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Evaluating multispectral remote sensing and spectral unmixing analysis for crop residue mapping

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ABSTRACT

Tillage practices can affect the long term sustainability of agricultural soils as well as a variety of soil processes that impact the environment. Crop residue retention is considered a soil conservation practice given that it reduces soil losses from water and wind erosion and promotes sequestration of carbon in the soil. Spectral unmixing estimates the fractional abundances of surface targets at a sub-pixel level and this technique could be helpful in mapping and monitoring residue cover. This study evaluated the accuracy with which spectral unmixing estimated percent crop residue cover using multispectral Landsat and SPOT data. Spectral unmixing produced crop residue estimates with root mean square errors of 17.29% and 20.74%, where errors varied based on residue type. The model performed best when estimating corn and small grain residue. Errors were higher on soybean fields, due to the lower spectral contrast between soil and soybean residue. Endmember extraction is a critical step to successful unmixing. Small gains in accuracy were achieved when using the purest crop residue- and soil-specific endmembers as inputs to the spectral unmixing model. To assist with operational implementation of crop residue monitoring, a simple endmember extraction technique is described.

1. Introduction

Tillage practices affect the long term sustainability of agricultural soils as well as a variety of soil processes that impact the environment. Tillage serves a number of purposes including preparing the soil for seeding, mitigating soil compaction, controlling weeds and incorporating fertilizers into the soil. However, tilling also disintegrates soil aggregates and reduces crop residue cover on the soil. Retention of surface crop residues is an important conservation practice as these residues protect the soil from wind and water erosion. Residues incorporated into the soil by tilling decompose more quickly. Consequently all other factors being equal, soils under no-till or conservation tillage management have higher levels of organic matter and sequester more carbon. The environmental benefits along with the savings in labour and fuel costs associated with reducing or eliminating tillage have resulted in increasing implementation of these practices. Yet growing interest in the use of crop biomass and crop residues for biofuel production may counter the benefits gained in the adoption of conservation practices (Lal & Pimentel, 2007). Consequently monitoring changes in residue management in response to policy and market influences is important.

Information on tillage activities and residue cover assists in implementing policies and programs to promote beneficial management practices (BMPs), and in monitoring the success of these initiatives. Crop residue estimates are also a critical parameter in estimating soil carbon and in modeling and monitoring improvements in carbon sequestration that follow from adjustments in land management approaches. The National Agri-environmental Health Analysis and Reporting Program (NAHARP) of Agriculture and Agri-Food Canada, Canada's agri-environmental indicator initiative, require tillage information as input to 15 of the existing 29 indicators. Since 1896, much of this information has been gathered through census surveys implemented every five years. These data are collected at the farm scale but survey results are reported in aggregate. Spatial allocation of the census data to the landscape, interpretation of census survey questions, and infrequent surveying (once every 5 years) can make it difficult to capture the spatial and temporal variability in tillage management practices (Lobb et al., 2007). Other field methods such as roadside visual surveys or line-point transects (Morrison et al., 1993) are often unable to characterize the variability of crop residue cover across an agricultural field. These methods are also tedious, time consuming and prone to human judgment errors. Rapid, accurate and objective methods to measure percent crop residue cover are thus required to meet the needs of policy, programs, land management decision-makers and carbon modelers.

With access to an increasing numbers of satellites, Earth observation can play an important role in providing residue and tillage information at spatial and temporal resolutions that support monitoring and modeling at regional and watershed scales. Several remote sensing methods have been developed to quantify percent crop residue cover, including a number of approaches that rely on

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spectral indices. Indices such as the Normalized Difference Index (McNairn & Protz, 1993), the Modified Soil Adjusted Crop Residue Index (Bannari et al., 2000) and the Cellulose Absorption Index (CAI) (Nagler et al., 2000) have demonstrated good correlations with ground residue measurements. However, these indices do not directly quantify residue cover and empirical models must be developed to relate percent cover to the index values. As with all empirical approaches, these models can lack robustness when applied temporally or spatially outside of the data upon which they are developed. In addition, indices such as the CAI require narrow bands in wavelengths currently unavailable on satellites with orbits and swaths needed for large area monitoring. Classification techniques such as linear spectral unmixing analysis provide an alternative to estimate percent crop residue cover (Arsenault & Bonn, 2005; Bannari et al., 2000, 2006; Pacheco et al., 2005; Roberts et al., 1993). Unlike residue indices, spectral unmixing analysis exploits the information from all available spectral bands to establish the contribution of crop residue and other land surface components (soil and vegetation) to total reflectance.

Spectral mixture analysis is based on the principal that reflectance recorded for each pixel within an image is a combination of the reflectance from all endmembers in that pixel (i.e. soil, vegetation, residue) (Adams et al., 1995; Smith et al., 1990). Spectral unmixing is a physical-based model that determines the relative contribution or abundance of each endmember, such as crop residue, to the total reflectance recorded for each pixel. The output of spectral unmixing is a series of fraction maps which indicate the proportion (0 to 1) of each endmember present in each pixel (Adams et al., 1995; Smith et al., 1990; Tompkins et al., 1997). Spectral unmixing analysis has typically been applied to derive the fraction of multiple endmembers using hyperspectral data (Boardman, 1995; García-Haro et al., 1999; Goetz et al., 1985; Martinez et al., 2006; Staenz, 1992). However, spectral unmixing analysis requires only that the number of spectral bands be one greater than the number of desired endmembers (Adams et al., 1995; Smith et al., 1990). This technique can in principal be applied to multispectral satellites if reflectance is being determined by only a limited number of endmembers, such as soil and residue.

Spectral unmixing analysis can be implemented to map residue cover over large geographic regions. If endmembers are retrieved directly from the image, spectral unmixing will be insensitive to variations in soil and residue spectra that may result from variable environmental conditions such as moisture levels in the soil or residue. In essence, given a representative pure endmember, spectral unmixing can be applied to imagery acquired at any spatial resolution, making this approach spatially scalable. The optimal spatial resolution will largely be governed by the size of the agricultural fields in the region under consideration. One constraint however is that both near infrared (NIR) and shortwave infra-red (SWIR) imaging bands are needed to characterize residue cover (Arsenault & Bonn, 2005; Bannari et al., 2000; Biard & Baret, 1997; Roberts et al., 1993) and thus residue estimation is dependent upon the availability of satellites with these critical bands. Elvidge (1990) noted that the spectral features of residue and soil are unique in the SWIR region due to the existence of a lignin and cellulose absorption for residue, which is absent for soils.

The objective of this study is to investigate the use of multispectral data and the spectral unmixing approach for estimating percent crop residue cover. To achieve this, various endmember extraction techniques are evaluated and remote sensing derived residue products are validated against ground measurements. The feasibility of operationalizing this crop residue mapping approach is also discussed.

2. Materials and methods

2.1. Study site

Crop residue information was collected over an agricultural site in the counties of Prescott and Russell, in Eastern Ontario (45° 28′ N, 74° 44′ W) (Fig. 1). Specifically, the study site area focused on a 20-km by 10-km area between the towns of Casselman and St. Isidore. The study site is located within the South Nation River watershed where topography is relatively flat. The cropping system consists mainly of corn, soybean, small grain (wheat and barley) and pasture-forage fields which is representative of agricultural production in this region of Canada. Producers use a variety of tillage implements including chisel ploughs, moldboard ploughs and disks, while others leave fields untilled. Producers may till up to three times between crop harvest in the fall and spring seeding. The combination of tillage implements, number of tillage passes, residue type and soil properties results in a wide range of residue levels across the study site from full residue cover to almost completely exposed soil. Agricultural fields used for this study were selected based on low topographic variability, homogeneity, size, residue type and soil texture. Surveyed agricultural fields were distributed over heavy clay, clay, loamy and sandy soils (Soil Landscapes of Canada Working Group, 2007).

2.2. Remote sensing and ground data

Multispectral image data were acquired over the 2007 fall and 2008 spring tillage seasons using the SPOT and Landsat satellite sensors. In total, four images (three SPOT and one Landsat) were acquired over the study site as described in Table 1.

Ground residue information was collected from selected fields near-coincident (within approximately 1–2 days) to optical image acquisitions. Surveyed fields were closely monitored to ensure no tillage activity occurred between ground and image data collection. Between 40 and 160 fields were surveyed for each acquisition, depending upon the availability of field resources (Table 1) and field tillage conditions. Ground observations were collected using an ArcPad® (ESRI) customized data entry sheet operated from a rugged mobile computer (Xplore Tablet PC) with a built-in GPS device. This approach greatly facilitated standardization and consistency in the ground data collection.

For each field, qualitative observations were collected of the tillage implement and tillage direction, residue type, residue position and direction, and residue height. In addition, percent crop residue cover for each field was measured over one sampling site using digital ground vertical photographs. A 100 × 75 cm quadrat was placed on the ground with its longest side positioned perpendicular to tillage direction capturing a minimum of two tillage rows. For each field, collection of quantitative data was limited to a 90 m × 90 m area in order to reduce the errors related to the variability of percent residue cover over a whole field. Five vertical photos were acquired in the 90 m × 90 m area in a cross pattern. One photo was taken in the centre of the cross with the remaining four at the appendages of the cross. The sampling sites were positioned within each field where residue conditions appeared visually homogeneous according to field visits and interpretation of previously acquired remote sensing images. The location of the sampling point at the bottom part of the cross was recorded using a Magellan GPS device (eXplorist 210) which provides positional accuracies less than or equal to 3 m.

2.3. Ground data pre-processing

To calculate percent ground residue cover, a digital grid (1 × 1 cm) was superimposed on the digital photographs. The number of grid intersections overlapping a piece of crop residue was visually counted and percent residue cover was calculated by summing the number of grid intersections falling on a piece of residue divided by the total number of intersections multiplied by 100. The estimates of ground residue cover from the five photos were then averaged to provide a single residue estimate per sampling site.