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Evaluation of potential of multiple endmember spectral mixture analysis (MESMA) for surface coal mining affected area mapping in different world forest ecosystems

Alfonso Fernández-Manso [a], Carmen Quintano [b,*], Dar Roberts [c]

[a] Agrarian Science and Engineering Department, University of León, 24400-Ponferrada, Spain
[b] Electronic Technology Department, University of Valladolid, 47014-Valladolid, Spain
[c] Department of Geography, University of California, Santa Barbara, CA 93106, United States

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ABSTRACT

Surface coal mining (SCM) has undergone dramatic changes in the last 30 years. Large-scale SCM practices are at the center of an environmental and legal controversy that has spawned lawsuits and major environmental investigations. SCM techniques extract multiple coal seams by removing an area of many square kilometers and creating serious environmental problems. Information about mining activities location is essential for environmental applications, specifically the temporal and spatial patterns of land cover/land use change (LCLUC). Advancements in satellite imagery analysis provide possibilities to investigate new approaches for LCLUC detection caused by SCM globally. However there is no study that analyzes the changes produced for SCM at a global scale. Our work examines three areas of coal extraction in the world: Spain, United States of America (USA), and Australia. We used Multiple Endmember Spectral Mixture Analysis (MESMA) applied to Landsat Thematic Mapper (TM) data to map SCM affected area. Endmember spectra of vegetation, soil, and impervious surfaces were collected from the Landsat TM image with the help of a fine resolution orthophotographs and the pixel purity index (PPI). Reference endmembers from an Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) spectral library were utilized as well. An unsupervised classifier was applied to the fraction images to obtain an estimation of active SCM affected area. Classification accuracy was reported using error matrixes and κ statistic using active SCM affected area perimeters digitized from fine resolution orthophotographs as reference data. In addition, we compared the accuracy of the MESMA based estimation to estimates using Spectral Mixture Analysis (SMA), and a spectral index traditionally used as Normalized Difference Vegetation Index (NDVI) testing statistical significance using a Z-test of their κ statistics. Results showed a significant improvement in the accuracy of the SCM affected area using MESMA with an average increase of the κ statistic of 31%. We conclude that MESMA-based approach is effective in mapping SCM active affected area.

1. Introduction

Mining, in general, and surface mining in particular may lead to severe environmental degradation. From an environmental point of view, surface coal mining (SCM) is a transforming activity with a high number of detrimental consequences, namely soil erosion, acid-mine drainage and increased sediment load as a result of abandoned and un-reclaimed mined lands (Parks et al., 1987). Over 6185 million tonnes (Mt) of hard coal is currently produced worldwide and 1042 Mt of brown coal/lignite. The largest coal producing countries are not confined to one region — the top five hard coal producers are China, the United States of America (USA), India, Australia and South Africa (World Coal Association, 2005). For example, surface mining accounts for around 80% of production in Australia; while in the USA it accounts for about 67% of production (International Energy Agency, 2011). These data indicate the importance of surface mining in the global production of coal.

SCM activity has important social, economic, political and environmental impacts on both local and global scale. At local scale many studies (e.g. García-Criado et al., 1999; Kennedy et al., 2003; Pond et al., 2008) have shown that coal mining activities negatively affect stream biota in nearly all parts of the globe. For example, Bernhardt and Palmer (2011) and Palmer et al. (2010) showed that the aquatic ecosystems of the Central Appalachians (USA) suffered water-quality degradation associated with acidic coal mine drainage as the sediments resulting from SCM (specifically mountain top removal), and chemical pollutants transmitted downstream through the river networks of the region. Similarly, Connor et al. (2004) showed a marked loss of biodiversity and water quality, as well as increased erosion, salinity, and siltation rates in large sections of the

* Corresponding author at: Electronic Technology Department, University of Valladolid, Industrial Engineering School (EII), C/ Francisco Mendizábal, s/n, 47014-Valladolid, Spain. Tel.: +34 983 186487; fax: +34 983 423490.
E-mail addresses: alfonso.manso@unileon.es (A. Fernández-Manso), menchu@tele.uva.es (C. Quintano), dar@geog.ucsb.edu (D. Roberts).

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Upper Hunter Valley (New South Wales, Australia). At the global scale, the cumulative effect of significantly increasing coal extraction has serious implications for global warming and climate change, regarded as the most challenging environmental issue confronting the global community in the twenty first century. Methane, an important greenhouse gas contributing to global warming (Wuebbles & Hayhoe, 2002), appears naturally during the coal extraction process. In addition, generation of electricity and heat is the largest producer of CO_2 emissions, being responsible for 41% of the world CO_2 emissions in 2009 (International Energy Agency, 2011; United States Energy Information Administration, 2011). Worldwide, this sector relies heavily on coal, the most carbon-intensive of fossil fuels, amplifying its share in global emissions. Coal is widely used as a natural fuel and provides more than half the electricity consumed in USA. Countries such as Australia, China, India, Poland and South Africa produce between 68% and 94% of their electricity and heat through the combustion of coal (International Energy Agency, 2011).

Quantification of the effects that mining activities have on ecosystems is a major issue in sustainable development and resources management (Latifovic et al., 2005). Generating an environmental database for carrying out environmental SCM impact assessment is a difficult task by conventional methods. Due to its synoptic coverage and repetitive data acquisition capabilities, remote sensing has become an effective alternative to conventional methods for monitoring SCM. Compared to other environmental land cover changes studies, such as forest fires, fewer studies (e.g. Lévesque & Staenz, 2008; Rathore & Wright, 1993; Schmidt & Glaesser, 1998; Schroeter, 2011) have evaluated the potential of remote sensing for monitoring environmental impacts in mining areas. Moreover, fewer studies have examined the use of remote sensing to map surface mines. An exception is the review by Slonecker and Benger (2002) regarding remote sensing research on surface mining. Another is a summary by Erener (2011) who provides a comprehensive list of remote sensing applications, including utility in: mapping surface mine extent through time (Prakash & Gupta, 1998; Townsend et al., 2009; Wen-bo et al., 2008); detecting and monitoring coal fires (Mansor et al., 1994; Martha et al., 2010; Voigt et al., 2004); monitoring environmental impacts of SCM (Charou et al., 2010; Haruna & Salomon, 2011; Schmidt & Glaesser, 1998); discriminating mined areas and mapping industrial open pit mines (Fernández-Manso et al., 2005; Nuray et al., 2011; Richter et al., 2008; Wright & Stow, 1999) and mapping of mine reclamation (Erener, 2011; Straker et al., 2004; Townsend et al., 2009).

Most of these studies were based on the use of Landsat Thematic Mapper (TM) data (e.g. Schmidt & Glaesser, 1998; Toren & Ünal, 2001; Townsend et al., 2009), although other data have been used. For example, Charou et al. (2010) based their study on Advanced Spaceborne Thermal Emission and Reflection (ASTER) data; Mars and Crowley (2003) mapped mines wastes using the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) imagery; and Ellis and Scott (2004) used Hymap data. Original bands and vegetation indexes have been widely used (Latifovic et al., 2005; Martha et al., 2010; Prakash & Gupta, 1998; Shank, 2008; Wen-bo et al., 2008). There are, however, some studies based on different techniques. Townsend et al. (2009) studied the changes in the extent of surface mining and reclamation in the Central Appalachians using Support Vector Machine (SVM); and Charou et al. (2010) assessed the impact of mining activities by using Artificial Neural Networks (ANN) to classify remotely sensed data. Spectral Mixture Analysis (SMA) was employed by several authors including Fernández-Manso et al. (2005), who mapped forest cover changes caused by mining activities, Lévesque and Staenz (2008) who monitored mine tailings re-vegetation using multitemporal hyperspectral image, Richter et al. (2008) who quantified the rehabilitation process in mine tailing areas and Shang et al. (2009) characterized mine tailings.

Simple SMA provides an estimate of the proportions of different basic land cover types within a mixed pixel by using a fixed suite of endmembers for the decomposition of all pixels. However, within class spectral variability, and pixel-to-pixel variability in the number of endmembers required to unmix a pixel can cause large errors in the estimated fractional cover using simple SMA. Multiple endmember SMA (MESMA) (Roberts et al., 1998) decomposes each pixel using different combinations of possible endmembers, allowing a large number of endmembers to be utilized across a scene and of the number of endmembers to vary between pixels. For a given mixed pixel, too many endmembers may overfit the data yielding an unstable solution, while too few endmembers results in large residuals with the fraction of an unmodeled component partitioned into the fraction estimate of the selected endmembers (Li et al., 2005). MESMA assumes that although an image contains a large number of spectrally distinct components, individual pixels contain a limited subset of these.

Given the advantages of MESMA over SMA, our study aims to use MESMA to map SCM affected area (SCMAA) using Landsat. We define SCMAA as the active mining area plus non-reclaimed areas. Reclaimed areas are not included in this definition of 'affected area'. We compare the accuracy of the SCMAA estimation obtained using MESMA to the accuracy of SCMAA estimation based on more traditional methods including simple SMA and spectral indexes. Statistical significance is evaluated by means of Z-test of their κ statistics. We are unaware of any study that has used MESMA to analyze SCMAA. The most similar study is by Bedini et al. (2009) who applied MESMA to Hymap imaging spectrometer data to map mineralogy in the Rodalquilar caldera (Spain). Moreover, our work has the potential to be applied to different world forest ecosystems. We consider three study areas located in three countries, the USA, Australia and Spain. Again, we could not find any study about SCMAA mapping in three different continents, so we believe that our study is the first study of this type. Specifically, the objectives of the study are: 1) to evaluate the potential of MESMA in the discriminating of mining activities using Landsat TM images; and 2) to map accurately the areas affected by SCM exploitations.

2. Materials and methods

2.1. Study areas

We performed a full analysis of the main SCM areas globally before selecting our study areas. The analysis was based on the InfoMine international data base (www.infomine.com) where mining activity is collected worldwide. The criteria used to select the study areas were to choose areas where SCM affected areas had high environmental value (mainly forests) and where environmental impacts have been greater. Additionally, we took into account the availability of cloud-free Landsat-5 TM images. We considered initially six potential study areas: El Bierzo (Castilla y León — Spain), Eastern Kentucky (USA), Upper Hunter Valley (New South Wales — Australia), Jharia (India), Seyitömer (Turkey), and Witbank (South Africa), though only the first three areas were ultimately selected: (Fig. 1, Table 1).

El Bierzo county (Spain) is in a sheltered mountain valley on the Northwestern boundary of the province of León, in the autonomous region of Castilla y León (Spain), and defined by longitude −6.64 E and latitude 42.99 N. Elevation ranges between 660 and 1900 m. Mean annual rainfall is 1500 mm and temperatures range from a summer high of 32 °C to a winter low of 1 °C with a year-round average of 10 °C (AEMET, 2011). El Bierzo has 6 mines currently in operation (3 open cut; 3 underground), and produced a total of 5 Mt of raw coal (anthracite) in 2009 (Spanish Ministry of Industry, Tourism and Business, 2009). The main vegetation cover is Atlantic oak forest (*Quercus* sp.) and scrub (*Erica* sp.).

The second study area, the Eastern Kentucky Coalfield Region, covers 31 counties with a combined land area of 35 km. It is part of