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Use of Normalized Difference Water Index for monitoring live fuel moisture

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Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) were compared for monitoring live fuel moisture in a shrubland ecosystem. Both indices were calculated from 500 m spatial resolution Moderate Resolution Imaging Spectroradiometer (MODIS) reflectance data covering a 33-month period from 2000 to 2002. Both NDVI and NDWI were positively correlated with live fuel moisture measured by the Los Angeles County Fire Department (LACFD). NDVI had R^2 values ranging between 0.25 to 0.60, while NDWI had significantly higher R^2 values, varying between 0.39 and 0.80. Water absorption measures, such as NDWI, may prove more appropriate for monitoring live fuel moisture than measures of chlorophyll absorption such as NDVI.

1. Introduction

Live fuel moisture is an important determinant of wildfire danger in fire-prone ecosystems. Low live fuel moisture creates a fuel environment susceptible to wildfire, especially in ecosystems that possess large amounts of live and dead fine fuels. Southern California chaparral is a fire-adapted ecosystem that exhibits large seasonal changes in live fuel moisture (Dennison *et al.* 2003).

Burgan and Hartford (1996) demonstrated use of the Normalized Difference Vegetation Index (NDVI) for monitoring live fuel moisture. NDVI measures chlorophyll absorption in the red portion of the spectrum relative to reflectance or radiance in the near-infrared. For Moderate Resolution Imaging Spectroradiometer (MODIS) data, NDVI is calculated as:

$$\mathrm{NDVI}=\frac{\rho_{857}-\rho_{645}}{\rho_{857}+\rho_{645}} \tag{1}$$

ρ_{857} is reflectance at 857 nm and ρ_{645} is reflectance at 645 nm. NDVI has been shown to vary with live fuel moisture in grasslands (Paltridge and Barber 1988,Chladil and Nunez 1995, Hardy and Burgan 1999), although Hardy and Burgan (1999) did not

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find significant relationships between NDVI and live fuel moisture in shrubland and coniferous forest.

NDVI does not change directly in response to vegetation moisture, but rather in response to vegetation greenness. Several remote sensing measures of vegetation moisture based on water absorption have been proposed, including indices based on near-infrared (NIR) absorption (Gao 1996) and short-wave infrared (SWIR) absorption (Hardisky *et al.* 1983, Hunt *et al.* 1987, Ceccato *et al.* 2002). Sims and Gamon (2003) compared the abilities of water indices based on NIR and SWIR wavelengths to estimate the vegetation water content of common vegetation species in southern California. They found an index based on a 1200 nm water absorption feature was the best predictor of canopy water content and was the least sensitive to atmospheric water vapour absorption.

Based on the results of Sims and Gamon (2003), the Normalized Difference Water Index (NDWI) was selected as an appropriate water absorption index for comparison with NDVI for the application of monitoring live fuel moisture. For MODIS data, NDWI is calculated as:

$$\mathrm{NDWI} = \frac{\rho_{857} - \rho_{1241}}{\rho_{857} + \rho_{1241}} \tag{2}$$

where ρ_{857} is the reflectance in a NIR reference band and ρ_{1241} is the reflectance at 1241 nm, which is within the water absorption band centred at 1200 nm (Gao 1996). Since NDWI is calculated using a water absorption band, it should be more closely related to live fuel moisture than the chlorophyll absorption-based NDVI. This study compares NDWI- and NDVI-derived estimates of live fuel moisture in southern California chaparral.

2. Methods

Live fuel moisture of six species was sampled by the Los Angeles County Fire Department (LACFD) at 12 sites within Los Angeles County, California, USA (table 1). Sampling protocols for the live fuel moisture measurements were established by Countryman and Dean (1979). Live samples consisting of leaves and stems less than 3.2 mm (1/8th inch) in diameter, including both old and new growth, were collected from multiple shrubs at each field site (Countryman and Dean 1979, Weise *et al.* 1998). These samples were weighed, dried at a temperature of 104°C for 15 h, and reweighed. Live fuel moisture was calculated as a percentage of dry mass:

$$M = \frac{m_w - m_d}{m_d} \tag{3}$$

where M is the live fuel moisture, m_w is the measured mass of the wet samples, and m_d is the measured mass of the dried sample. Live samples of chamise (*Adenostoma fasciculatum*) were measured at the 11 sites dominated or co-dominated by this species (table 1). At four of these sites, live samples of co-dominant species, including big pod ceanothus (*Ceanothus megacarpus*), hoary-leaf ceanothus (*C. crassifolius*), and black sage (*Salvia mellifera*) were also measured. Live fuel moisture was also measured at a twelfth site co-dominated by California sagebrush (*Artemisia californica*) and purple sage (*Salvia leucophylla*). Live fuel moisture was measured roughly once every three weeks over the period 2000–2002, and published in a series of reports by the LACFD (LACFD 2000, 2001, 2002).

Table 1. Species and number of sampling dates between March 2000 and November 2002 for each LACFD live fuel moisture site.

Site	Species	Common name	Latitude/ longitude	Number of samples
Bitter Canyon 1	*Artemisia californica*	California sagebrush	34° 30′ N 118° 36′ W	56
	Salvia leucophylla	purple sage		55
Bitter Canyon 2	*Adenostoma fasciculatum*	Chamise	34° 31′ N 118° 36′ W	56
Bouquet Canyon	*Adenostoma fasciculatum*	Chamise	34° 30′ N	53
	Salvia mellifera	black sage	118° 29′ W	53
Clark Motorway	*Adenostoma fasciculatum*	Chamise	34° 05′ N	56
	Ceanothus megacarpus	big pod ceanothus	118° 52′ W	56
La Tuna Canyon	*Adenostoma fasciculatum*	Chamise	34° 15′ N 118° 18′ W	54
Laurel Canyon	*Adenostoma fasciculatum*	Chamise	34° 07′ N 118° 22′ W	55
Pico Canyon	*Adenostoma fasciculatum*	Chamise	34° 22′ N 118° 34′ W	56
Placerita Canyon	*Adenostoma fasciculatum*	Chamise	34° 22′ N 118° 29′ W	56
Schueren Road	*Adenostoma fasciculatum*	Chamise	34° 05′ N 118° 39′ W	54
Sycamore Canyon	*Adenostoma fasciculatum*	Chamise	34° 09′ N	51
	Ceanothus crassifolius	hoary-leaf ceanothus	118° 48′ W	51
Trippet Ranch	*Adenostoma fasciculatum*	Chamise	34° 06′ N	56
	Salvia mellifera	black sage	118° 36′ W	56
Woolsey Canyon	*Adenostoma fasciculatum*	Chamise	34° 14′ N 118° 40′ W	56

Live fuel moisture reported on up to 56 dates was compared to NDVI and NDWI derived from a MODIS time series. MODIS data acquired from the National Aeronautics and Space Administration (NASA) Terra platform between March 2000 and November 2002 were used to construct the time series. The MODIS 500 m spatial resolution daily surface reflectance product (MOD09GHK version 4) was used to calculate the median reflectance for each band during a 10-day window. Clouds, cloud shadow, and snow were masked using the MODIS 1 km spatial resolution surface reflectance quality product (MOD09GST version 4) resampled to 500 m. The resulting 10-day reflectance composites possessed a ground sample distance of 500 m. Composites were used to calculate NDVI and NDWI using formulas (1) and (2) respectively. NDVI and NDWI values were extracted from three-by-three pixel windows for each site centred on coordinates provided by LACFD (table 1). The three-by-three windows were averaged for each site to compensate for possible errors in georectification of the MODIS products. Since actual sampling dates for each site were not published in the LACFD reports, the date of each live fuel moisture report was used to determine the composite used for comparison.

Relationships between the indices and live fuel moisture were determined using linear regression. Goodness-of-fit of the best fit line was measured using the coefficient of determination (R^2). To test whether the correlation coefficients for

NDWI were significantly higher than those for NDVI, correlation coefficients were transformed to a normalized distribution using a Fisher z-transform (Papoulis 1990):

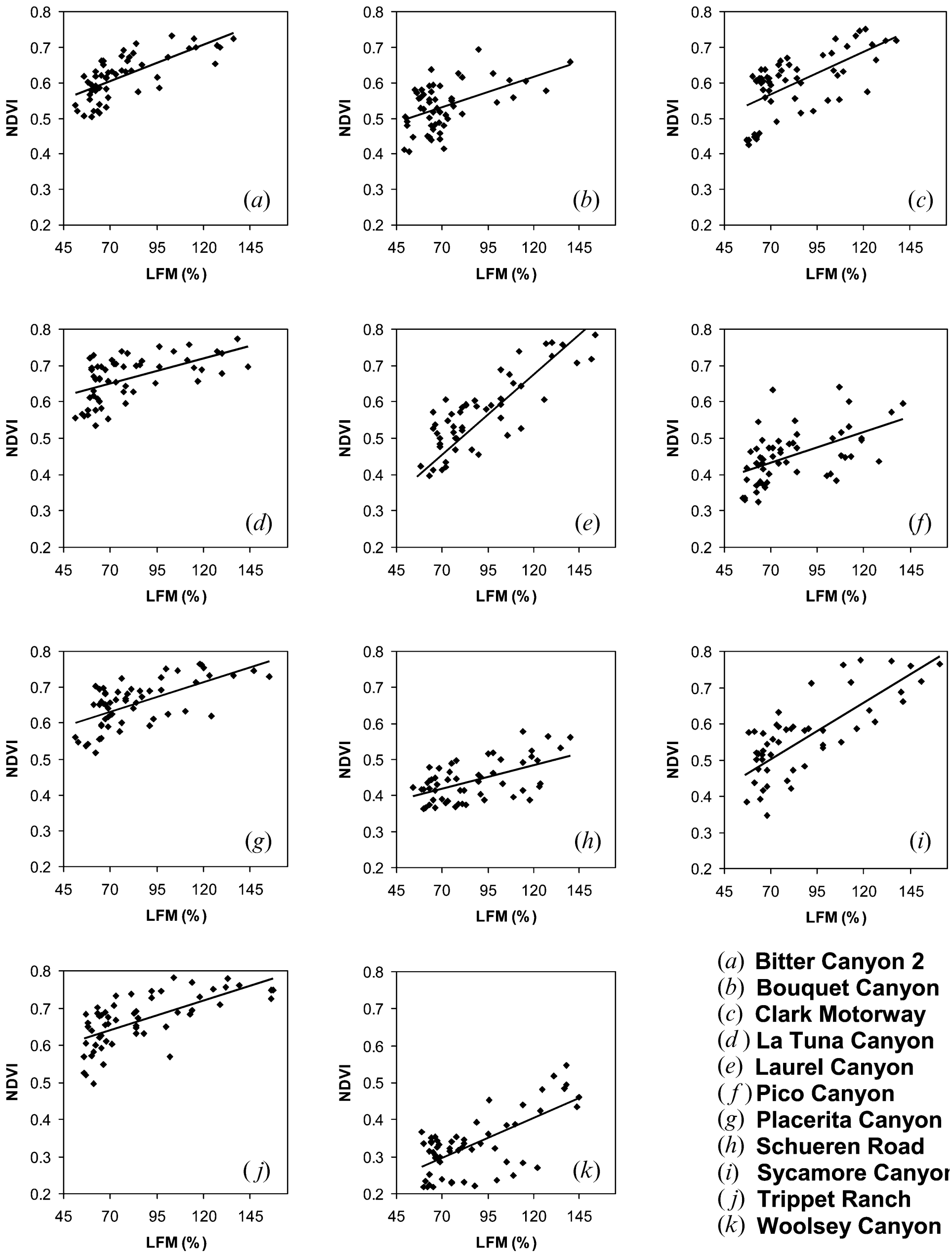

Figure 1. Plots of percentage live fuel moisture (LFM) versus NDVI for chamise (*Adenostoma fasciculatum*) at 11 sites sampled by LACFD. Each sampling date during the 2000–2002 period is represented by a point, while the lines indicate the best fit line.

Table 2. R^2, slope (m), and y-intercept (b) values for best fit linear relationships between live fuel moisture and NDVI, and between live fuel moisture and NDWI.

Site	Species	NDVI R^2	NDVI m	NDVI b	NDWI R^2	NDWI m	NDWI b
Bitter Canyon 1	California sagebrush	0.50	0.08	0.35	0.69	0.04	−0.12
Bitter Canyon 1	purple sage	0.50	0.20	0.46	0.69	0.17	−0.22
Bitter Canyon 2	chamise	0.46	0.09	0.35	0.67	0.05	−0.12
Bouquet Canyon	black sage	0.42	0.07	0.47	0.64	0.03	−0.04
Bouquet Canyon	chamise	0.25	0.17	0.41	0.43	0.08	−0.07
Clark Motorway	big pod ceanothus	0.53	0.19	0.43	0.80	0.12	−0.18
Clark Motorway	chamise	0.41	0.24	0.40	0.70	0.16	−0.20
La Tuna Canyon	chamise	0.30	0.14	0.55	0.47	0.10	−0.10
Laurel Canyon	chamise	0.60	0.44	0.15	0.72	0.17	−0.24
Pico Canyon	chamise	0.28	0.17	0.31	0.39	0.11	−0.16
Placerita Canyon	chamise	0.40	0.17	0.52	0.52	0.12	−0.17
Schueren Road	chamise	0.31	0.13	0.33	0.42	0.09	−0.13
Sycamore Canyon	chamise	0.53	0.31	0.28	0.62	0.14	−0.21
Sycamore Canyon	hoary-leaf ceanothus	0.49	0.29	0.31	0.62	0.13	−0.20
Trippet Ranch	black sage	0.44	0.05	0.59	0.52	0.04	−0.12
Trippet Ranch	chamise	0.43	0.16	0.53	0.55	0.12	−0.16
Woolsey Canyon	chamise	0.44	0.22	0.15	0.58	0.09	−0.19

$$z_f = 0.5 \ln\left(\frac{1+r}{1-r}\right) \tag{4}$$

where r is Pearson's correlation coefficient. The difference between z_f for NDWI and NDVI was calculated as (Papoulis 1990):

$$z = \frac{z_{f\mathrm{NDWI}} - z_{f\mathrm{NDVI}}}{\sqrt{\frac{1}{n_{\mathrm{NDWI}}-3} + \frac{1}{n_{\mathrm{NDVI}}-3}}} \tag{5}$$

where n is the number of samples. A one-tailed test was used to determine whether z was significantly positive to indicate a stronger correlation for NDWI than for NDVI.

3. Results and discussion

NDVI varied widely by site and by season, but in all cases NDVI was positively correlated with live fuel moisture (figure 1). Slopes of the best fit line for each site were also variable, with the steepest slopes occurring for the Laurel Canyon and Sycamore Canyon chamise samples (table 2). R^2 values ranged between 0.25 and 0.60. The Pico Canyon, La Tuna Canyon, and Schueren Road sites demonstrated low correlations between live fuel moisture and NDVI. The Pico Canyon and Schueren Road sites showed little difference in NDVI across a wide range in live fuel moisture (figure 1).

NDWI was also positively correlated with live fuel moisture (figure 2). Slopes of the best fit line were steepest for the Laurel Canyon and Clark Motorway chamise samples (table 2). Most NDWI values were slightly negative, indicating greater reflectance at longer infrared wavelengths. R^2 values ranged between 0.39 and 0.80

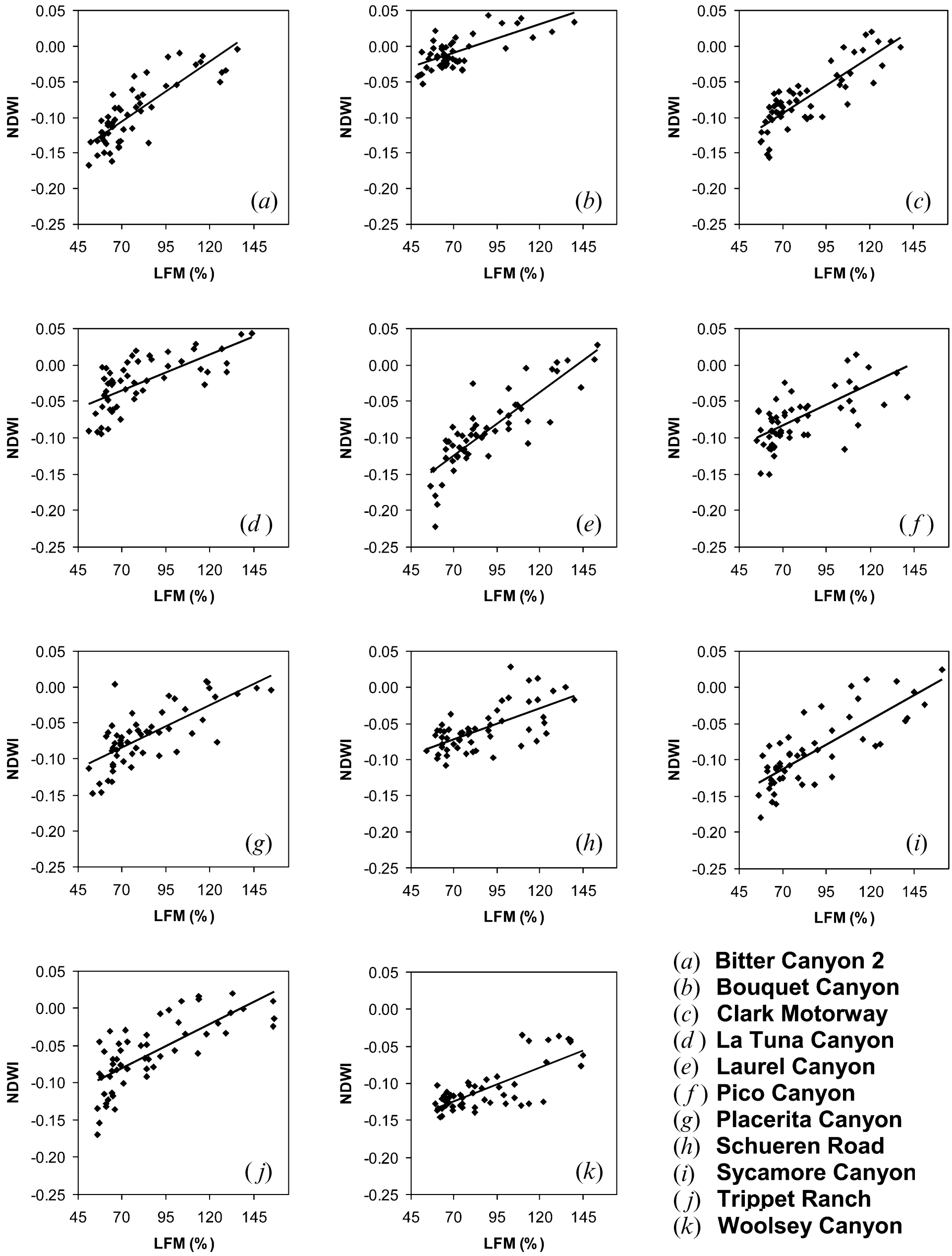

Figure 2. Plots of percentage live fuel moisture (LFM) versus NDWI for chamise (*Adenostoma fasiculatum*) at 11 sites sampled by LACFD. Each sampling date during the 2000–2002 period is represented by a point, while the lines indicate the best fit line.

(table 2). Plots of live fuel moisture versus NDWI generally demonstrated less scatter than plots of live fuel moisture versus NDVI. R^2 values were higher for NDWI for all 17 samples (table 2). NDWI correlation coefficients were found to be significantly higher than NDVI correlation coefficients. p-values ranged from less than 0.01 to 0.28, and NDWI z-scores were significantly higher for three of the 17

Table 3. z difference values for NDWI and NDVI . p-values in bold indicate a confidence level greater than 0.95.

Site	Species	$Z_{NDWI} - Z_{NDVI}$	Significance (p)
Clark Motorway	big pod ceanothus	2.76	**0.00**
Clark Motorway	chamise	2.38	**0.01**
Bitter Canyon	purple sage	1.68	**0.05**
Bouquet Canyon	black sage	1.60	0.05
Bitter Canyon	California sagebrush	1.54	0.06
Bitter Canyon	chamise	1.51	0.07
Bouquet Canyon	chamise	1.14	0.13
La Tuna Canyon	chamise	1.11	0.13
Laurel Canyon	chamise	1.09	0.14
Woolsey Canyon	chamise	1.02	0.15
Sycamore Canyon	hoary-leaf ceanothus	0.92	0.18
Placerita Canyon	chamise	0.84	0.20
Trippet Ranch	chamise	0.84	0.20
Pico Canyon	chamise	0.78	0.22
Schueren Road	chamise	0.74	0.23
Sycamore Canyon	chamise	0.66	0.26
Trippet Ranch	black sage	0.60	0.28

samples at the 95% confidence level. Statististical significance did not appear to be species dependent (table 3).

NDWI, an index based on water absorption, has a stronger statistical relationship with live fuel moisture compared to NDVI, an index based on chlorophyll absorption. The strength of the relationship between live fuel moisture and NDWI is impressive considering differences in temporal and spatial scales between live fuel moisture sampling and the MODIS composites. The actual dates of live fuel moisture sampling were not reported, but likely occurred over a period of three days, prior to the report date (J. Lopez, LACFD, personal communication, 2004). Thus it is possible that sampling occurred during a composite period previous to the one assigned based on the report date. There was a large disparity between the spatial scales of the sample site and a three-by-three window of MODIS pixels. While the actual size of the sample sites is unknown, Countryman and Dean (1979) recommended that frequently sampled sites possess a size of approximately 3–4 ha. In contrast, a single 500 m MODIS pixel contains 25 ha, within which significant variation in land cover type and topography can occur. Variation in density and type of vegetation cover within each three-by-three pixel window may be responsible for variation in the slope and intercept terms of the chamise sample sites.

NDWI derived from MODIS data has potential for seasonal monitoring of live fuel moisture. Spatial characterization of vegetation species and age may permit determination of more precise relationships between NDWI and live fuel moisture. Further investigation will be required to link NDWI to live fuel moisture in other vegetation types. NDWI may be less sensitive to moisture changes in vegetation containing small amounts of water, such as grasslands. Saturation of NDWI in vegetation containing larger amounts of water, such as forest canopies, is also unknown. In addition, further investigation of NDWI response changes in solar zenith angle and multiple scattering effects is needed.

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