Computers and Electronics in Agriculture 108 (2014) 173–182

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Identifying representative crop rotation patterns and grassland loss in the US Western Corn Belt

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ARTICLE INFO

Article history:
Received 18 February 2014
Received in revised form 28 July 2014
Accepted 5 August 2014

Keywords:
Cropland data layer
Crop rotations
US Midwest
RECRUIT algorithm
Prairie pothole region

ABSTRACT

Crop rotations (the practice of growing crops on the same land in sequential seasons) reside at the core of agronomic management as they can influence key ecosystem services such as crop yields, carbon and nutrient cycling, soil erosion, water quality, pest and disease control. Despite the availability of the Cropland Data Layer (CDL) which provides remotely sensed data on crop type in the US on an annual basis, crop rotation patterns remain poorly mapped due to the lack of tools that allow for consistent and efficient analysis of multi-year CDLs. This study presents the Representative Crop Rotations Using Edit Distance (RECRUIT) algorithm, implemented as a Python software package, to select representative crop rotations by combining and analyzing multi-year CDLs. Using CDLs from 2010 to 2012 for 5 states in the US Midwest, we demonstrate the performance and parameter sensitivity of RECRUIT in selecting representative crop rotations that preserve crop area and capture land-use changes. Selecting only 82 representative crop rotations accounted for over 90% of the spatio-temporal variability of the more than 13,000 rotations obtained from combining the multi-year CDLs. Furthermore, the accuracy of the crop rotation product compared favorably with total state-wide planted crop area available from agricultural census data. The RECRUIT derived crop rotation product was used to detect land-use conversion from grassland to crop cultivation in a wetland dominated part of the US Midwest. Monoculture corn and monoculture soybean cropping were found to comprise the dominant land-use on the newly cultivated lands.

1. Introduction

1.1. Background

As the dominant land-use type on Earth, agro-ecosystems cover more than a third of ice-free land surface (Ramankutty et al., 2008). They have a profound impact on the environment which is manifested through global fluxes of greenhouse gases (McCarl and Schneider, 2001), soil carbon dynamics (Lal, 2004), increased surface temperature and drought conditions (Hertel et al., 2010), and provision of ecosystem services (Foley et al., 2011). Human management of these agro-ecosystems, based on economic realities and ecological conditions, can influence both the magnitude and the nature of impact on ecosystem services (Robertson et al., 2000).

A key management activity performed by farmers is the development of crop rotation plans based on economic opportunities and adapted to environmental conditions. Crop rotations have been practiced for thousands of years but crop rotations practiced today are much simpler than those practiced in the past (Bullock, 1992 and Plourde et al., 2013). Compared to a monoculture cropping system supplied with optimum nutrient levels, the practice of crop rotations usually leads to higher yields, which are mainly attributed to improved soil fertility and tilth (Hesterman et al., 1987 and Pierce and Rice, 1988), as well as enhanced pest, disease and weed control (Liebman and Dyck, 1993 and Tilman et al., 2002). When practiced together with a low-intensity tillage regime, crop rotations can potentially reduce the global warming potential of agro-ecosystems (West and Post, 2002). Conversely, the simplification of agro-ecosystems, through expansion of agricultural land supporting a single crop type is an important cause behind the decline in farmland biodiversity (Bianchi et al., 2006). Consequently, ecosystem services associated with diversified crop

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http://dx.doi.org/10.1016/j.compag.2014.08.005

rotations, like nutrient recycling, addition of organic matter and microclimate regulation have also deteriorated. Beyond their ecological importance, these ecosystem services provide other tangible benefits. For instance, the suppression of pest populations in crops by natural enemies can reduce yield loss and the need for increased use of pesticides (Landis et al., 2008; Gardiner et al., 2009 and Meehan et al., 2011), although there is uncertainty about the linkage between landscape simplification and pesticide use (Larsen, 2013).

With the advent of synthetic fertilizers and pesticides in the 1950s, use of crop rotations declined (Bullock, 1992). However, the increased intensification did not boost yields in comparison to a judicious crop rotation scheme (Mannering and Griffin, 1981). Amidst mounting concerns over the impacts of increased chemical inputs on surface and groundwater quality (Turner and Rabalais, 2003), there has been a renewed interest in crop rotations over the last couple of decades. A confluence of factors is expected to influence the crop rotation patterns and the area dedicated to crop production in the future as well. Favorable market conditions have led to an increase in corn (*Zea mays*) area nationally by almost 20% from 2006 to 2007 (Landis et al., 2008 and USDA, 2008) reaching a peak in 2010 (Plourde et al., 2013 and USDA, 2011a). A parallel development has been the availability of additional cropland for cultivation because of the decrease in the maximum area enrolled in the Conservation Reserve Program (Westcott, 2007). Farmer acceptance for using cellulosic feedstock has also grown (James et al., 2010), bringing new energy crops into the mix.

1.2. Mapping cropland areas and crop rotation patterns

The United States Department of Agriculture (USDA) tracks agricultural activity in the US at scale of individual counties as part of the census of agriculture (USDA, 2009). The analysis of these data provides valuable information on US farms, ranches and feedlots and the farmers who operate them. Due to the expensive and time consuming nature of this activity, new data are made available only once every five years. The coarse spatial resolution and sparse temporal availability precludes the derivation of fine resolution (<1 ha) annual crop production and rotation maps. The other major source of agricultural activity monitoring is the Acreage (USDA, 2011b), which aggregates crop production information from surveying nearly 3 million ha of agricultural land. While produced annually, this information is provided at the scale of US states, and is therefore unsuitable for fine resolution mapping.

Remotely-sensed data provide a way to mitigate the temporal frequency and spatial resolution limitations of ground based surveys. National scale corn and soybean (*Glycine max*) area estimates obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) data at 250 m and 500 m resolution compare favorably with the USDA's National Agricultural Statistics Service (NASS) survey based area estimates (Change et al., 2007 and Wardlow and Egbert, 2008). While the MODIS satellite follows a rapid 16-day repeat cycle and the average farm size of 175 ha (Dimitri et al., 2005) far exceeds MODIS resolution, its utility in determining crop rotations is limited because crop rotations for individual fields in a farm can vary at sub-MODIS resolutions. This limitation is even more evident when using the 1-km resolution Advanced Very High Resolution Radiometer (AVHRR) data to classify crop cover types (Jakubauskas et al., 2002). A capable alternative is the USDA NASS Cropland Data Layer (CDL) which classifies more than 100 crop types in coterminous US at a resolution of 30/56 m (Boryan et al., 2011). The oldest CDL product dates back to 1997 for North Dakota. While initially focused on the major crop producing states, the program has expanded to cover the conterminous US from 2008 onwards. The CDL has been used widely in land-cover change detection (Wright and Wimberly, 2013), watershed runoff modeling (Srinivasan et al., 2010), habitat monitoring (Meehan et al., 2010) and in process-based models for biofuel feedstock production analysis (Gelfand et al., 2013).

The simulation of biomass yields, evapotranspiration, runoff and related outcomes in a process-based model, are affected by soil properties, crop types and climatic conditions (Izaurralde et al., 2007). Therefore, it is critical to get both the spatial extent and temporal coverage of crop rotation patterns right for land-cover change analysis and ecosystem modeling. A variety of approaches have been developed to construct crop rotation patterns. These approaches fall into three categories: (a) Methods based on a mathematical framework: Crop rotations are modeled either as a transition matrix with implicit path dependency (Castellazzi et al., 2008) or are based on linear programming models (Detlefsen and Jensen, 2007). While these methods attempt to incorporate expert knowledge on suitable crop rotation patterns, they usually do not include the market drivers that influence farmer's decisions on an annual basis. Instead, they are more useful for exploratory modeling studies (Dogliotti et al., 2003). (b) Crop rotation patterns determined through consultation with field experts, USDA extension agents or from NASS survey data (Arabi et al., 2008): Unless the study area is a small farm, it is difficult to obtain spatially explicit information on land-cover and land-cover change through this approach. Therefore, approaches that rely on expert knowledge can be difficult to scale without prior information on what crop rotations are practiced in a region (Xiao et al., 2014), and are susceptible to biases or gaps in that information. (c) Crop rotation patterns determined through remotely-sensed data like CDL: While spatially explicit and generally accurate for major production crops in the US, combining multiple years of CDL to get crop rotation information results in a large number of factorial crop combinations (Stern et al., 2012). The large number of crop rotations are combined with a wide range of other input choices for chemicals and irrigation to generate management scenarios. Modeling frameworks face computational bottlenecks in efficiently simulating a large number of management scenarios. Some modeling studies try to bypass this limitation by selecting far fewer crop rotations based on their area (Srinivasan et al., 2010 and Muth et al., 2013). These studies only use a subset of all existing crop rotations and do not quantify the error introduced in the output as a result. Others greatly simplify each crop rotation pattern to focus on general trends i.e. whether the crop rotation is a monoculture or alternating (biannual, triennial, and quadrennial) in nature (Stern et al., 2012, Mehaffey et al., 2011; Secchi et al., 2011 and Plourde et al., 2013). Further, no attempt has been made in existing literature to produce a parsimonious selection of representative crop rotations for a region with area estimates comparable to NASS data.

1.3. Objectives and preview

The objectives of this research are to: (a) quantify the diversity of crop rotation patterns and (b) to examine land-cover transitions occurring in the agronomically productive and ecologically sensitive parts of the WCB. In order to achieve these objectives, we developed a novel two-parameter algorithm for identifying crop rotation patterns in the WCB during a three year period (2010–2012). We examined the tradeoff between number of representative crop rotations and accuracy by comparing estimated area against CDL and NASS crop area data. A sensitivity analysis of the algorithm parameters was conducted to assess its performance across the study region. Finally, we used the crop rotation product to estimate grassland conversion to crop cultivation in a wetland dominated part of the WCB. In summary, we examined the effectiveness of the algorithm in reducing the number of crop rotation patterns required to map and model each state by several orders of magnitude, while adequately capturing crop area and land-cover change trends.