ISPRS Journal of Photogrammetry and Remote Sensing 131 (2017) 121–133

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Multi-temporal mesoscale hyperspectral data of mixed agricultural and grassland regions for anomaly detection

Cooper McCann [a], Kevin S. Repasky [b,*], Rick Lawrence [c], Scott Powell [c]

[a] Physics Department, Barnard Hall Room 264, Montana State University, Bozeman, MT 59717, United States
[b] Electrical and Computer Engineering, Cobleigh Hall Room 610, Montana State University, Bozeman, MT 59717, United States
[c] Land Resources and Environmental Sciences, 334 Leon Johnson Hall, Montana State University, Bozeman, MT 59717, United States

ARTICLE INFO

Article history:
Received 21 April 2017
Received in revised form 28 July 2017
Accepted 31 July 2017

Keywords:
Multi-temporal
Hyperspectral
Vegetation
Mesoscale
Anomaly
Classification

ABSTRACT

Flight-based hyperspectral imaging systems have the potential to provide valuable information for ecosystem and environmental studies, as well as aid in land management and land health monitoring. This paper examines a series of images taken over the course of three years that were radiometrically referenced allowing for quantitative comparisons of changes in vegetation health and land usage. The study area is part of a geologic carbon sequestration project located in north-central Montana, approximately 580 ha in extent, at a site requiring permission from multiple land owners to access, making ground based validation difficult. Classification based on histogram splitting of the biophysically based parameters utilizing the entire three years of data is done to determine the major classes present in the data set in order to show the constancy between data sets taken over multiple years. Additionally, a method of anomaly detection for both single and multiple data sets, using Median Absolute Deviations (MADs), is presented along with a method of determining the appropriate size of area for a particular ecological system. Detection of local anomalies within a single data set is examined to determine, on a local scale, areas that are different from the surrounding area and depending on the specific MAD cutoff between 50–70% of the anomalies were located. Additionally, the detection and identification of persistent (anomalies that occur in the same location over multiple data sets) and non-persistent anomalies was qualitatively investigated.

1. Introduction

Multi-temporal imaging is a valuable tool for monitoring a multitude of changes over time from land coverage/usage change (Byrne et al., 1980; Lunetta et al., 2006; Rogan et al., 2002) to disease spread (Franke and Menz, 2007; Liangyun et al., 2004; Liu et al., 2006) to urban expansion (Gomez-Chova et al., 2006; Li and Yeh, 1988; Maktav and Erbek, 2005; Xian et al., 2008) and many others (Demirel et al., 2011; Hong et al., 2010; Travelletti et al., 2012; Tripathy et al., 1996). This technique has been driven by free access to high quality satellite data and the long time-frame of operation of these satellites, most prominently Landsat and MODIS. Multi-spectral satellites have dominated the multi-temporal field, but multi-temporal hyperspectral data would allow for further advances in the areas mentioned previously. This paper outlines two uses for multi-temporal radiometrically referenced hyperspectral data, multi-year classification and single- and multi-year anomaly detection, though the potential uses for radiometrically referenced data are extensive.

While there are several multi-temporal hyperspectral studies utilizing ground based sampling (Lausch et al., 2013; Nguyen and Lee, 2006; Strachan et al., 2002; Stuckens et al., 2011; Xie et al., 2013) this paper focuses on flight-based multi-temporal hyperspectral studies (Franke and Menz, 2007; Liu et al., 2010) of which there are limited examples especially at the mesoscale. With constantly improving technology in terms of the sensors and more advanced atmospheric models there is an ever-increasing array of problems that can be addressed by multi-temporal hyperspectral imaging. A sizable percentage of these problems will require high quality radiometrically referenced data to draw quantitative conclusions. Many multi-temporal studies rely on satellite or flight data that lacks any type of absolute calibration to surface reflectance (Conese and Maselli, 1991; Goenaga et al., 2013; Mallet et al., 2015; Petitjean et al., 2012; Yuan et al., 2015). This approach relies on unchanging atmospheric conditions and that the

* Corresponding author.
E-mail address: repasky@ece.montana.edu (K.S. Repasky).

http://dx.doi.org/10.1016/j.isprsjprs.2017.07.015
0924-2716/

calibration of the sensor is maintained, limiting the quantitative information that can be obtained.

One specific use of multi-temporal hyperspectral data is monitoring of geologic carbon sequestration sites. Geologic carbon sequestration (Li et al., 2006; Zhang et al., 2002) provides a means of capturing carbon dioxide (CO_2) (Cuffey and Vimeux, 2001; Monnin et al., 2001; Pachauri and Reisinger, 2007; Petit et al., 1999; Siegenthaler et al., 2005) at a facility such as a power plant and storing this captured CO_2 underground in geologic formations. The stored CO_2 is removed from the atmosphere providing a mitigation technique for CO_2 emission directly to the atmosphere. Successful carbon sequestration requires the development of a variety of technologies including carbon capture, understanding the storage capacity and safety of the various geologic formations (Benson et al., 2004; Cortis et al., 2008; Knauss et al., 2005; Oldenburg et al., 2009; Pruess, 2008; Wilson et al., 2007), and monitoring and verification technologies (Spangler et al., 2010; Strazisar et al., 2009) and techniques to ensure the efficacy of the carbon sequestration site. Monitoring and verification technologies need to be able to efficiently monitor the large areas associated with carbon sequestration sites, which are on the order of tens to hundreds of square kilometers (Rutqvist et al., 2010; Korbøl and Kaddour, 1995; Whittaker, 2004; Maldal and Tappel, 2004).

Airborne remote sensing is one technique proposed for monitoring the large areas associated with carbon sequestration sites. Flight based hyperspectral imaging has the potential to monitor vegetation for signs of stress that may be associated with water deficiency (Behmann et al., 2014; Dobrowski et al., 2005; Jones et al., 2004; Kim et al., 2011; Suárez et al., 2008; Tilling et al., 2007; Zhao et al., 2005), nitrogen deficiency (Strachan et al., 2002; Tilling et al., 2007; Zhao et al., 2005), and elevated CO_2 in the soil (Bateson et al., 2008; Bellante et al., 2013; Bergfeld et al., 2006; Keith et al., 2009; Maček et al., 2005; Male et al., 2010; Noomen et al., 2008; Noomen and Skidmore, 2009; Pickles and Cover, 2004), or other types of stress (Apan et al., 2004; Dobrowski et al., 2005; Smith et al., 2004; Zhang et al., 2003). Remote sensing-based surveys of carbon sequestration sites by flight based hyperspectral imaging can then be used to direct more expensive, time consuming, and resource intensive sensors (such as hand-held CO_2 sensors) to potential problem areas.

Hyperspectral imaging systems provide a reflectance spectra for each pixel in the digital image. Low-cost hyperspectral imaging systems can provide reflectance spectra in the 400–950 nm spectral range containing important spectral features associated with vegetation including the low spectral reflectance in the visible associated with absorption of the chlorophyll, the rapid rise in the reflectance spectra between 700 nm and 800 nm often referred to as the red-edge, and the high spectral reflectance in the near infra-red (IR) associated with the leafy mesophyll.

Elevated CO_2 levels in the soil can cause stress in vegetation which can manifest in changes in the spectral reflectance. Stress causes a reduction of the photosynthetic pigments which results in an increase in visible portion of the reflectance spectra (Carter et al., 1992; Knipling, 1970). Furthermore, stress affects the internal structure of plant cells that decrease the reflectance spectra in the near-IR portion of the reflectance spectra (Carter, 1991; Knipling, 1970; Li et al., 2005). Both effects could be used as an early indicator of stressed vegetation (Carter and Knapp, 2001; Luther and Carroll, 1999; Eitel et al., 2011). The changes in the reflectance spectra resulting from vegetation stress can be monitored via flight-based hyperspectral imaging. In particular, a time series of flight based hyperspectral images, either from aircraft, unmanned aerial vehicles (UAV's), or drones, will allow the monitoring of the evolution of vegetation stress over the course of a growing season and/or from year to year.

Initial experiments demonstrating the ability of hyperspectral imaging to detect stressed vegetation were conducted during controlled sub-surface release experiments at the Zero Emission Research Technology (ZERT) field site. Detecting vegetation stress using a ground based hyperspectral instrument has been demonstrated (Keith et al., 2009). Subsequent work by Bellante et al. and others (Bellante et al., 2013; Male et al., 2010; Pickles and Cover, 2004; Spangler et al., 2010), also performed at the ZERT field site, demonstrated the ability of a flight based hyperspectral imaging system to detect the evolution of the vegetation stress resulting from a sub-surface release. During this experiment, eight flights were conducted over the ZERT field sites, and data was collected over an area of approximately 1 ha. Georeferencing corrections were achieved using ground based targets that could have been used for atmospheric correction as well.

Initial demonstrations of hyperspectral imaging indicate that it is a viable method of monitoring carbon sequestration sites. Recent work (McCann et al., 2017a) has demonstrated the ability to use U.S. Geological Survey (USGS) 0.3 m resolution orthoimages for georectification and the Landsat 8 surface reflectance data product to produce radiometrically referenced large area hyperspectral images with minimal ground access. Furthermore, a method of fitting reflectance spectra with basis functions based on biophysically relevant fit parameters as a means of data and noise reduction (McCann et al., 2017a) has been demonstrated. Additionally, using these fit parameters, an unsupervised classification technique based on histogram splitting of the fit parameters has been demonstrated (McCann et al., 2017a).

This paper looks at three georectified, surface reflectance referenced data sets from hyperspectral imaging flights conducted on 06/21/2014, 06/24/2015, and 06/26/2016 at the Big Sky Carbon Sequestration Partnership (BSCSP) site in north-central Montana. This data is examined using an unsupervised classification technique based on biologically relevant fit parameters, the results are used to look at changes in land usage throughout the time series. Additionally, these clusters can be used in determining large scale management areas or as inputs to a supervised classification technique as a training data set. A method of local anomaly detection is presented using Median Absolute Deviations (MADs). These local anomalies were used as a proxy for detection of a CO_2 leaks. If CO_2 was present in the soil in higher concentrations than the surrounding area the vegetation would appear stressed and appear different spectrally and would be detected as a local anomaly. These anomalies may also be related to different levels of stress within a plant species, different species within the same area (such as weeds in an agriculture field), different land use, soil differences (such as a saline seep), etc. To better isolate local anomalies of interest multiple data sets were compared to eliminate anomalies that are present in the same location across multiple data sets. This isolates anomalies that have developed (or become more anomalous) between data sets indicating a local change that in the case of a CO_2 sequestration site might be an indicator on a leak, which would warrant further investigation.

2. Materials and methods

2.1. Study area and imaging system

The primary study area (N48°51′43″, W111°44′10″, elevation 1143 m) was located in north-central Montana at the Big Sky Carbon Sequestration Partnership demonstration shown in Fig. 1. The region of interest examined herein, the northern most region, Site C, outlined in green in the inset of Fig. 1, was approximately 580 ha, and contained regions of fallow fields, planted wheat/barley fields, grassland, arroyos, draws, and some buildings and roadways.