfer equation for multi-layer canopies is given, which allows calculating top-of-canopy (TOC) reflectance and the flux profile. The latter is used for the simulation of fluorescence emission and photosynthesis of every leaf through the leaf radiative transfer model Fluspect and a biochemical model. The radiative transfer of fluorescence in multi-layer canopies is solved numerically in mSCOPE to obtain TOC bidirectional fluorescence. The significant effect of vertical heterogeneity of leaf properties on TOC reflectance, fluorescence and photosynthesis is demonstrated by different scenarios with customized vertical profiles of leaf chlorophyll content and leaf water content, and also with measured vertical profiles of leaf chlorophyll content in corn canopies. A preliminary validation of the reflectance calculating routine of mSCOPE is conducted by comparing measured and simulated TOC reflectance spectra of the corn canopies. We conclude that it is important to consider the vertical heterogeneity of leaf properties for the prediction of reflectance, fluorescence and photosynthesis. The model mSCOPE could serve as a tool to better understand vertically heterogeneous vegetation canopies.

1. Introduction

Vegetation models are powerful tools to understand a variety of plant physiological processes. Radiative transfer models (RTMs), as a major class of vegetation models, are widely used in remote sensing applications because they offer an explicit connection between the top of canopy (TOC) observations and vegetation properties (e.g., chlorophyll, leaf area index) (Houborg et al., 2007; Ustin et al., 2009). Vegetation models that simulate photosynthesis (De Wit, 1962; Myneni, 1991) include, besides an RTM, also a leaf photosynthesis model such as Farquhar et al. (1980) or Collatz et al. (1992). The RTM simulates the light distribution within the canopy, while the photosynthesis model simulates the energy partitioning in photosystems.

SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes) is an integrated radiative transfer and energy balance model (Van der Tol et al., 2009) that simulates the spectrum of TOC reflected radiation, fluorescence emission in the viewing direction and photosynthesis as functions of leaf properties, vegetation structure, and micro-meteorological conditions. The model has been widely applied to enhance the understanding of remotely sensed data and canopy photosynthesis, and to support the quantitative use of reflectance and fluorescence for estimation of plant functional traits (Zhang et al., 2014; Damm et al., 2015; Van der Tol et al., 2016; Drusch et al., 2017).

The SCOPE model assumes that vegetation canopies are vertically homogeneous and horizontally infinite, as its radiative transfer routines are based on the classical 1-D SAIL model (Verhoef, 1984, 1985). However, in reality, canopies generally exhibit large vertical heterogeneity of both biophysical and biochemical properties (Dreccer et al., 2000; Valentinuz and Tollenaar, 2004; Ciganda et al., 2008). Vertical heterogeneity of chlorophyll and leaf water has been found in winter wheat (Liu et al., 2015; Zhao et al., 2017), corn (Ciganda et al., 2008) and beech tree (Wang and Li, 2013). A multi-layer structure of

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vegetation canopies is very common, for example, forests with a grass or bush layer, field crops with a weed layer and vegetation in the senescent stage (Kuusk, 2001; Verhoef and Bach, 2007; Ciganda et al., 2008; Liu et al., 2015).

The vertical heterogeneity in canopies has been included in some models, and simulations with these models show that its effect on top of canopy (TOC) reflectance is not negligible (Kuusk, 2001; Verhoef and Bach, 2007; Wang and Li, 2013). However, the effect of vertical heterogeneity on photosynthesis and fluorescence is unknown. It is expected that the vertical distribution of leaf properties can affect the light distribution in the canopy, and thereby fluorescence emission and photosynthesis of leaves. The vertical heterogeneity may also influence the re-absorption and scattering (radiative transfer) of the emitted fluorescence and thus directly affect TOC fluorescence. The simplification of vertically complex canopies to homogeneous canopies, with either mean values of phytometric and optical parameters of all leaves, or values of upper leaves, may lead to bias in the prediction of reflectance, fluorescence and photosynthesis by SCOPE. The inclusion of vertical heterogeneity of leaf properties in SCOPE will promote a better understanding of the link between remote sensing observations and plant functional traits.

This study presents a multi-layer reflectance, fluorescence and photosynthesis model based on SCOPE, called mSCOPE. The model mSCOPE considers the vertical variation of leaf biochemical and biophysical properties. The analytical solution of radiative transfer of the incident fluxes in SAIL (Verhoef, 1984) and the numerical solution of radiative transfer of the emitted fluorescence in SCOPE (Van der Tol et al., 2009) are not applicable in mSCOPE, because the assumption of the vertical homogeneity of canopy components (leaves) does not hold in mSCOPE. Therefore, we briefly introduce the theory of mSCOPE by giving the solutions of radiative transfer of incoming radiation and emitted fluorescence in multi-layer canopies. Several example simulations are presented to illustrate the effects of vertical heterogeneity of leaf chlorophyll and leaf water content on TOC reflectance, fluorescence and canopy photosynthesis. The model mSCOPE is also preliminary validated.

2. Description of mSCOPE

2.1. Overview

The model mSCOPE extends the 1-D model SCOPE for a homogeneous canopy to a vertically heterogeneous vegetation canopy. It has the same architecture of SCOPE: leaf and canopy RTMs combined with an energy balance model. At leaf level, Fluspect (Vilfan et al., 2016) is used to simulate leaf reflectance, transmittance, and fluorescence. At canopy level, RTMo and RTMf (Van der Tol et al., 2016), which are two SAIL based models, compute the radiative transfer of incident radiation and emitted fluorescence, respectively. All the four models (Fluspect, RTMo, RTMf, and the energy balance model) are internally connected. Fluspect provides necessary input for canopy RMTo and RMTf. RTMo predicts the distribution of irradiance and net radiation over surface elements (leaves and soil), which are inputs to the energy balance module and RTMf.

The model mSCOPE retains the assumption of homogeneity in the horizontal direction in SCOPE, but it incorporates vertical heterogeneity of leaf properties. The type of input parameters in mSCOPE is the same as in SCOPE (Table 1). The difference is that mSCOPE accepts different values of leaf properties for up to 60 layers (Table 2). In other words, the user is allowed to deviate from the default, uniform profile of the leaf properties, and specify vertical profiles. The operational efficiency of mSCOPE is similar to that of SCOPE, and the same output variables are generated.

2.2. Radiation fluxes

In order to calculate photosynthesis and fluorescence, the radiation distribution in the canopy is required. In mSCOPE, this is computed using the classical SAIL 4-stream theory. The radiative transfer of the direct solar flux (E_s), downward diffuse flux (E^-), upward diffuse flux (E^+) and flux in the viewing direction (E_o), is analytically represented by four linear equations:

$$\frac{dE_s}{Ldx} = kE_s \tag{1a}$$

$$\frac{dE^-}{Ldx} = -sE_s + aE^- - \sigma E^+ \tag{1b}$$

$$\frac{dE^+}{Ldx} = s'E_s + \sigma E^- - aE^+ \tag{1c}$$

$$\frac{dE_o}{Ldx} = wE_s + vE^- + v'E^+ - KE_o \tag{1d}$$

where x is the vertical relative height to the canopy bottom surface, and L is canopy LAI. The extinction coefficients (k and K) depend on canopy structural characteristics (i.e., LAI and leaf angle distribution) and sun-observer geometry. The scattering coefficients (s,a,σ,s',w,v,v') depend on canopy structural characteristics, sun-observer geometry and the optical characteristics (i.e., leaf reflectance ρ and transmittance τ) of foliar elements. These nine coefficients, first defined by Verhoef (1984), are given in Appendix A.

In mSCOPE, due to the consideration of vertical leaf properties heterogeneity, leaf reflectance, transmittance and the scattering coefficients may vary vertically. This has no impact on the extinction coefficients (K and k). Therefore, only the calculation of the diffuse fluxes (E^- and E^+) needs to be adapted in mSCOPE, while the calculation of the directional fluxes remains the same as in SCOPE (i.e., Eqs. (1a) and (1d)).

The vegetation layer's scattering matrix is given by

Table 1
Main input parameters of SCOPE.

Parameter	Explanation	Unit	Standard value	Range
C_{ab}	Chlorophyll $a + b$ content	$\mu g\ cm^{-2}$	40	0–100
C_{dm}	Leaf mass per unit area	$g\ cm^{-2}$	0.01	0–0.02
C_w	Equivalent water thickness	cm	0.015	0–0.05
C_s	Senescence material (brown pigments)	fraction	0.1	0–1
C_{ca}	Carotenoid content	$\mu g\ cm^{-2}$	10	0–30
N_l	Leaf structure parameter	-	1.5	1–3
LAI	Leaf area index	-	3	0–6
LIDFa	Leaf inclination function parameter a	-	−0.35	−1 to 1
LIDFb	Leaf inclination function parameter b	-	−0.15	−1 to 1
ϵ_1	Fluorescence efficiency of photosystem I	-	0.004	0–0.01
ϵ_2	Fluorescence efficiency of photosystem II	-	0.02	0–0.05
θ_s	Sun zenith angle	°	45	0–90
ψ	Relative azimuthal angle	°	0	0–360
PAR	Photosynthetically active radiation	$\mu mol\ m^{-2}s^{-1}$	1200	0–2200

Table 2
Extra input parameters of mSCOPE compared with SCOPE.

	mSCOPE				SCOPE
Layer index	1	2	…	N	
Leaf properties	$v(1)$	$v(2)$	…	$v(N)$	v_{canopy}
LAI	$L(1)$	$L(2)$	…	$L(N)$	L_{canopy}

Note: leaf properties parameters include C_{ab}, C_{dm}, C_w, C_s, C_{ca} and N_l.