Ecological Indicators 95 (2018) 595–605

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

Integration of historical map and aerial imagery to characterize long-term land-use change and landscape dynamics: An object-based analysis via Random Forests

Dan Liu[a], Elizabeth Toman[a], Zane Fuller[a], Gang Chen[b], Alexis Londo[a], Xuesong Zhang[c,d], Kaiguang Zhao[a,e,*]

[a] School of Environment and Natural Resources, Environmental Science Graduate Program, The Ohio State University, Columbus, OH 43210, USA
[b] Laboratory for Remote Sensing and Environmental Change, Department of Geography and Earth Sciences, University of North Carolina at Charlotte, Charlotte, NC 28223, USA
[c] Joint Global Change Research Institute, Pacific Northwest National Laboratory/University of Maryland, College Park, MD 20740, USA
[d] Earth System Sciences Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA
[e] Ohio Agricultural Research and Development Center, School of Environment and Natural Resources, The Ohio State University, Wooster, OH 44691, USA

ARTICLE INFO

Keywords:
Historical map
Ancient map
Military map
Landscape ecology
Landscape change
Environmental management
Object-based image analysis
Segmentation
Random Forests
Land-use change

ABSTRACT

Tracking Earth's past helps us to move from hindsight to foresight in seeking landscape sustainability, a pursuit aided by modern mapping capabilities but hindered by a dearth of historical landscape information. To fill the data gap and exemplify the use of old maps for land-use change sciences, we combined an old paper-based US civil war map and modern aerial photos to derive land-use history and landscape dynamics at fine scales for a region near Chancellorsville, USA, from 1867 to 2014. We also tested how advanced algorithms—object-based image analysis and Random Forests (RF)—could aid in data processing. Automatic classification of the scanned 1867 paper map proved difficult, but its manual digitization could benefit from object-based image segmentation. Classifying digital aerial images was more accurate via the object-based than pixel-based method, but only if the images were segmented appropriately. In the object-based classification, spectral-based features were much more important and useful than shape/geometry features for land-cover discrimination, as ranked by RF. During the 147 years, 32% of the region changed in land type. Settlement and roads increased in extent by 1850% and 691%, respectively, and woodland decreased by 19%. These changes fragmented the landscape, altered the hydrological regime, and affected river morphology. The utility of old maps exemplified here provides an impetus for leveraging extant old maps or historical records to support land-use and global change research. Our study also connotes the importance of preserving and geotagging current non-traditional data, such as photos, videos, and citizen science data, that can serve as a baseline to document future landscape change.

1. Introduction

The pace of contemporary global environmental change is unprecedented, driven largely by humans. Of the myriads of ways we affect Earth, land alteration stands out (Foley et al., 2005). Land-use activities often clear natural vegetation, disturb carbon pools, impair biodiversity, modify hydrology, and impact climate, among others (Bright et al., 2017; Lambin and Geist, 2008; Mahowald et al., 2017). Understanding the patterns, drivers, and impacts of landscape change, therefore, is essential to seeking solutions for landscape sustainability (Wu, 2013). Central to these pursuits are observations and technologies capable of accurately tracking where, when, and how lands have changed (Olah, 2009; Zhao et al., 2018).

Nowadays, monitoring land status is dominated by the use of spatial imaging technologies (Joshi et al., 2016). The wealth of remotely-sensed imagery captures vagaries of Earth's dynamic landscapes across spatial scales, be it a treefall, a new plantation, a wildfire, a removed dam, or an expanding city (Arnett et al., 2015; Chen et al., 2015; Gitas et al., 2014; Shalaby and Tateishi, 2007; Xiao et al., 2006; Zhou et al., 2015). Their use is helping glean insights into land-use change

* Corresponding author at: Ohio Agricultural Research and Development Center, School of Environment and Natural Resources, The Ohio State University, Wooster, OH 44691, USA.
E-mail address: zhao.1423@osu.edu (K. Zhao).

https://doi.org/10.1016/j.ecolind.2018.08.004
Received 2 April 2018; Received in revised form 13 July 2018; Accepted 2 August 2018

processes, such as the underlying socioeconomic drivers and associated climatic impacts, and inform sound decisions (Mahowald et al., 2017; Newbold et al., 2015; Zhao and Jackson, 2014). Such mapping capabilities continue to advance, enabling us to routinely observe areas as large as the globe and as fine as a tree or even finer (Congalton et al., 2014; Pu and Landry, 2012; Zhao et al., 2015). The recent opening of Landsat archives, for example, allows mapping forest loss and gain for each 30-m land pixel of the globe (Hansen et al., 2013); even more, such information can be put at our fingertips instantly through webGIS portals or digital earth platforms (e.g., Google Earth).

Accompanying the rapid growth of geospatial data is steady improvement in data analytics. For example, the set of algorithms for classifying land-cover and vegetation type has been expanding, including many machine learning tools such as Random Forests, Gaussian Processes, and Support Vector Machine (Belgiu and Drăguţ, 2016; Li et al., 2016; Zhao et al., 2011). The past two decades also saw a rise in the use of high-resolution imagery that can resolve individual spatial entities, fostering a new analysis paradigm known as object-based image analysis (OBIA) (Chen et al., 2012; Walter, 2004). Its essence is to group neighboring pixels into objects, a process aided by the development and availability of image segmentation algorithms. OBIA is not just conceptually appealing but practically powerful. Experimental evidence is accumulating to exemplify its advantages over pixel-based image classification, especially when analyzing high-resolution images with limited spectral information (e.g., three or four bands) and for heterogeneous landscapes (Blaschke, 2010). The recent surge in OBIA is attributed largely to the growing availability of software. The majority of published studies, for example, rely on eCognition, a mainstream commercial OBIA software system (Blaschke, 2010). Meanwhile, the use of OBIA still faces some practical challenges, as highlighted in a recent review by Hussain et al. (2013). Examples of questions to be further explored include how to find the optimal segmentation parameter for a given scene, how to address change detection at object levels when confronted with some inevitable sources of error, and how to leverage machine learning techniques to further improve OBIA.

Despite the well-established capabilities for mapping current land status, there is a scarcity of historical land-use/land cover data (Prestele et al., 2017). Modern remote sensing began long after World War II (Jensen, 2009). Maps of landscape composition prior to that are rare or nonexistent for large parts of the world, but historical landscape data have critical roles to play. They document past human impacts and provide clues on tackling current environmental issues, such as urban planning, food security, land policy, and climate mitigation (Lambin and Geist, 2008): A lack of data of the past makes it hard to build predictive understandings for the future. We can't observe Earth retrospectively, so all extant data can be valuable for inferring the past landscape. Goldewijk (2001) translated historical population density into global cropland distributions for the past 300 years. In the US, paper records of witness trees helped to reconstruct pre-settlement vegetation pattern (Srinath and Millington, 2016). Relicts such as stonewalls under forests aid in delimiting long-abandoned agriculture fields (Johnson and Ouimet, 2016). Other examples include the use of deeds and sale records, tax valuation, travelogue, ancient script, diary, letter, folklore, drawings, and old maps (Killeen et al., 2008; Orwig and Abrams, 1994; Ostafin et al., 2017).

Of all extant historical sources describing landscapes, old maps are of particular importance. Historical drawings or paper maps, such as topographic, cadastral, and military maps, are the only data sources that capture the past landscapes of a region in a true spatially-explicit manner. These maps sometimes are dated back several centuries and are valuable for studying long-term land-use history and vegetation dynamics. Their utility is growingly recognized; community interest in mining old maps is rising (Bičík et al., 2015). As examples, Cousins (2001) combined non-geometric historical maps with aerial photos to analyze land use/land cover change in south-east Sweden. Haase et al. (2007) analyzed multiple old topographic maps for Saxony, Germany to track landscape changes and tackle contemporary environmental issues. Fuchs (2015) incorporated historic statistics and old topographic maps into reconstructions of land cover/land use for Central Europe back to 1900.

Use of old maps to fill data gaps not just brings prospects to land change research but also presents some practical challenges. Foremost, old maps are diverse in nature and are incompatible with modern digital maps in terms of map projection, survey methods, spatial details and scales, and thematic representation (Foster, 1992; Loran et al., 2017; Petit and Lambin, 2002a; Schaffer and Levin, 2016). Most early maps are non-geometric (Cousins, 2001). Map distortion is difficult to quantify and rectify, even with many ground control points. The geometric correction may be invalid for local features, which is of no concern for coarse-level analyses but problematic for fine-scale analyses. Further, unlike remote sensing imagery that records true physical signals, old maps are secondary—sometimes, subjective—representations of spatial objects. Their interpretation needs expertise, caution, and even educated guesses. This is particularly true if metadata are lacking or information desired is rendered only implicitly in the old maps. Currently, old maps are predominantly analyzed manually (Pavelková et al., 2016). Uncertainties exist regarding how modern image analysis techniques can facilitate the information extraction from old maps. Overall, large gaps still remain in research on the integrated use of old paper maps and modern digital imagery for landscape change analysis, urging for more cases studies, especially those focusing on fine-scale landscape characterization.

This study aims to exemplify the use and value of historical map in characterizing land-use history and landscape dynamics. We conducted a case study for a region near Chancellorsville, Virginia, USA, through the combined use of an 1867 civil war map and modern aerial images. Our purpose is three-folded. First, we attempted to determine the extent to which the modern image analysis technique—object-based analysis—can improve the processing of historical map. We also examined the use of machine learning—Random Forests—in aiding in object-based classification of digital aerial images. Second, we provided fine-scale characterization and maps of land-use history from 1867 to 2014 for the region, a product not previously available for this historically important landscape. Third, we sought to demonstrate the implications of the new land change maps by explaining the patterns or drivers of the landscape dynamics and quantifying the associated consequences in terms of changes in landscape metrics as well as in river morphology.

2. Materials and methods

2.1. Study area

Our study area is a 110 km^2 region near Chancellorsville, Virginia, a place known for the Battle of Chancellorsville in 1863 (Fig. 1). Large part of it falls within Spotsylvania County, which was established in 1721. The region straddles the Piedmont Plateau and Coastal Plain physiographic provinces, with characteristic soils being strongly acidic and low in fertility. Vegetation prior to 1721 (i.e., pre-European settlement) was mixtures of deciduous forests and was believed to be disturbed by Indians to some degree through frequent burning of woodlands (Mansfield, 1977). This fire regime had favored fire-resistant oaks, leading to a climax landscape of oak-hickory forests. European settlement transformed the landscape dramatically (Orwig and Abrams, 1994). Large fractions of the forests were cleared for firewood to support iron production or for agriculture lands to produce tobacco and cotton. Poor cultivation practices soon led to severe soil erosion and eventually to agriculture abandonment. Much of the cleared lands then became recovered to forests. The modern landscape of the region has also seen rapid changes during the past few decades, attributed in part to the rise in population.