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Monitoring and verifying agricultural practices related to soil carbon sequestration with satellite imagery

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Abstract

The Kyoto Protocol entering into force on 16 February 2005 continues to spur interest in development of carbon trading mechanisms internationally and domestically. Critical to the development of a carbon trading effort is verification that carbon has been sequestered, and field level measurement of C change is likely cost prohibitive. Estimating C change based on agricultural management practices related to carbon sequestration seems more realistic, and analysis of satellite imagery could be used to monitor and verify these practices over large areas. We examined using Landsat imagery to verify crop rotations and quantify crop residue biomass in north central Montana. Field data were collected using a survey of farms. Standard classification tree analysis (CTA) and boosted classification and regression tree analysis (BCTA) were used to classify crop types. Linear regression (LM), regression tree analysis (RTA), and stochastic gradient boosting (SGB) were used to estimate crop residue. Six crop types were classified with 97% accuracy (BCTA) with class accuracies of 88–99%. Paired *t*-tests were used to compare the difference between known and predicted mean crop residue biomass. The difference between known and predicted mean residues using SGB was not different than 0 (p-value = 0.99); however root mean square error (RMSE) was large (1981 kg ha^{-1}), implying that SGB accurately predicted regional crop residue biomass but not local predictions (i.e., field or farm level). The results of this study, and previous research classifying tillage practices and estimating soil disturbance, supports using satellite imagery as an effective tool for monitoring and verifying agricultural management practices related to carbon sequestration over large areas.
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Keywords: Carbon sequestration; Crop types; Crop residue biomass; Classification and regression tree; Boosting; Landsat imagery

1. Introduction

The Kyoto Protocol (KP) entered into force on 16 February 2005 (http://unfccc.int, 22 April 2005). This event has continued interest in the development of carbon trading mechanisms. The United States chose not to participate in KP; however, the current administration has vowed to address domestic carbon dioxide emissions, and carbon trading will be a part of that effort (Pianin, 2002). Agricultural soils have the potential to sequester C from the atmosphere and help mitigate global climate change (Lal et al., 1998). Critical to the development of a carbon trading effort is verification that carbon has been sequestered. Field level measurement of C change is cost prohibitive with currently available technologies. Thus, estimating C change based on agricultural soil management practices is more feasible at this time.

Previous efforts modeling agricultural C dynamics reveal that several key agricultural practices are primarily responsible for changes in agricultural soil C (Parton et al., 1988, 1987). These practices include tillage systems, levels of soil disturbance, crops grown, including crop rotation practices, and amount of residual crop left after harvest. Satellite remote sensing has the potential to monitor and verify all of these practices over regional scales.

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Tillage disturbance has been shown to greatly influence soil C dynamics due to increased erosion and microbial decomposition (Paustian et al., 1997). The adoption of no-till (NT) can reduce losses of soil and can increase soil organic C (Lal et al., 1998). Previous studies have used remote sensing to predict tillage systems using various classification methods. Logistic regression (LR) of Landsat Enhanced Thematic Mapper Plus (ETM+) imagery had >95% accuracy in verifying NT fallow fields in a study in north central Montana (Bricklemyer et al., 2002). LR had 93% map accuracy using Landsat Thematic Mapper (TM) data in a corn/soybean rotation in Ohio (vanDeventer et al., 1997). Landsat TM and logistic regression have also been used to map tillage practices in the lower Minnesota River watershed using logistic equations developed by vanDeventer et al. (1997) and TM band 5 or the difference between TM bands 3 and 5 with 70–77% accuracy (Gowda et al., 2001). Logistic models applied to IKONOS imagery principal component (PC) 2 and PC 4 had 80 and 77% overall accuracy for discriminating corn/soybean residues and conventional/conservation tillage in Nebraska, respectively (Vina et al., 2003). Finally, the Crop Residue Index Multiband (CRIM) model using ETM+ imagery of the Minnesota River Basin, although not specifically addressing the NT/tillage question, had 79–80% accuracy classifying two categories, 0–30 and 31–100% residue cover, which were equivalent to conventional and NT management, respectively (Thoma et al., 2004). Additionally, soil disturbance has been estimated using regression tree analysis of Landsat ETM+ images (Bricklemyer et al., 2006a).

Monitoring cropping systems requires identification of various crop types. Identifying crop types and estimating yields using Landsat satellite imagery has been a focus of remote sensing experiments beginning with the Large Area Crop Inventory Experiment or LACIE in the middle 1970s (MacDonald et al., 1975). Studies subsequently have investigated improving classification methods for increasing crop type discrimination accuracy by overcoming a primary issue of separating crops. That primary issue was identified as the variability in crop maturity that can occur within a Landsat scene (Wheeler and Misra, 1980). Methods used to improve classification accuracy include the use of maximum likelihood classification (MLC) of single and multidate Landsat imagery, principal component analysis, discriminant analysis, and using active microwave response. Using an iterative MLC approach for classifying rice, maize, sorghum, and soybean, accuracy increased from 89% using single date imagery to >95% using 2 and 3 image dates (Van Niel and McVicar, 2004). Using MLC of a single date and including middle infrared bands and principal component analysis, 97% accuracy was achieved for discriminating oilseed crops from orchards, scrubs, and forest (Sharma et al., 1995). Classification of maize, durum wheat, and bread wheat using MLC and a single image date had an overall accuracy of 72% for Landsat ETM+ imagery and 81% for Earth Observing-1 Advanced Land Imager imagery (Lobell and Asner, 2003). Discriminant analysis of combined visible, near infrared, and active microwave response data had 92% accuracy for classifying corn, bare soil, bare soil + weeds, pasture, millet, weeds, and wheat stubble (Macelloni et al., 2002; Rosenthal and Blanchard, 1984). Dryland agriculture in the northern Great Plains, particularly Montana, has been a void for agricultural remote sensing research related to carbon sequestration and crop types. The diversity in crop types and seeding dates in semi-arid farming can be substantial.

Related to crop type is the amount of crop residue remaining after harvest. The Century model for agricultural C dynamics uses a crop production submodel to estimate crop biomass, yield, and residue biomass using inputs of crop type, fertilizer application, annual climatic data, and harvest practices (Parton et al., 1987). Site-specific data could be used instead of existing databases and would likely enhance the predictive capabilities of the model (Bricklemyer, 2003). Studies specifically quantifying crop residue biomass have not been documented. Previous studies, however, have successfully estimated the proportion of crop residue covering the soil using remote sensing techniques such as radar satellite data (McNairn et al., 1998), laser induced flouresence (Daughtry et al., 1996; McMurtrey et al., 1993), and Landsat TM and ETM+ (McNarin and Protz, 1993; Thoma et al., 2004; vanDeventer et al., 1997).

The overall objective of this research was to monitor and verify agricultural practices that influence soil carbon sequestration in farm fields, namely tillage systems, soil disturbance, crop types, and crop residue biomass. Tillage systems and soil disturbance have been previously addressed (Bricklemyer et al., 2006a). The present study focused on predicting crop types and estimating residue biomass. To meet these objectives we compared using: (1) classification tree analysis (CTA) and boosted classification tree analysis (BCTA) for predicting crop types and (2) linear regression (LM), regression tree analysis (RTA), and stochastic gradient boosting (SGB) for estimating crop residue biomass.

2. Methods

2.1. Study area

The study area was located in the north central Montana region known as the ‘‘Golden Triangle’’. The Golden Triangle is predominantly a dryland wheat (*Triticum aestivum* L.) production region roughly bounded by Great Falls to the south, Cut Bank to the northwest, and Havre to the northeast (Fig. 1). Spring wheat (SW), winter wheat (WW), and barley (Bly) (*Hordeum vulgare* L.) are the primary crops grown in the region with smaller acreages of lentils (Len) (*Lens culinaris* Medik). The area is semi-arid with 250–375 mm of average annual precipitation, the majority of which occurring May to mid-July.