Remote Sensing of Environment 188 (2017) 164–176

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

High-resolution global maps of 21st-century annual forest loss: Independent accuracy assessment and application in a temperate forest region of Atlantic Canada

Julia Linke [a,*], Marie-Josée Fortin [a], Simon Courtenay [b], Roland Cormier [c]

[a] Landscape Ecology Laboratory, Department of Ecology & Evolutionary Biology, University of Toronto, 25 Harbord Street, Toronto, ON, M5S 3G5, Canada
[b] School of Environment, Resources and Sustainability, Canadian Rivers Institute and Canadian Water Network, University of Waterloo, 200 University Ave. W., Waterloo, ON N2L 3G1, Canada
[c] Centre for Materials and Coastal Research, Institute for Coastal Research, Helmholtz-Zentrum-Geesthacht, Max-Planck-Straβe 1, 21502 Geesthacht, Germany

ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form 30 September 2016
Accepted 28 October 2016
Available online xxxx

Keywords:
Accuracy assessment
Clear-cutting
Forest harvesting
Forest loss
Landsat
Miramichi River
Monitoring
Multi-temporal analysis
Object-based validation

ABSTRACT

Monitoring forest ecosystems requires accurate and up-to-date information on the type and extent of forest depletions, which may exist but are not always open and transparent. The ever growing, freely accessible Landsat archive provides data to derive such information; however, the manipulation of raw imagery can constitute a barrier to those lacking remote sensing expertise. The Landsat-based, global dataset of annual forest loss (version 1.0, Hansen et al., 2013) makes such information readily available. While the accuracy of this dataset has been assessed at the global scale, its applicability for reliable local monitoring of forest harvesting has not yet been validated. Here we undertake such an exercise in a temperate forest in Atlantic Canada. We used a census, polygon-based approach to comprehensively assess thematic, temporal and structural accuracy. We vectorized Hansen's forest loss raster for the 8,520 km^2 of public lands in the Miramichi River basin (13,496 km^2), which yielded 9299 polygons of 1 ha minimum size. Then we used the provincial forest harvest inventory as reference. User's and producer's accuracies were 81% and 82% based on area, and 86% and 85% based on polygon counts. Detection probability decreased with decreasing cutblock size and harvest intensity. From all Hansen polygons, 85% had the correct harvest year and 88% structurally matched one or more reference polygons either alone or together with other Hansen polygons. After the validation, we used the Hansen dataset to derive trends for the entire basin. Mean annual harvest rate was 0.92 ha/km^2/year between 2000 and 2012. Most of the catchments around the western headwaters of the Miramichi River underwent intensive harvesting, underscoring the need of further monitoring. Our results indicate that the Hansen dataset could be used as a surrogate harvest layer for temperate forests where clear-cutting is common and fire is rare.

1. Introduction

Human land use activities have become an important force for changes in forest cover (Foley et al., 2005; Lambin et al., 2001) that contribute to the rapid biodiversity decline world-wide (Butchart et al., 2010; Hansen et al., 2001). Tree cover extent (i.e., forest area) is among the biodiversity indicators proposed for monitoring conservation progress (Pereira et al., 2013; Secades et al., 2014). Furthermore, accurate and up-to-date assessments of forest area and rates of depletion are fundamental to the development of improved strategies for forest and ecosystem management (Skole et al., 1997; Townshend et al., 2011). Satellite imagery offers spatially and temporally consistent observations to derive this information from the local to global level (Hansen and Loveland, 2012; Townshend et al., 2012; Zhu et al., 2012), a role that is increasingly recognized among conservation biologists and ecologists (Buchanan et al., 2009; O'Connor et al., 2015, Pettorelli et al., 2014). The public release, free of charge, of the over 40-year old, continuously run Landsat archive (Woodcock et al., 2008) represents a tremendous opportunity for the monitoring needs of the international community (Wulder et al., 2012; Wulder et al., 2015), providing data continuity, affordability and ease of access (Leidner et al., 2012). However, manipulation of raw imagery is a barrier to the conservation and biodiversity communities, who may lack in-house expertise to process and analyze the imagery (Turner et al., 2015). The global dataset of forest change version 1.0 developed by Hansen et al. (2013), hereafter *the Hansen dataset*, takes advantage of the free Landsat archive and makes tree cover information readily available to these and other communities, including those interested in biodiversity, climate change mitigation and adaption, and sustainability issues.

* Corresponding author at: Department of Geography, University of Calgary, 2500 University Drive N.W., Calgary, AB, T2N 1N4, Canada.
E-mail address: julia.linke@ucalgary.ca (J. Linke).

http://dx.doi.org/10.1016/j.rse.2016.10.040
0034-4257/

The Hansen dataset covers latitudes between 80°N and 60°S, is distributed in granules of dimensions 10 by 10°, and consists of the following 28-m raster files (tif format): (1) percent tree cover within each pixel in the year 2000, where cover refers to canopy closure for all vegetation taller than 5 m in height; (2) forest cover loss 2000–2012, a mask of stand-replacing disturbances in that period where the remaining percent tree cover is <25% (e.g. clear-cuts, wildfires); (3) forest cover gain 2000–2012, a mask of change from non-forest to forest for that period; and (4) year of gross forest cover loss event, encoded as either 0 (no loss) or else a value in the range 1–12, representing the year when the loss was detected. Class membership (gain, loss or no-change) was derived from decision trees based on the temporal profile of spectral metrics derived from Landsat-7 ETM+ data from the growing season of the studied years. Validation was based on 1500 square blocks of 120 m side that were selected using stratified random sampling by biome and by change type (in each of the five biomes, 150 blocks for no-change, 90 for change and 60 for gain). Each block was photo-interpreted for the proportion of each change type by visualizing in Google Earth the complete time series of imagery available for that block. For forest cover loss, user's and producer's accuracies were found to exceed 80% in each biome and for the whole world. In particular, for the temperate and the boreal biomes, user's and producer's accuracies are 88% and 94% respectively.

While the Hansen dataset was validated globally, to the best of our knowledge, there is no comprehensive and independent assessment for the local utility of the annual forest loss raster (raster file #4 above) available for a particular biome, region or application. A field validation exercise was performed in western Alberta (GFWC, 2014), however, it tested only the accuracy of forest gain (raster file #3 above). In our case, we were interested to know if the annual forest loss maps could be used to reliably capture forest harvesting in temperate regions where there are no other major stand-replacing disturbances and where there is a lack of publicly available, spatially explicit information on the harvest operations. This question arose while investigating the multi-annual cumulative effects of climate change, forestry and agriculture on the aquatic systems across the many catchments of the Miramichi River basin, New Brunswick, Canada. We wanted to study varying forest harvest intensities in each catchment and analyze them by land ownership and holder of public timber license, but we were unable to obtain the required annual harvest layers for 40% of the basin that is privately owned by companies or individuals. We tackled this lack of transparency by using the governmental layers from the 60% publicly owned portion to validate the applicability of the Hansen annual forest loss map as a surrogate layer of forest harvesting.

The goal of this paper is to report on this validation exercise and to demonstrate the application of the Hansen dataset to the estimation of areal rates of harvest in temperate forests. We used a census (as opposed to a sample), polygon-based validation approach for the Hansen annual forest loss map across the 8,520 km^2 of public lands of the Miramichi basin between the years 2000 and 2012. Specifically, we (1) converted the Hansen raster to a polygon vector layer and adapted select parameters from the integrated framework for assessing the accuracy of object-based land-cover products (Castilla et al., 2012) to determine Hansen's thematic, temporal and structural accuracy; (2) assessed the impact of harvest type and block size on the probability of detection by the Hansen map; and (3) quantified and compared trends of mean annual harvest rates for the entire basin across ownership regimes, public timber management licenses and catchments over the 12-year monitoring horizon.

2. Materials and methods

2.1. Study area

Our 13,496 km^2 study area is the Miramichi River basin, which occupies about a quarter of the province of New Brunswick, Canada. The Miramichi River originates in the uplands of north-western New Brunswick at an elevation of around 470 m (Moore and Chaput, 2007), flows as an extensive network through 74 catchments, and drains over the eastern lowlands into the Northumberland Straight of the southern Gulf of St. Lawrence (Fig. 1). The basin is situated within the temperate forest biome as defined by the biome-wide forest cover loss indicator maps (Hansen et al., 2010), and is covered by the Acadian forest (Rowe, 1959) that has been shaped by commercial forest harvesting for over 200 years, with clear-cutting becoming the dominant harvesting method in the past 60 years (Loo and Ives, 2003; Aubé, 2008). While the dominant natural dynamics range between smaller gap disturbances, such as wind damage and disease, and larger forest-replacing events, such as fire and outbreaks of spruce budworm (*Choristoneura fumiferana* Clemens) (Blais, 1983; Loo and Ives, 2003), the latter have actively been controlled through fire suppression, pesticide spraying and salvage logging since the 1950s (Aubé, 2008). The Acadian forest of the Miramichi is characterized by red spruce (*Picea rubens* Sarg.), balsam fir (*Abies balsamea* (L.) Mill), yellow birch (*Betula alleghaniensis* Britt.) sugar maple (*Acer sccharum* Marsh), and declining amounts of white pine (*Pinus strobus* L.), eastern cedar (*Thuja occidentalis* L.), eastern hemlock (*Tsuga canadensis* (L.) Carrieère) and beech (*Fagus grandifolia* Ehrh.) (Rowe, 1959; Hosie, 1990; Loo and Ives, 2003; Aubé, 2008).

Although the floodplains of the basin support some agriculture, forestry and the recreational Atlantic salmon-fishing industry are the two main economical drivers of this region (Aubé, 2008; Bruce, 2010). Around 63% of the sparsely populated (<50,000 inhabitants, Statistics Canada 2016) Miramichi basin is public (8,520 km^2 so called "Crown land"), which largely overlaps with eight timber management licenses that are leased as four groups, each to a large forestry company (Fig. 1): Group I contains licenses 2,3,4 and was managed by UPM-Kymmene Miramichi Inc. between 2000 and 2010 and then by Fornebu Lumber Company Inc. from 2011; Group II contains license 5 which was managed by Weyerhaeuser Company Ltd. between 2000 and 2007, then taken over by the provincial government; group III consists of licenses 6 and 7 and was managed by J.D. Irving Ltd. continuously; and group IV is made up of licenses 9 and 10 and was managed by Fraser Paper Nexfor between 2000 and 2010, and then by Twin Rivers Paper Company from 2011. Only around 2.6% of the Miramichi Crown land is protected (i.e., 224 km^2) with restricted industrial and recreational activities (Fig. 1). In addition, 2586 km^2 of the Miramichi basin are classified as industrial freehold, that is land owned by companies, of which 89% is owned and managed by J.D. Irving Ltd.; and 2110 km^2 are zoned as private land, where land is owned by individuals (Fig. 1). The private land contains numerous, generally elongated land parcels that on average are 3 ha in size and do not exceed 320 ha. The remaining 280 km^2 of the basin consist of municipal lands with small towns and villages (Fig. 1).

2.2. Reference harvest data

We obtained from the New Brunswick Department of Natural Resources (DNR) a shapefile containing the full inventory of all polygons that were harvested on the public lands of the Miramichi basin between 2000 and 2012 (Fig. 2a). The polygon database contains the actual harvest block information recorded during the harvest operations by the license holders, whereby each polygon represents the area of a given harvest cutblock, and provides information about the year (Fig. 2b) and type of harvest. All harvest activities >1 ha on the public lands are captured in this database, and the boundaries of cutblocks are based on ground-measured GPS locations provided by the forestry operator and later corrected by DNR based on post-harvest aerial photography (Adam Dick, DNR, pers. Comm, July 12, 2016). We categorized the harvest types into two strata in addition to the conventional 'clear-cut' type (Table 1): 'select cuts', where a minimum of 70% canopy cover remains; and 'full-opening cuts', where comparatively less canopy cover remains