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Spectral considerations for modeling yield of canola☆

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ABSTRACT

Prominent yellow flowers that are present in a *Brassica* oilseed crop such as canola require careful consideration when selecting a spectral index for yield estimation. This study evaluated spectral indices for multispectral sensors that correlate with the seed yield of *Brassica* oilseed crops. A small-plot experiment was conducted near Adams, Oregon in which spring canola was grown under varying water regimes and nitrogen treatments to create a wide range in oilseed yield. Plot measurements consisted of canopy reflectance at flowering using a handheld spectroradiometer and seed yield at physiological maturity. Spectroradiometric measurements were converted to MODIS band equivalent reflectance. Selected indices were computed from spectra obtained with the radiometer and correlated with seed yield. A normalized difference yellowness index (NDYI), computed from the green and blue wavebands, overcame limitations of the normalized difference vegetation index (NDVI) during flowering and best modeled variability in relative yield potential. NDYI was more linear and correlated with county-wide oilseed yield data and MODIS satellite data from North Dakota ($r^2 \le 0.72$) than NDVI ($r^2 \le 0.66$). NDYI only requires wavebands in the visible region of the spectrum and can be applied to any satellite or aerial sensor that has blue and green channels. These findings highlight the benefit of using a spectral index that is sensitive to reproductive growth of vegetation instead of vegetative growth for crops with spectrally prominent reproductive canopy elements. Our results indicate that NDYI is a better indicator of yield potential than NDVI during mid-season development stages, especially peak flowering.

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1. Introduction

Remote sensing has provided a means for regional assessment of the yield of economically important crops (Doraiswamy & Cook, 1995; Groten, 1993; Maas, 1988; Tucker & Sellers, 1986) and within-field characterization of spatial differences in crop growth and development (Dalla Marta et al., 2015; Pinter et al., 2003; Yang, Everitt, & Bradford, 2006). The normalized difference vegetation index (NDVI) is the most commonly used spectral index for estimating yield from either a mid-season image or time-series of images, and has long been recognized for its value in monitoring crop conditions and forecasting crop yields (Doraiswamy, 2004; Johnson, 2014; Rouse, Haas, Schell, & Deering, 1974; Tucker, 1979).

The NDVI is theoretically an effective yield estimator because it correlates well with photosynthetic capacity (Becker-Reshef, Vermote, Lindeman, & Justice, 2010). NDVI's link to photosynthetic capacity is largely due to the use of a NIR waveband in its formulation. Within a species, NIR reflectance may positively correlate with photosynthetic potential since higher numbers of intercellular air spaces in leaf mesophyll cause more refractions and therefore increased multiple scattering. Specifically, the ratio of mesophyll cell surface area exposed to intercellular air spaces per unit leaf area corresponds to greater surface area for CO_2 diffusion into Rubisco, where carboxylation takes place (carbon fixation) (Slaton, Raymond Hunt, & Smith, 2001). In addition, low reflectance in the red waveband used in NDVI is strongly related to chlorophyll absorption, with greater absorption being proportional to higher chlorophyll content and therefore greater potential for carbon fixation since chlorophyll molecules receive internally diffused CO_2 along with water to synthesize carbohydrates. These carbohydrates are used for respiration, energy storage, and soluble photosynthate that is translocated from the leaf to other organs as plant development progresses.

NDVI is very useful for remote sensing of such crops as wheat and corn that have inconspicuous flowers and simply “green-up” and then “green-down” after entering the reproductive growth stages. However, many *Brassica* oilseeds “green-up” then “yellow-up” with the appearance of conspicuous yellow flowers and have an overlap of “yellow-down and green-down” during maturation. This spectral-temporal variability requires careful consideration when selecting a spectral index to correlate with a physiologically meaningful quantity such as seed yield. Spectral-temporal variability is a function of the morphological development of canola (*Brassica napus* L.)- an edible oilseed crop that is grown for both food and biofuel in many parts of the world. Canola undergoes three distinct canopy morphologies during development. The first is dominated by leaves, the second is characterized by yellow

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(less commonly white or beige) flower petals, and the last is mainly pods and branches. Each canopy morphology strongly influences how solar radiation is intercepted (Leach, Milford, Mullen, Scott, & Stevenson, 1989).

During the flowering stage there is reduced interception of photosynthetically active radiation (Yates & Steven, 1987). Yellow flowers contribute red light (yellow = green + red) to a canopy-level signal and this added radiation reduces NDVI values (Behrens, Müller, & Diepenbrock, 2006; Piekarczyk, 2011; Shen, Chen, Zhu, Tang, & Chen, 2009), which adversely affects the performance of NDVI to map variability in biomass (Shen, Chen, Zhu, Tang, & Chen, 2010; Sulik & Long, 2015) or yield potential. For instance, if there is a field of flowering radish, turnip, mustard, or other *Brassica* crop- any flower where there is a substantial red light component (i.e., white, red, yellow), then the red channel's value will be a combination of foliar (what NDVI is supposed to index) and floral reflectance.

The floral contribution to the reflectance is manifest most strongly in the green waveband (Sulik & Long, 2015). Yellow canola petal coloration is due to carotenoid absorption (Zhang et al., 2015) at ~450 nm. Canola petals are yellow because carotenoids in the petal absorb blue light and therefore reflect a mixture of green and red light that we perceive as yellow. Flowering canopies reflect more and absorb less between 500 nm and 700 nm (Yates & Steven, 1987), reflect less and absorb slightly more than vegetative canopies between 400 nm and 500 nm (Yates & Steven, 1987), and have little impact on the red edge or NIR (Migdall, Ohl, & Bach, 2010). Therefore, NDVI does not index solely vegetative growth during flowering.

The fact that NDVI is confounded by spectral variation of the yellow flowers in a canola canopy motivated us to implement a spectral index that is directly sensitive to variation in yellowness. It turns out that the reflection of radiation from flowers can provide us with clues about reproductive potential. The authors found that a ratio of green to blue wavebands positively correlates with the number of flowers per unit area (Sulik & Long, 2015). By directly capturing the spectral variation in yellow flower density, we are able to acquire information about the relative yield potential further into the growing season than an index that is more suitable for plant development stages that occur before reproductive growth commences. Moreover, final seed yield for canola does not solely hinge on information about photosynthetic capacity or vegetative growth potential because canola yield components are composed of more than merely the result of photosynthesis. Yield per unit area depends on stand density, the number of pods per plant, the number of seeds per pod, and seed weight (Diepenbrock, 2000). Though canola produces roughly twice as many flowers than pods, remote sensing can give us an indication of variability in future pod development by gleaning information about flower density. Flower density reflects accumulated dry matter (ADM) and leaf area index (LAI) at anthesis (Faraji, 2010), and indicates potential for pod development. For example, the number of pods and seeds generated after flowering depends on the supply of assimilates. Stocks of carbon assimilate at the onset of flower initiation, as well as shading factors, can have strong influence on flower, pod and seed number (Tayo & Morgan, 1979). Photosynthetic capacity alludes to the accumulation of carbon and nitrogen that may contribute to reproductive growth; however, those nutrients must also flow to reproductive organs. For canola, available stocks of carbon and nitrogen determine the growth of flowers and pods (Brunel-Muguet et al., 2013).

During flowering, nitrogen is mainly sourced from leaves and sunk into flowers; however, the factors that determine the efficiency of amino acid remobilization are not fully understood and may depend on canopy structural characteristics that affect leaf shading (Brunel-Muguet et al., 2013), among other things. Fortunately, the distribution and intensity of flowers reflect the ability of a canopy to translocate nitrogen and carbon to reproductive growth, which builds upon the vegetative growth accumulated as a function of photosynthetic capacity. As the number of flowers per plant increases, the number of pods increases (Faraji et al., 2008). As the number of pods increases there is more opportunity for seeds to set, barring any high stress impacts at this stage such as heat stress (Morrison, 1993) or a combination of heat and water stress (Angadi et al., 2000) and hence greater seed yield. Therefore, more flowers per unit area should correspond to more pods and therefore more seed yield.

1.1. Canola yield modeling using remote sensing

Prior remote sensing research on canola has demonstrated the importance of timing for image acquisition if estimating relationships with grain yield. It has already been established that flowers in a canola canopy are problematic for relating NDVI to yield (Basnyat, McConkey, Lafond, Moulin, & Pelcat, 2004; Piekarczyk, 2011). An important temporal finding is that the relationship between NDVI and yield declines as flowering increases (Piekarczyk, 2011); however, no spectral solution to this problem has been offered to-date. Holzapfel et al. (2009) found that NDVI data acquired between the six-leaf stage and the beginning of flowering were correlated to canola seed yield ($R^2 = 0.35$; $p < 0.001$). Optical sensing is conducted at such an early development stage in order to estimate nitrogen requirements for variable rate fertilizer recommendations before flowering and is useful for back-calculating fertilizer requirements in order to help meet yield expectations rather than for actually determining final seed yield (Holzapfel, Lafond, Brandt, May, & Johnston, 2007; Osborne, 2007).

A forecasting exercise carried out to predict final seed yield employed MODIS 10-day composite NDVI data from late July to early August in Canada (Mkhabela, Bullock, Raj, Wang, & Yang, 2011), which is typically during the flowering and grain filling period. Satellite imagery was combined with canola yield data for Census Agricultural Regions in the Canadian Prairies and resulted in very low correlations for canola, especially in semi-arid environments. However, a crop mask was not applied to the satellite sensor imagery analyzed and so the results cannot strictly be interpreted with respect to the spectral-temporal properties of canola.

Indeed, canola crop yield estimates have been reported to be too low, which may be attributed to the fact that remote sensing indices such as NDVI are intended to sense vegetative growth (Pratt, 2013). For crops like canola there is interest in the seed, which is reproductive growth. Therefore, the most proximate thing to the seed that can be remotely sensed is the flower that precedes the pods that eventually bear seed. The objective of this study was to evaluate the performance of remote sensing indices that are designed to sense reproductive growth in predicting canola yield. Results from a small plot experiment with spring canola in Oregon are presented to support the theoretical arguments outlined above. To cross-verify our biophysical theory and reinforce the findings from the small-plot study, the practical application of reproductive indices is illustrated with results from remotely sensed prediction of county-wide canola yields in North Dakota. Study sites and sensor systems are disparate with respect to geographic scale as needed to assess robustness of correlation between index values and yield at mid-season.

2. Methods

2.1. Small-plot field experiment

A two-year (2013–2014) experiment was conducted on Walla Walla silt loam soils (coarse-silty, mixed, superactive, mesic Typic Haploxerolls) at the USDA-ARS Columbia Plateau Conservation Research Center near Adams, Oregon, USA (45°43.1′ N. Lat.; −118°37.7′ W. Lon.). The study was moved to a different site before the beginning of each season. An irrigation system was used to create three distinct water regimes according to the following scheduling scheme. The high water regime applied water during the growing season to maintain soil water content at 20% on a dry-mass basis. The intermediate regime