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Remote sensing of fuel moisture content from ratios of narrow-band vegetation water and dry-matter indices

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ABSTRACT

Fuel moisture content (FMC) is an important variable for predicting the occurrence and spread of wildfire. Because FMC is calculated from the ratio of canopy water content to dry-matter content, we hypothesized that FMC may be estimated by remote sensing with a ratio of a vegetation water index to a vegetation dry-matter index. Four vegetation water indices, six dry-matter indices, and the resulting water/dry-matter index ratios were calculated using simulated leaf reflectances from the PROSPECT model. Two water indices, the Normalized Difference Infrared Index (NDII) and the Normalized Difference Water Index (NDWI), were more correlated with leaf water content than with FMC, and were not correlated with leaf dry-matter content. Two dry-matter indices, the Normalized Dry Matter Index (NDMI) and a recent index (unnamed) were correlated to leaf dry matter content, were inversely correlated with FMC, and were not correlated with water content. Ratios of these water indices and these dry-matter indices were highly and consistently correlated with FMC. Ratios of other water indices with other dry-matter indices were not consistently correlated with FMC. The ratio of NDII with NDMI was strongly related to FMC by a quadratic polynomial equation with an R^2 of 0.947. Spectral reflectance data were acquired for single leaves and leaf stacks of *Quercus alba*, *Acer rubrum*, and *Zea mays*; the relationship between FMC and NDII/NDMI had an R^2 of 0.853 and was almost identical to the equation from the PROSPECT model simulations. For the SAIL model simulations, the relationship between NDII/NDMI and FMC at the canopy scale had an R^2 of 0.900, but the quadratic polynomial equation differed from the equations determined from the PROSPECT simulations and spectral reflectance data. NDMI requires narrow-band sensors to measure the effect of dry matter on reflectance at 1722 nm whereas NDII may be determined with many different sensors. Therefore, monitoring FMC with NDII/NDMI requires either a new sensor or a combination of two sensors, one with high temporal resolution for monitoring water content and one with high spectral resolution for estimating dry-matter content.

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1. Introduction

Fuel moisture content (FMC) is one of the main parameters for predicting the occurrence and spread of wildfire, because it is a critical variable for both fire ignition and fire propagation (Hardy & Burgan, 1999; Keane et al., 2010; Rollins et al., 2004). FMC is the mass of water per unit mass of dry matter in vegetation (Ceccato et al., 2003; Chuvieco et al., 2002). As the foliar water content in vegetation canopies decreases, there is decreased absorption of shortwave-infrared radiation, which may be monitored with remotely sensed data (Hunt & Rock, 1989; Tucker, 1980; Ustin et al., in press). A major problem restricting the use of remote sensing for estimating FMC is determining the amount of dry matter in fresh leaves, because many species of concern for fire management have more variation in leaf dry-matter content than variation in leaf water content (Ceccato et al., 2003).

Currently, the most promising approach is retrieval of FMC by inversion using leaf and canopy radiative-transfer models because leaf water and dry-matter contents are model parameters (Riaño et al., 2005; Yebra & Chuvieco, 2009; Yebra et al., 2008; Zarco-Tejada et al., 2003). However, spectral indices have one advantage enabling rapid analysis of large volumes of remotely sensed data. A number of studies have found that vegetation water indices are correlated with FMC because of the liquid water term in the numerator of FMC (Ceccato et al., 2003; Chuvieco et al., 2002; Dennison et al., 2005; Roberts et al., 2006). There are a large number of potential indices for estimating either liquid water or dry-matter contents, several of which are listed in Table 1. Half of the dry-matter indices in Table 1 were originally developed to detect crop residue or non-photosynthetic vegetation based on the absorption features of lignin and cellulose. Wang et al. (2011a, 2011b) recently proposed the Normalized Dry Matter Index (NDMI, Table 1) based on the C–H bond stretch overtone at 1722 nm (Peterson & Hubbard, 1992). C–H bonds are found in all leaf biochemical constituents: carbohydrates (including cellulose), lignin, proteins, lipids and nucleic acids.

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Table 1
Spectral indices for dry-matter (type = D) and water content (type = W) in leaves and canopies.

Index	Abbreviation	Type	Equation [a]	Reference
Normalized Dry Matter Index	NDMI	D	$(\rho_{1649}-\rho_{1722})/(\rho_{1649}+\rho_{1722})$	Wang et al. (2011a, 2011b)
Normalized Difference Tillage Index	NDTI	D	$(\rho_{1650}-\rho_{2215})/(\rho_{1650}+\rho_{2215})$	van Deventer et al. (1997)
Cellulose Absorption Index	CAI	D	$0.5(\rho_{2031}-\rho_{2211})-\rho_{2101}$	Nagler et al. (2000)
Normalized Difference Lignin Index	NDLI	D	$[\log(1/\rho_{1754})-\log(1/\rho_{1680})]/[\log(1/\rho_{1754})+\log(1/\rho_{1680})]$	Serrano et al. (2002)
Normalized Difference Nitrogen Index	NDNI	D	$[\log(1/\rho_{1510})-\log(1/\rho_{1680})]/[\log(1/\rho_{1510})+\log(1/\rho_{1680})]$	Serrano et al. (2002)
Ligno-Cellulose Absorption Index	LCA	D	$2\rho_{2205}-(\rho_{2165}+\rho_{2330})$	Daughtry et al. (2005)
Shortwave Infrared Normalized Difference Residue Index	SINDRI	D	$(\rho_{2210}-\rho_{2260})/(\rho_{2210}+\rho_{2260})$	Serbin et al. (2009)
Dry Matter Content Index [b]	DMCI	D	$(\rho_{2305}-\rho_{1495})/(\rho_{2305}+\rho_{1495})$	Romero et al. (2012)
Normalized Difference Infrared Index	NDII	W	$(\rho_{860}-\rho_{1650})/(\rho_{860}+\rho_{1650})$	Hardisky et al. (1983)
Reciprocal of Moisture Stress Index	RMSI	W	ρ_{860}/ρ_{1650}	Hunt and Rock (1989)
Normalized Difference Water Index	NDWI	W	$(\rho_{860}-\rho_{1240})/(\rho_{860}+\rho_{1240})$	Gao (1996)
Simple Ratio Water Index	SRWI	W	ρ_{860}/ρ_{1240}	Zarco-Tejada et al. (2003)

[a] ρ is reflectance and the subscript is wavelength (nm).
[b] Romero et al. (2012) did not name this index; the name used here is for convenience only.

Because FMC is the ratio of water content to dry-matter content, we hypothesized that a ratio of a remotely-sensed water index to a remotely-sensed dry-matter index would better estimate FMC compared to either water indices or dry-matter indices separately. Ideally, dry-matter indices would be highly correlated with dry-matter content and not correlated with water content. Furthermore, ideal water indices would be highly correlated with water content and not correlated with dry-matter content. With an index ratio, many of the factors that affect both the water and dry-matter indices may cancel out, such as leaf structure, leaf angle distribution (LAD), and Leaf Area Index (LAI). The problem is that both water and dry-matter indices are both formulated using wavelengths in the shortwave infrared, so ratios of different water and dry-matter indices need to be evaluated. Radiative-transfer model simulations at the leaf scale were used to test this hypothesis; results of the simulations were then evaluated with spectral reflectance data acquired in the laboratory. Finally, radiative-transfer model simulations at the canopy scale were used to assess the potential for estimating FMC from satellites.

2. Methods

2.1. Remote sensing indices for FMC

Leaf FMC (dimensionless) was estimated from the ratio of leaf water content C_w (g cm^{-2}) to leaf dry-matter content C_m (g cm^{-2}). Eqs. (1)–(3) were used to calculate C_w, C_m and FMC:

$$C_w = (W_f - W_d)/A \tag{1}$$

$$C_m = W_d/A \tag{2}$$

$$\mathrm{FMC} = (W_f - W_d)/W_d = C_w/C_m \tag{3}$$

where: W_f was the leaf fresh weight (g), W_d was the leaf dry weight (g), and A was the leaf area (cm^2). Canopy C_w and C_m were the leaf C_w and C_m multiplied by Leaf Area Index (LAI). The ratio of C_w/C_m was used for both leaves and canopies because leaf area canceled out.

Besides NDMI, other indices related to dry-matter content were selected (Table 1): the Normalized Difference Tillage Index (NDTI; van Deventer et al., 1997), the Cellulose Absorption Index (CAI; Nagler et al., 2000), the Normalized Difference Lignin Index (NDLI; Serrano et al., 2002), the Normalized Difference Nitrogen Index (NDNI; Serrano et al., 2002), the Lingo-Cellulose Absorption Index (LCA; Daughtry et al., 2005), and the Shortwave Infrared Normalized Difference Residue Index (SINDRI; Serbin et al., 2009). Furthermore, we used a recently-published unnamed index from Romero et al. (2012), which for convenience was called the Dry Matter Content Index (DMCI) for this study (Table 1).

Two normalized-difference indices and two ratio indices were selected for analysis of leaf water content (Table 1), with one normalized-difference index and one ratio index based on the local absorption maximum of liquid water at 1240 nm, and one normalized-difference index and one ratio index based on the local absorption minimum at 1650 nm. The indices were the Normalized Difference Infrared Index (NDII; Hardisky et al., 1983), the Reciprocal of the Moisture Stress Index (RMSI; Hunt & Rock, 1989), the Normalized Difference Water Index (NDWI; Gao, 1996), and the Simple Ratio Water Index (SRWI; Zarco-Tejada et al., 2003). RMSI was used instead of the Moisture Stress Index, because RMSI increases with increasing FMC allowing for better comparisons among water/dry-matter index ratios.

2.2. PROSPECT and SAIL model simulations

In order to generate water and dry-matter indices for various FMC, the leaf radiative-transfer model, PROSPECT version 4 (Féret et al., 2008; Jacquemoud et al., 2009), was used to simulate leaf reflectance and transmittance from 400 to 2500 nm. For a total of 250 simulations, input parameters (C_w, C_m and the leaf parameter N) were randomly generated using a uniform distribution within a selected range for each variable (Table 2). Total chlorophyll a and b content (C_{ab}) was held constant at 40 μg cm^{-2} because variation of C_{ab} had no effect on the indices used in Table 1. The range selected for each parameter was set to exceed all reasonable combinations expected to occur, based on data from ground measurements and the published literature (Féret et al., 2011).

The Scattering by Arbitrarily Inclined Leaves (SAIL) model (Verhoef, 1984) was used to simulate canopy spectral reflectance as a function of leaf reflectance and transmittance, soil background reflectance, LAI, and LAD (Table 2). Spectral reflectances and transmittances from the 250 PROSPECT simulations were used as inputs to the SAIL model. A total of 4500 simulations were made using the 250 PROSPECT simulations, with 6 different LAI and 3 LAD (Table 2). The spectral reflectance of a dry Othello silt loam (fine silty, mixed, active, mesic Typic Endoaquult) from Salisbury, Maryland, was used for the background reflectance (Daughtry, 2001). The background reflectances of this soil caused many of the indices to be unstable at low LAI, therefore only LAI ≥ 1.5 were used (Table 2).

2.3. Spectral reflectance measurements

Spectral reflectances of individual leaves and stacks of leaves were used to determine the relationship between FMC and water/dry-matter index ratios. Leaves of white oak (*Quercus alba* L.), red maple (*Acer rubrum* L.) and maize (*Zea mays* L.) were collected at the USDA-ARS Beltsville Agricultural Research Center, Beltsville, MD. Leaves (many more than were necessary for the measurements)