Can Hyperspectral Remote Sensing Be Used to Estimate Fuel Moisture Content?

INTRODUCTION

Remote sensing is a way of measuring the world from afar, using sensors to measure electromagnetic radiation (EMR) reflecting off of materials. Electromagnetic waves can be characterized in two ways, frequency and wavelength. Frequency is the amount of times EMR waves travel from peak to peak in one second. Wavelength is the distance from peak to peak. Wavelength and frequency are inversely related and EMR with shorter wavelengths have higher energy.

EMR interacts with matter in 4 ways. Absorbance, refraction, reflectance, and scattering. Hyperspectral remote sensing measures the reflectance off matter at specific wavelengths. Different materials absorb and reflect EMR uniquely and this can be measured via their spectra. A spectra is information about the percent reflectance by wavelength (Figure1). Spectroscopy, the study of the absorption and reflectance of electromagnetic radiation by matter, can be used to detect specific absorption features within spectra due to the chemical bonds in specific molecules or elements.

One possible application of hyperspectral remote sensing is for estimating fuel moisture content (FMC). Fuel moisture content characterizes the water content within vegetation and other potential wildfire fuel. FMC is the most important factor determining the likelihood and amount of fuel available for combustion. Fire risk increases as fuel moisture declines. Fire danger rating systems used globally require FMC as a critical variable.

Previous research has demonstrated that leaf spectra carry information about fuel moisture content (Li et al, 2021, Zhang et al, 2022). Remote sensing of fuel moisture content is often based on water absorption features found in leaf spectra at 970 nm and 1240 nm (Figure1). The depth of the water absorption feature can be used to characterize FMC.

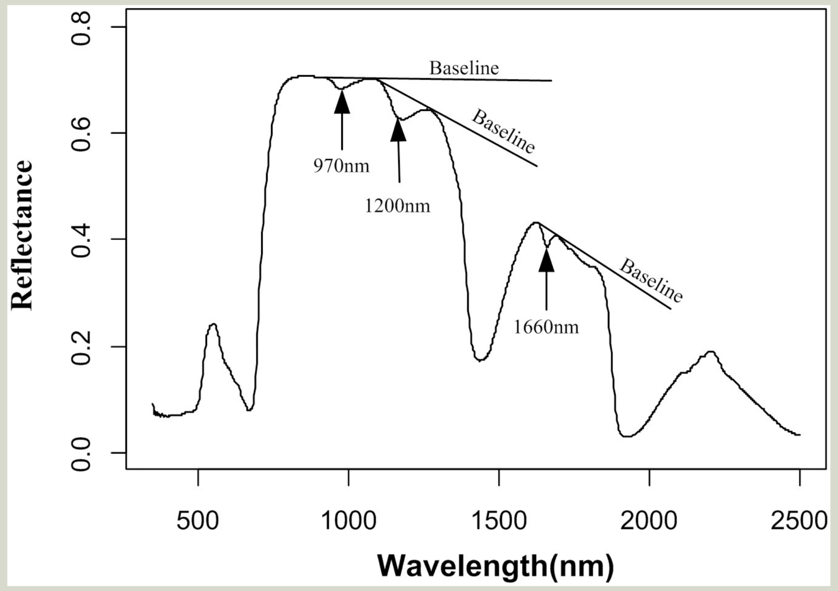

Figure 1. Reflectance spectra of a leaf between 350 and 2500 nm with examples of water absorption features at 970, 1200, 1660 nm. (Figure from: Li et al, 2021)

PURPOSE OF STUDY

The purpose of this study is to determine if spectroscopy can be used to remotely estimate fuel moisture content. Direct measurements of fuel moisture content are time consuming and require destructive sampling. Remote sensing may allow for fuel moisture content estimates to be done more efficiently and over larger areas using aerial or satellite-based sensors. FMC is an important variable for quantifying fire danger, but it is also the least well characterized. Improved fire risk ratings would allow for better wildfire management and emergency response preparedness. This project will develop a predictive model that can estimate fuel moisture content given leaf spectra.

METHODS

This study was conducted using a dry-down experiment of 5 leaves with repeated hyperspectral measurements.

Steps:

1. Set up a 250 watt halogen lamp as a light source for the experiment. Place black fabric over the work surface. Set up the fiber-optic sensor (ASD FieldSpec Spectrometer) to measure reflectance off the work surface.
2. Water plants (2 *Spathiphyllum wallisii*) plants until the soil is at field capacity. Wait 30 minutes.
3. Cut off 5 leaves randomly off the plants. Label each leaf 1 to 5.
4. Measure the leaf weight in grams.
5. Take spectral measurement of white reference panel (Spectralon) to quantify irradiance (Figure 2).
6. Take spectral measurement of leaves (Figure 2) in wavelengths between 350-2500 nm. Save the spectra for each measurement (Figure 3).
7. Dehydrate the leaves for one hour at 35° C.
8. Repeat steps 4-7 15 times.
9. Dehydrate the leaves for 6 hours at 74° C for measuring dry weight.
10. Measure the dry weight of the leaves.
11. Relative fuel moisture content (RFMC) is the ratio of the current moisture content to the maximum moisture content of a fully hydrated leaf. This was calculated using the following formula:

$$RFMC = (CW-DW)/(FW-DW)$$

Where CW = current weight (g); DW = dry weight(g); FW = fresh weight (g)

12. Water index (WI) is a spectral index that measures the depth of a water absorption feature. This was calculated with the following formula:

$$WI = \rho_{900}/\rho_{970}$$

Where ρ_{900} = reflectance at 900 nm (%); ρ_{970} = reflectance at 970 nm (%)

13. Normalized difference water index (NDWI) is another spectral index that measures the depth of a water absorption feature. This was calculated using the following formula:

$$NDWI = (\rho_{860}-\rho_{1240})/(\rho_{860}+\rho_{1240})$$

Where ρ_{860} = reflectance at 860 nm (%); ρ_{1240} = reflectance at 1240 nm (%)

14. Fit a polynomial regression model to the data using the lm function within R version 3.6.2

Note: All figures, tables, and analysis by Zealand Dobrowski using R version 3.6.2 unless otherwise noted.

ABSTRACT

This study used spectroscopy to remotely estimate fuel moisture content (FMC), a key variable used in fire danger rating systems globally. FMC characterizes the water content within vegetation and other potential wildfire fuels. This study was conducted using a dry-down experiment of 5 leaves with repeated hyperspectral measurements. During each time step of the dry-down, spectral and weight measurements were taken. The weight measurements were used to calculate FMC at each step. The spectral measurements were used to calculate spectral indices that describe the water absorptions features of the leaf spectra. I found that the spectral indices showed an asymptotic relationship with FMC. Using a regression model, I found that FMC explained 70-89% of the variance in the spectral indices. A logical next step would be to use remote estimates of FMC in natural environments to improve fire danger risk ratings.

Figure 2. Sequence of spectral measurements of white reference panel followed by paired spectral measurements of a leaf target. Photos by: Solomon Dobrowski

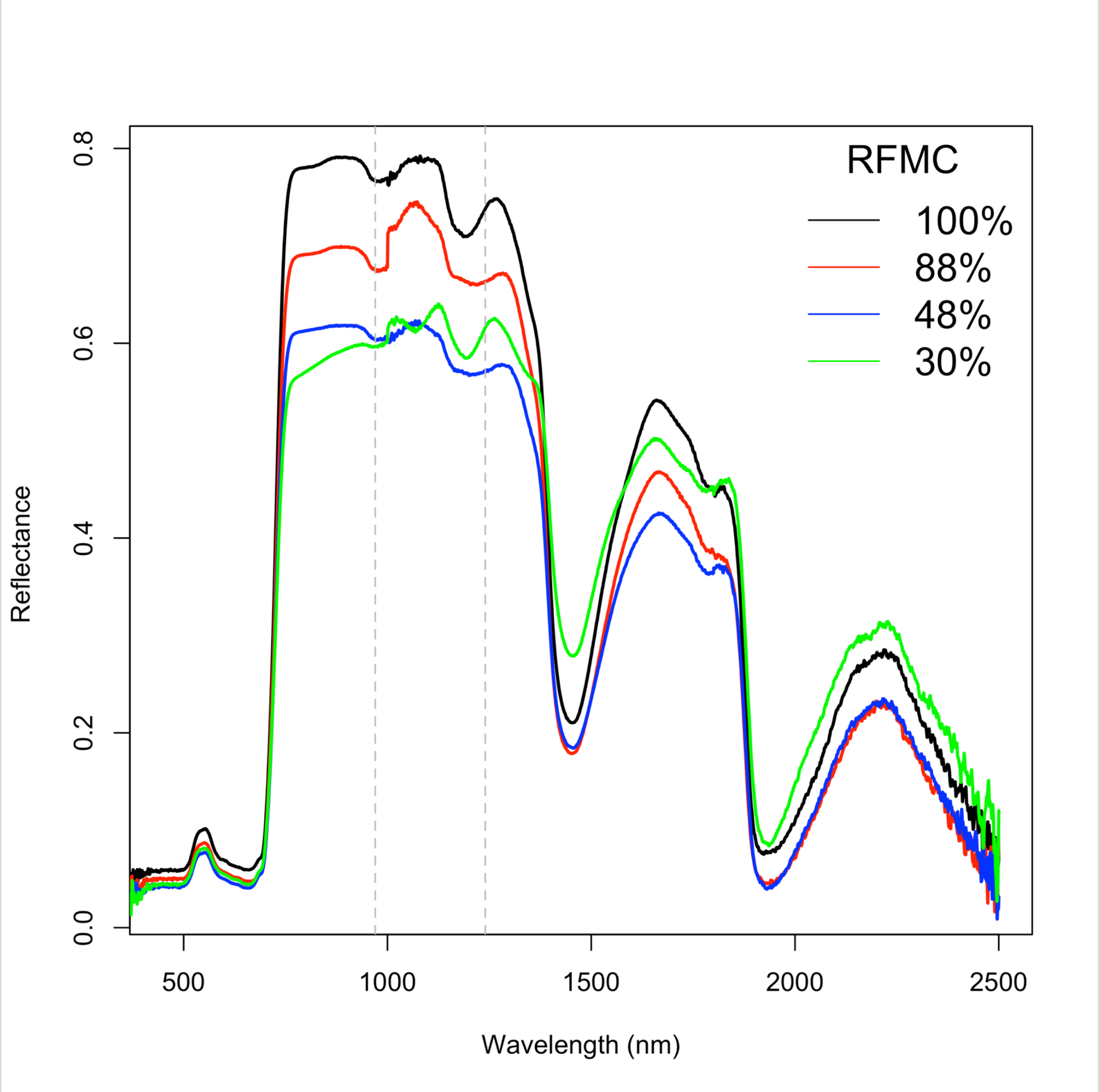

Figure 3. A subset of spectra for a single leaf taken during the experiment. RFMC = relative fuel moisture content. Dashed vertical lines depict water absorption features.

HYPOTHESIS

I expected that water index and normalized difference water index would be positively correlated with fuel moisture content because these spectral indices characterize the depth of the water absorption features within the leaf spectra.

RESULTS

The water absorption features in the leaf spectra varied by relative fuel moisture contents (Figure 3). As the relative fuel moisture content decreased, the spectral indices declined (Figure 4). However, for RFMCs above 70%, spectral indices showed little sensitivity. All 5 leaves show similar relationships as shown by similar coefficients (Table 1). Regression models fitted for WI explained on average 90% of the variance in the data. Regression models fitted for NDWI (figure not shown) explained on average 70% of the variance in the data (Table 1).

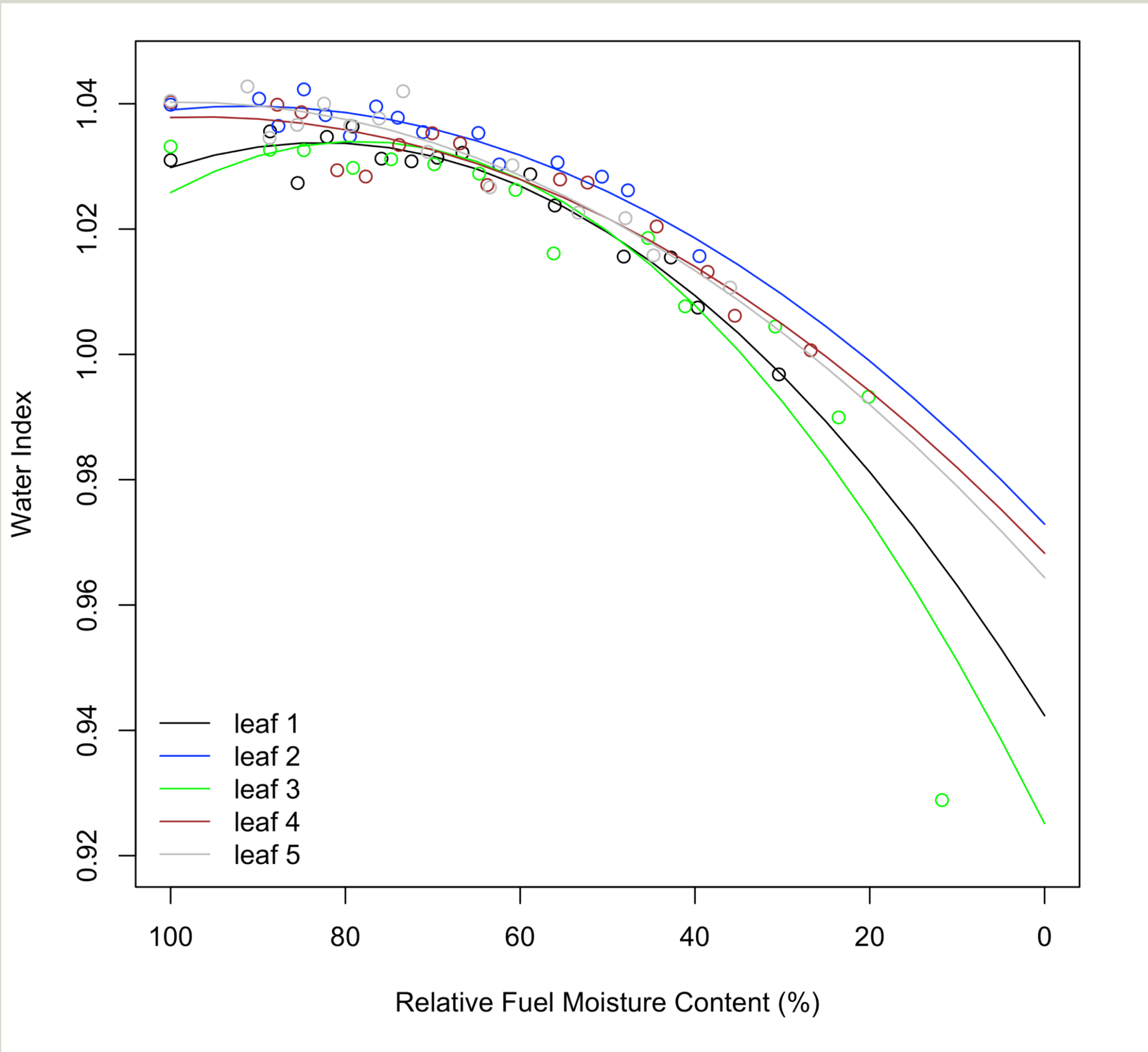

Figure 4. Water index as a function of relative fuel moisture content.

Table 1. Coefficients and model fit (R^2) for regression models relating spectral indices to leaf moisture content. Regressions take the following form: $y=\beta_0+\beta_1 x+\beta_2 x^2$.
$WI=(\rho_{900}/\rho_{970})$; $NDWI=((\rho_{860}-\rho_{1240})/(\rho_{860}+\rho_{1240}))$

Leaf #	Spectral index	β_0	β_1	β_2	R^2
1	WI	0.94	0.22	-0.13	0.94
2	WI	0.97	0.15	-0.08	0.89
3	WI	0.93	0.28	-0.18	0.84
4	WI	0.97	0.14	-0.07	0.90
5	WI	0.96	0.15	-0.08	0.90
Average		**0.95**	**0.19**	**-0.11**	**0.90**
1	NDWI	-0.12	0.45	-0.30	0.80
2	NDWI	-0.02	0.168	-0.08	0.50
3	NDWI	-0.12	0.42	-0.28	0.73
4	NDWI	-0.04	0.16	-0.07	0.77
5	NDWI	-0.05	0.20	-0.12	0.67
Average		**-0.07**	**0.28**	**-0.17**	**0.70**

DISCUSSION

Using a dry-down experiment and paired spectral measurements, I show that as RFMC declines, the spectral indices decline (Figure 4). All five leaves followed a similar pattern as shown by the regression coefficients (Table 1). The WI was more closely related to RFMC than NDWI. I used a polynomial regression model to approximate an asymptotic relationship shown by the data. These results demonstrate that spectroscopy can be used to estimate the fuel moisture content of plants.

This dry-down experiment was run in a controlled setting with one independent variable - fuel moisture content. I kept the light environment, the sensor position, and ambient conditions constant. The application of hyperspectral remote sensing in natural environments would be more challenging because of conditions that could vary. These include the light environment, weather, soil background, and the sensor angle all of which can cause variability in the EMR incident on the sensor.

Fuel moisture content is important for wildfire danger rating systems and is poorly estimated. For example, Jolly et al (2024) states that "The live fuel moisture model in USNFDRS [U.S national fire danger rating system]… has long been known to be the weakest module of the entire system… it lacks sufficient generality to be applicable to a wide range of ecosystems and it has no actual physiological foundations." Operational remote sensing of fuel moisture content would both strengthen the fuel moisture module and allow for application over a wide range of ecosystems. Applying these findings using similar models with remotely sensed data from aerial or satellite sensors would be a logical next step. For example, the recent deployment of a hyperspectral satellite-based sensor (Tanager, PlanetLabs) could allow for estimating fuel moisture content over broad scales. Wildfire managers could use fuel moisture content estimates over large areas to improve estimates of fire risk.

Estimating fuel moisture content with hyperspectral remote sensing could have societal benefits (Figure 5). Wildfires are dangerous when near populated areas and wildfire smoke affects human health. My results confirm that remote sensing can be used to estimate the fuel moisture content of leaves. Wildfire managers can use remote sensing to improve wildfire risk ratings.

Figure 5. A U.S. National Fire Danger Rating System sign near the Tamarack Fire on July 17, 2021. Photo by: Ty O'Neil / "This Is Reno" July 22, 2022

LITERATURE CITED

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