Application of radiative transfer models to moisture content estimation and burned land mapping.

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1 INTRODUCTION

Virtually all kinds of vegetation are subject to wildfires. Research programs conducted during the last three decades on fire risk assessment have emphasized the role of vegetation water content to understand biomass burning processes. They nevertheless did not produce satisfying operational methods to determine risk levels. Two different procedures are commonly used to monitor the evolution of fire risk over time (Dauriac et al., 2001):

- The use of meteorological variables averaged over a surface area of 1000 km^2 to calculate the water balance of the site;
- The measurement of vegetation water content in a limited number of control plots.

Water balance is the most important factor controlling aboveground primary production, and then fire frequency and intensity. For instance, the arid areas of southern hemisphere Africa burn infrequently because there is rarely enough fuel present to carry a fire across the landscape (a minimum of about 0.5-1 t/ha is needed). Several years of fuel accumulation or an exceptionally wet growing season are required to generate this minimum fuel load in arid areas (FAO, 2001). Where a sufficient amount of fuel accumulates, water content is definitely a key factor in assessing flammability and combustibility. Although there are many measurements of vegetation water content (leaf water potential, stomatal aperture, specific water density, equilibrium moisture content, etc.), Fuel Moisture Content (FMC), Relative Water Content (RWC), and Equivalent Water Thickness (EWT) are commonly used by plant physiologists to determine plant water stress:

$$FMC = \frac{fw - dw}{dw} \qquad RWC = \frac{fw - dw}{tw - dw} \qquad EWT = \frac{fw - dw}{A}$$

where fw is fresh weight, dw is dry weight, A is the leaf area, and tw is the turgid weight. FMC defined as the ratio between the quantity of water and either the fresh or dry (formula above) weight is routinely used by forest services to assess fire danger (NPS, 2001). RWC is the ratio of the actual leaf water content to the maximum water content at full turgor. It has been demonstrated to be directly related to leaf water potential, which controls plant response to water stress. However, different species may have the same RWC values with different amounts of water in their leaves because of variance in turgid weight and dry matter weight in nature (Ceccato et al., 2001). In contrast, EWT only depends on the amount of water in the leaf, corresponding to a hypothetical thickness of a single layer of water averaged over the whole leaf area. Ripple (1984)

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mentioned that traditional techniques for accurate ground-based evaluation of plant water relations were time consuming, costly, and spatially restrictive, and proposed to combine them with remote sensing techniques for large-area evaluations. Remote sensing is indeed an adapted tool to monitor vegetation moisture, from local to global scale, operationally, and over different ecosystems. As leaves represent the main surfaces of plant canopies, their optical properties are essential to understanding the transport of photons within vegetation, but the "scaling-up" of water estimation methods from leaf- to canopy-level is still a point at issue as seen below, because plant canopies are considerably more complex targets than are leaves.

2 REMOTE SENSING OF MOISTURE CONTENT AT THE LEAF LEVEL

Hundreds of papers have detailed variation in spectral properties in relation to leaf biochemical composition and structure, which themselves depend on many factors including the species, developmental or microclimate position of the leaf on the plant, and whether it is stressed or not. One classically divides the optical domain from 400 to 2500 nm in three parts: the visible (400-700 nm) characterized by a strong absorption of light by photosynthetic pigments in a green leaf; the near-infrared plateau (700-1100 nm) where absorption is limited to dry leaf matter but where multiple scattering within the leaf, related to the fraction of air spaces, i.e., to the internal structure, drives the reflectance and transmittance levels; and the middle-infrared (1100-2500 nm) which is also a zone of strong absorption, primarily by water in fresh leaves and secondarily, by dry matter (dry carbon compounds like cellulose and lignin, nitrogen, sugars, and other plant compounds) when the leaf wilts and dries (Figure 1). All of these observations are a prerequisite to extracting biophysical information.

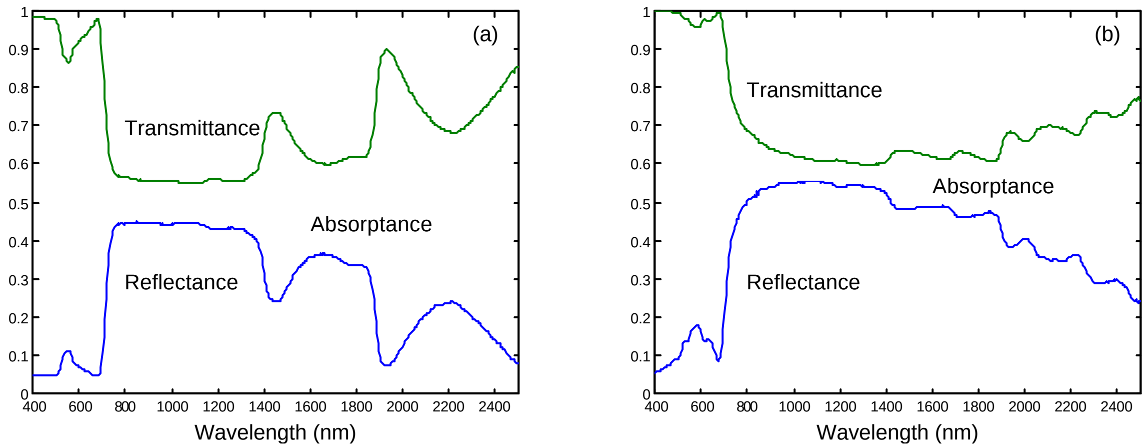

Figure 1. Reflectance and transmittance spectra of (a) fresh and (b) dry poplar (*Populus canadensis*) leaves in the solar domain.

There are two major water absorption features centered near 1450 and 1950 nm that affect the reflectance of healthy leaves, and two minor centered near 970 and 1200 nm. These absorption features result from vibrational transitions involving various overtones and combinations of water's three fundamental vibrational transitions: V1 (H–O–H symmetric stretch mode transition), V2 (H–O–H bending mode transition), and V3 (H–O–H asymmetric stretch mode transition). The absorption feature centered near 970 nm is attributed to a 2V1 + V3 combination, the one near 1200 nm to a V1 + V2 + V3 combination, the one near 1450 nm to a V1 + V3 combination, and the one near 1950 nm to a V2 + V3 combination. Various methods have been developed to extract leaf water content from leaf optical properties.

2.1 *The semi-empirical approach*

The first methods consist of relating spectral indices based on a ratio or some other simple mathematical formula of reflectance, or its derivative, at one or more selected wavelengths – ρ_{900}/ρ_{970}, ρ_{1650}/ρ_{1430}, $(\rho_{850}-\rho_{2218})/(\rho_{850}-\rho_{1928})$, $(\rho_{850}-\rho_{1788})/(\rho_{850}-\rho_{1928})$, among others – to leaf water content:

$$FMC \text{ or } RWC \text{ or } EWT = f\left(r\left(l_1\right), \ldots, r\left(l_n\right)\right)$$

RWC (Hunt et al., 1987, 1989; Bowman, 1989; Inoue et al., 1993; Peñuelas et al., 1993; Peñuelas and Inoue, 1999; Yu et al., 2000; etc.) and EWT (Aoki et al., 1988; Danson et al., 1992; Datt, 1999; Yu et al., 2000; Ceccato et al., 2001; etc.) have been determined this way. Continuum removal, i.e., integration of the area in the absorption below the continuum, has been applied by Tian et al. (2001) to the curve between 1650 and 1850 nm, to estimate RWC. Finally, multiple stepwise regression analysis which establishes a direct regression equation between leaf reflectance (or transmittance) at a few wavelengths, selected by the procedure, and leaf biochemistry has been used by Fourty and Baret (1998) and Gillon et al. (2002) to estimate EWT and FMC, respectively. However, the accuracy of these estimations lack predictability because these relationships do not take into account the partially co-varying anatomical structure and specific leaf area differences between species or leaves.

2.2 *The Modeling approach*

While experimental measurements of leaf optical properties were progressing, deterministic models based on diverse representations of light interactions with plant leaves were also developed. These models are distinguished by the underlying physics and by the complexity of the leaf. The simplest ones consider the blade as a single scattering and absorbing layer. In the most complicated ones, all cells are described in detail (shape, size, position, and biochemical content). Whatever the approach, these models have improved our understanding of the interactions of light with plant leaves. Information about the refractive index and the specific absorption coefficient of leaf constituents is almost always required. Figure 2 presents the latter for chlorophyll, water, and dry matter as a function of the wavelength. One recognizes in the action spectrum of water the three main peaks near 1450, 1950, and 2500 nm, and two minor ones at 970 and 1200 nm. The 970 nm absorption band has very little effect on leaf optical properties so that it sometimes does not occur on leaf spectra.

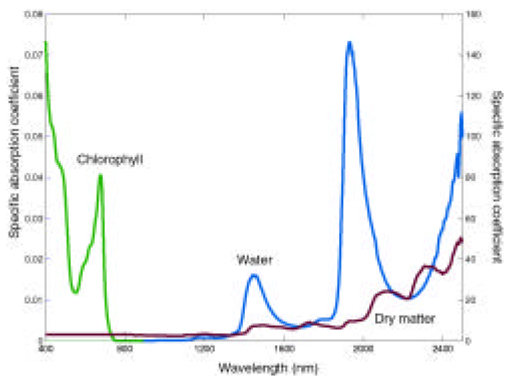

Figure 2. Specific absorption coefficient a) of chlorophyll a+b ($cm^2\ \mu g^{-1}$) on the left scale b) of water (cm^{-1}) and dry matter ($cm^2\ g^{-1}$) on the right scale.

Ustin et al. (1999) already extensively reviewed computer-based leaf models from the late sixties to the present. Table 1 categorizes radiative transfer models in three main classes, arranged in increasing order of complexity:

Radiative transfer models	Stochastic models	Monte Carlo approaches
PROSPECT, LIBERTY, LEAFMOD, FRT	SLOP	RAYTRAN, ABM
- structure parameter - biochemical contents	- probabilities of scattering and absorption	- description of the leaf internal structure in three dimensions
→ spectral properties → chlorophyll fluorescence	→ spectral properties → chlorophyll fluorescence	→ spectral properties → directional properties → absorption profiles
direct + inverse mode		direct mode

Table 1. Comparison of several leaf optical properties models used in remote sensing.

2.2.1 *PROSPECT*

Now in widespread use in the remote sensing community, PROSPECT was among the first model to accurately simulate the hemispherical reflectance and transmittance of various plant leaves (monocots or dicots, fresh or senescent leaves) over the solar spectrum. The leaf is represented as a pile of absorbing plates with rough surfaces giving rise to isotropic diffusion (Figure 3). Originally the model used three input parameters (Jacquemoud and Baret, 1990): the structure parameter N (number of compact layers specifying the average number of air / cell walls interfaces within the mesophyll), the chlorophyll a+b concentration C_{ab} (µg cm^{-2}), and the equivalent water thickness EWT noted C_w (cm or g cm^{-2}).

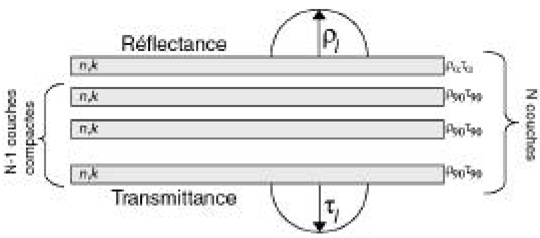

Figure 3. Schematic representation of PROSPECT.

During the summer of 1993 an experiment at the Joint Research Centre (Ispra, Italy) built a database, LOPEX, associating visible / infrared spectra of dry and fresh vegetation elements (leaves, conifer needles, stems, etc.) with physical measurements (thickness, water content, specific leaf area) and biochemical analyses (chlorophyll a+b, proteins, cellulose, lignin, etc.) (Hosgood et al., 1995). LOPEX was used to introduce the full leaf biochemistry into PROSPECT (Jacquemoud et al., 1996). A limit of this process arose however in the inversion of the model when it was discovered that protein content could not be retrieved because of strong water absorption features and cellulose and lignin could not be consistently identified and quantified. As a consequence, the model was simplified to the point that it now considers the dry matter content C_m (g cm^{-2}) as a whole instead of treating the leaf biochemical constituents individually (Baret and Fourty, 1997; Jacquemoud et al., 2000). In short, the four input parameters of PROSPECT today are: leaf structure parameter, the chlorophyll a+b concentration, the equivalent water thickness, and the dry matter content. Recent studies based on statistical methods like the Design Of Experiments for Simulation (DOES, Bacour et al., 2002) or the Extended Fourier Amplitude Sensitivity Test (EFAST, Ceccato et al., 2002a) permitted the quantification of the contribution of each of the input parameters to the model outputs, as well as their interactions. Figure 4 shows that variation in transmittance values – it would be similar with reflectance values – are exclusively influenced by N, C_w and C_m in the near and middle infrared. As expected, water has the greatest influence with 80-90% of contribution in the absorption peaks, but N and C_m also significantly affect transmittance values within this range.

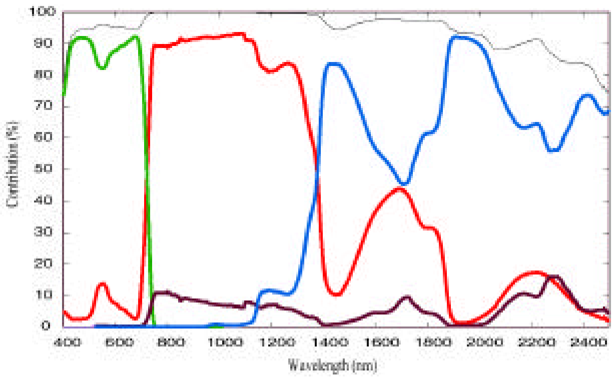

Figure 4. Contribution of chlorophyll concentration C_{ab} (green), equivalent water thickness C_w (blue), dry matter content C_m (brown) and structure parameter N (red) to the leaf transmittance as simulated by PROSPECT. The black curve is the sum of the contributions (Pavan, unpublished).

PROSPECT has been validated by iterative inversion of the model on reflectance and transmittance spectra of about sixty leaves of various species from the LOPEX database, and fourteen leaves of cereal crops (Newnham and Burt, 2001). It generally performs well in terms of spectrum reconstruction. The comparison between measured and estimated values of C_{ab}, C_w, and C_m also gives satisfactory results on fresh leaves (Table 2).

	Constituent	***R^2***	**RMSE**
Baret and Fourty (1997)	C_w	×	0.0025 cm
	C_m	×	0.0016 g cm^{-2}
Jacquemoud et al. (2000)	C_{ab}	0.67	9.1 µg cm^{-2}
	C_w	0.95	0.0018 cm
	C_m	0.65	0.0022 g cm^{-2}
Newnham and Burt (2001)	C_{ab}	0.78	×
	C_w	0.93	×

Table 2. Retrieval of leaf biochemical constituents by inversion of PROSPECT.

2.2.2 LIBERTY *(Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yields)*

This model was developed specifically to calculate the optical properties of both dried and fresh stacked conifer needles (Dawson et al., 1998a), and to date, it remains the only one designed for this purpose. However, it can also be used for predicting the reflectance and transmittance spectra of a leaf or a stack of leaves in the solar domain. By treating the leaf as an aggregation of cells, with multiple radiation scattering between cells, output spectra are a function of three structural parameters (cell diameter in µm, intercellular air space, leaf thickness) and the combined absorption coefficients of leaf biochemicals (chlorophyll concentration in mg m^{-2}, water content in g m^{-2}, lignin and cellulose content in g m^{-2}, and nitrogen content in g m^{-2}). Dawson et al. (1998b) ran LIBERTY to generate reflectance spectra of slash pine needles containing various water, lignin+cellulose, and nitrogen concentrations. This data set was then used for training an artificial neural network which proved to produce more accurate FMC when compared against those generated with spectral indices alone.

2.2.3 *Other models*

Although PROSPECT and LIBERTY are the most popular leaf optical properties models in remote sensing, other codes have been developed which also take into account leaf water content and are potentially useful in the remote sensing of fire risk assessment: LEAFMOD (*Leaf Experimental Absorptivity Feasibility MODel*, Ganapol et al., 1997) directly based on the radiative transfer equation, SLOP (*Stochastic model for Leaf Optical Propertie*, Maier et al., 1999) where the leaf is partitioned into different tissues and their optical properties simulated by a Markov chain.

3 REMOTE SENSING OF MOISTURE CONTENT AT THE CANOPY LEVEL

It would be convenient to be able to estimate the water content of whole canopies in the field using leaf-level methods described above, but extending laboratory results to the field presents some problems (Rollin and Milton, 1998). Besides leaf optical properties, canopy reflectance also depends on plant structure (leaf area index, leaf orientation, leaf size, etc.), background (soil and/or non-photosynthetically active vegetation) optical properties, and viewing geometry (solar and view zenith and azimuth angles). Most of these parameters vary spatially and temporally. For that very reason, it is questionable whether the semi-empirical relationships established at leaf level can be "scaled-up" to whole canopies: How can canopy water content be mapped?

3.1 *The semi-empirical approach*

There are few studies that have examined the relationships between total canopy water content and spectral reflectance indices. Sims and Gamon (2003) recently proposed the Canopy Structure Index (CSI) that combines the low absorptance water band at 1180 nm with the simple ratio vegetation index to account for the amount of vegetation: CSI produced good correlations with EWT at all canopy thicknesses. Rolin and Milton (1998) defined the Relative Depth Index (RDI) to estimate FMC. Both indices have been tested with reflectance spectra acquired by field portable spectrometers on a limited number of validation points. The Normalized Difference Water Index (NDWI) demonstrated its potential applicability for canopy-level EWT estimation with AVIRIS (Airborne Visible Infrared Imaging Spectrometer) imagery (Gao, 1996; Serrano et al., 2000). More sophisticated techniques like Hierarchical Foreground / Background Analysis (HFBA) introduced by Ustin et al. (1998) also performed well in the retrieval of canopy water content from AVIRIS imagery (Figure 5). The cartography of FMC in urbanized landscapes, such as the chaparral systems of semiarid shrubs in California, is critical to fire assessment. Finally, Ceccato et al. (2002a, 2002b) were innovating in designing a Global Vegetation Moisture Index (GVMI) based on radiative transfer model simulations and adapted to the SPOT-VEGETATION sensor. Field measurements of EWT carried out at canopy level on different formations of West Africa (shrub steppe, shrub savannah, tree savannah, and savannah woodland) validated the new index.

Most of these indices based on spectral variations of the reflectance however pose a problem because water stress is not only manifested in water content change but also in plant architecture change (Jackson, 1986). As wilting progresses, the leaves become more vertical, the cover fraction and consequently, the reflectance, decrease. Radiative transfer models which incorporate the effects of viewing geometry, leaf orientation, and other describers of canopy complexity into reflectance might be better suited to accurately retrieve water content.

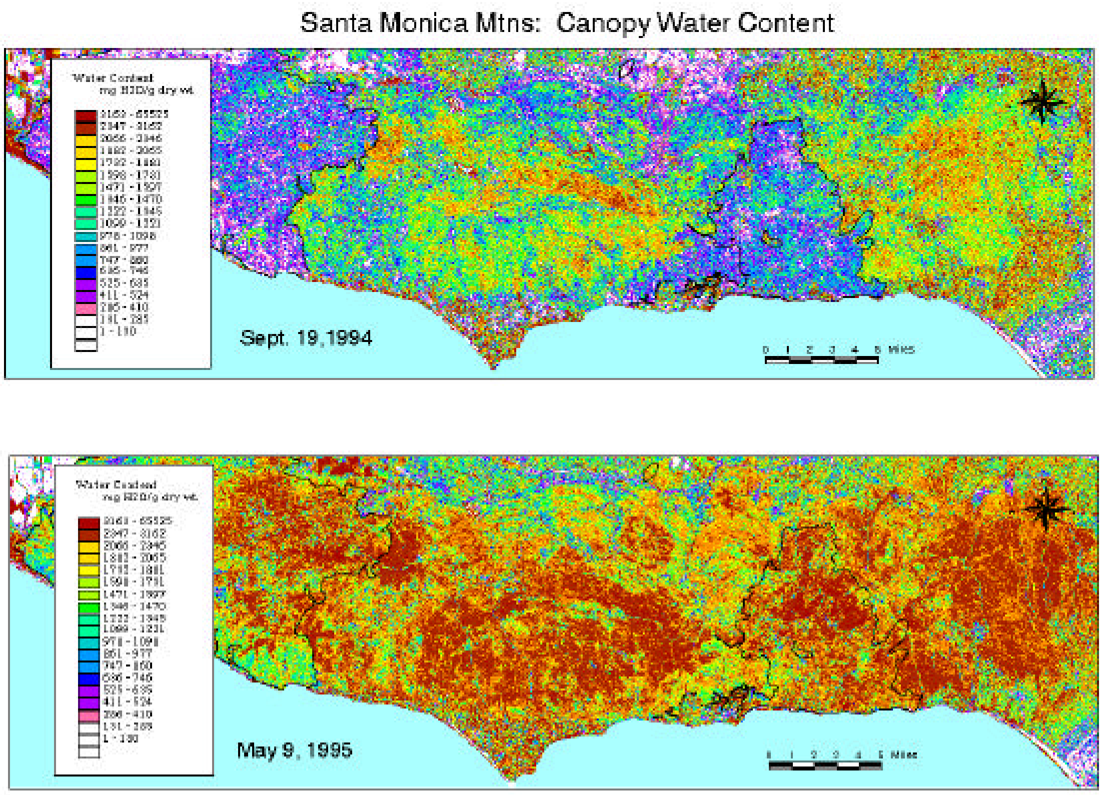

Figure 5. Canopy water content of chaparral communities in the Santa Monica Mountains, bordering Los Angeles and the San Fernando Valley, California, an area subject to frequent catastrophic wildfires in the shrub savanna grasslands. The images were measured in September, at the end of the extended dry season (approximately six months without rain) and in the following spring at the end of the winter rainy season. Data were composited from three AVIRIS flightlines (16 scenes) and atmospherically collected reflectance (after ustin et al., 1998).

3.2 *The modeling approach*

Fewer investigations have applied radiative transfer models and inversion techniques for estimating leaf water content from canopy reflectance imagery. The first attempts are quite simple: Schmuck et al. (1993) regarded an AVIRIS spectrum as a linear mixing of soil and vegetation spectra, the latter being modeled with a Kubelka-Munk formula modified to fit an optically thick homogeneous medium. Two spectral windows were use in the fitting: the 500-730 nm region for chlorophyll estimates and the 1500-1650 nm region for water estimates. Compared with the Moisture Stress Index calculated at two dates, the retrieved EWT demonstrated a higher sensitivity. By expressing the reflectance spectrum by modified Beer-Lamber laws, Gao and Goetz (1995) and Roberts et al. (1997) mapped EWT.

Jacquemoud and Baret (1993) were the first to link a leaf optical properties model, PROSPECT, to a canopy reflectance model, SAIL, namely PROSAIL, and to invert it on reflectance spectra (Figure 6). They estimated EWT by iterative inversion of the coupled model on sugar beet (*Beta vulgaris* L.) reflectance spectra acquired at nadir. Such a procedure has been later on successfully extented to AVIRIS and TM equivalent data (Jacquemoud, 1993; Jacquemoud et al., 1995). Danson and Aldakheel (2000) followed the same approach to study diurnal water stress, but nevertheless pointed out the limit of radiative transfer models to represent heterogeneities (clumping effect) in sugar beet crops, and then to simulate a correct reflectance. Finally, Zarco-Tejada et al. (2003) recently showed that canopy water content could be retrieved by inversion of SAILH from MODIS

(MODerate Resolution Imaging Spectroradiometer) reflectance bands, validating that seasonal desiccation of the canopy over the California summer drought can be measured by spectral changes in water absorption for chaparral communities in southern California.

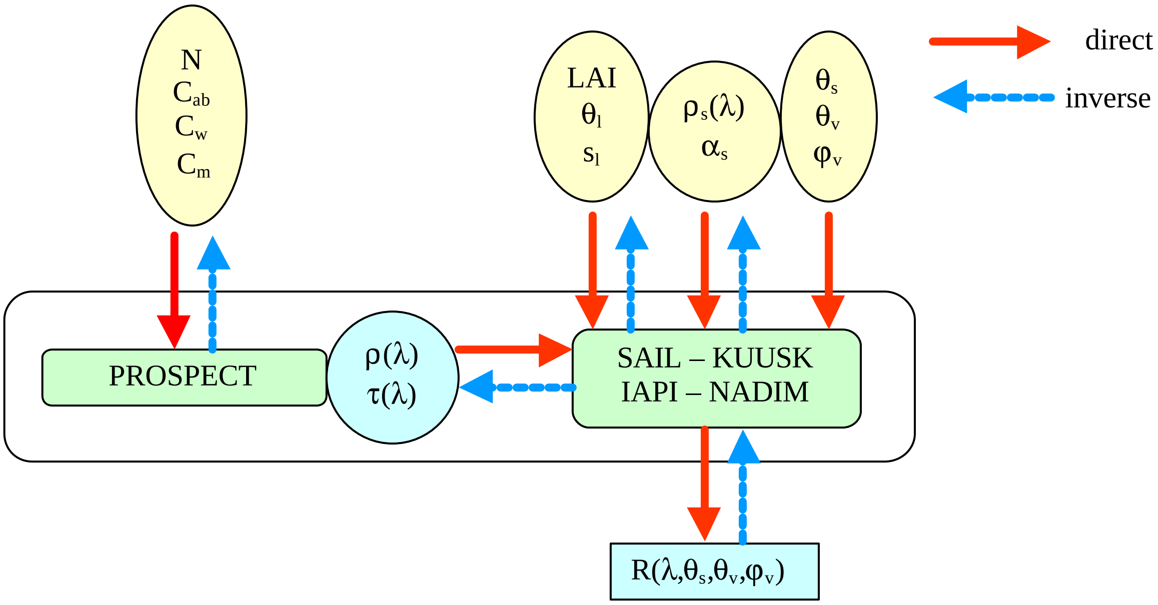

Figure 6. Schematic representation of the PROSPECT + SAIL (or any other canopy reflectance model) model, in direct and inverse modes.

4 CONCLUSION

The use of radiative transfer models to estimate moisture content is still in its infancy. Much more work is required before we completely understand the spectral variations of vegetation in relation to changes of water content, both at the leaf and canopy levels. This knowledge is nevertheless crucial to developing more accurate retrieval methods: models can be use in direct mode to build new indices optimized for the wavebands / view angles of actual sensors, but also in inversion. Although iterative inversions are still time consuming and not operational to date, artificial neural networks or look-up table techniques can be set up and tested on VEGETATION data on SPOT4, or MODIS data on TERRA satellites. Of course, emphasis must be placed on supporting field measurements to validate them.

The mapping of burned areas with models has not been evaluated in this review because of the small numbers of studies: Roy et al. (2002) proposed to detect variations in observed MODIS reflectance by inverting a parametric BRDF model. Finally, the spectral and bidirectional radiative properties of burnt scenes surprisingly have not given rise to any extensive study despite obvious usefulness.

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