Remote Sensing of Environment 194 (2017) 161–176

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Global bare ground gain from 2000 to 2012 using Landsat imagery

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ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form 9 February 2017
Accepted 24 March 2017
Available online xxxx

Keywords:
Bare ground gain
Urbanization
Resource extraction
Area estimation
Uncertainty quantification
Accuracy assessment
Stratified sampling
Land cover and land use change
Landsat

ABSTRACT

Bare ground gain, or vegetative cover loss, is an important component of global land cover change resulting from economic drivers such as urbanization and resource extraction. In this study, we characterized global bare ground gain from Landsat time series. The maps were then used to stratify the globe in creating a sample-based estimate of global bare ground gain extent, land cover/land use outcomes, and associated uncertainties from 2000 to 2012. An estimated total of 93,896 km^2 ($\pm$9317 km^2 for 95% confidence interval) of bare ground gain occurred over the study period. Human-induced bare ground gain accounted for 95% of the total and consisted of the following components: 39% commercial and residential development, 23% resource extraction, 21% infrastructure development, 11% transitional, and 1% greenhouses. East Asia and the Pacific accounted for nearly half of all global bare ground gain area (45%), with China alone accounting for 35% of global gain. The United States was second to China, accounting for 17% of total bare ground gain. Land cover/land use outcomes of bare ground gain varied between regions and countries, reflecting different stages of development and the possible use of bare ground gain as an indicator of economic activity.

1. Introduction

Land cover dynamics have been recognized as a key component of global environment change (Foley et al., 2005) and an important driver to a wide range of ecological, hydrological and climatic processes (Vitousek et al., 1997). Examples include deforestation, urbanization, and agricultural expansion, among others. Each land dynamic has a unique set of socio-economic-political drivers and resulting impacts on the earth system. The complete removal of vegetation due to land use changes such as the expansion of human settlements, open pit mining and infrastructure development represents an extreme land cover transition. This dynamic, which we term bare ground gain (Hansen et al., 2014), includes all vegetation cover loss. Though the conversion of vegetation cover to bare ground cover accounts for a small proportion of global land area, it merits attention for the following reasons. First, bare ground cover is a fast growing land cover type associated with increasing population growth and urbanization. More than half of the world's 7 billion people live in urban areas with an additional 1.3 million urbanites per week (IPCC, 2015). The expected increase in urban area in the first three decades of the 21st century is projected to be greater than the cumulative urban expansion of all human history; urban area is growing on average twice as fast as urban population (IPCC, 2015). Second, bare ground gain completely alters the structure and functioning of ecosystems (Alberti, 2005; Foley et al., 2005; Vitousek et al., 1997) due to the permanent or semi-permanent removal of vegetation, resulting in lower land carbon storage (Seto et al., 2012), reduced landscape evapotranspiration (Moran et al., 1996; Shukla et al., 1990), and increased surface albedo (Bonan et al., 1992); these effects impact ecosystem functions such as biogeochemical cycling of carbon and water, energy exchange, and biodiversity (Grimm et al., 2008; Kalnay and Cai, 2003). Lastly, bare ground gain merits attention because bare ground cover exhibits complicated spatio-temporal dynamics related to variations in driving forces (Ellis and Ramankutty, 2008; Lambin et al., 2003). For example, economic, demographic and institutional factors and their interactions not only drive local expansion of residential clusters, transportation infrastructure and industrial development (Seto et al., 2012), but also influence land-use change elsewhere (DeFries et al., 2010; Geist and Lambin, 2002). An improved understanding of bare ground gain and associated drivers at a global scale can inform future climate change mitigation actions and human adaptation strategies (IPCC, 2015).

Remotely sensed airborne/satellite data have long been used for bare ground-related land cover themes (Friedl et al., 2002; Gong et al., 2013; Hansen et al., 2003, 2011; Homer et al., 2004; Loveland et al., 2000) and bare ground gain (Hansen et al., 2014) monitoring at various

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http://dx.doi.org/10.1016/j.rse.2017.03.022

spatial scales. However, definitions related to bare ground cover vary, e.g., continuous versus discrete (Hansen et al., 2003, 2011; Zhan et al., 2002), permeable versus impervious surface (Gong et al., 2013; Homer et al., 2004; Xian and Homer, 2010), natural exposed soil, rock or sand versus anthropogenic built-up environments (Friedl et al., 2002; Loveland et al., 2000). Hansen et al. (2014) featured bare ground gain in strictly cover terms (i.e., the change from vegetation to non-vegetated state) whereas other studies (Schneider, 2012; Sexton et al., 2013; Wang et al., 2010, 2012; Xian and Homer, 2010) characterized impervious surface (non-evaporating, non-transpiring imperviousness) or contiguous patches of human built-up area as an indicator of urban land use extent. Stable night light data from DMSP-OLS (the U.S. Air Force Defense Meteorological Satellite Program-Operational Linescan System sensors) and VIIRS (Visible Infrared Imaging Radiometer Suite) have been used to map the extent and growth of lighted areas associated with urban areas with limitations related to per capita energy use and satellite intercalibration (Small et al., 2005; Zhang and Seto, 2011). Land uses such as open pit mining or quarries fall outside of most natural bare land, impermeable surface or built-up land cover classification legends. In our definition, bare ground cover includes natural and anthropogenic non-vegetated land surfaces. Hence, we characterize bare ground gain as complete land conversion from vegetative cover to non-vegetative cover.

Following previous research by Hansen et al. (2003, 2011, 2014), bare ground gain is defined as a process of land cover change featuring complete or semi-permanent (at least 3 years) clearing of vegetative cover (i.e., a pixel experiences an increase in bare ground cover of over 50% or experiences a transition to 80% or greater bare ground cover) by either human or natural-induced disturbances. This land cover dynamic has the advantage of being defined without regard to land use or attributes such as imperviousness, allowing for a more efficient algorithmic implementation. As a result, a generic spectral signature of vegetated to non-vegetated state can be characterized and extended over large areas; herein, we employ 30 m spatial resolution Landsat data to map bare ground cover and bare ground gain at the global scale.

Human-induced bare ground gain is due to residential, commercial, industrial, and transportation development as well as excavation and infrastructure related to resource extraction. Naturally-induced bare ground gain results in the exposure of rubble, lava, sand bars and other features caused by, for example, landslides, volcanic eruptions, and river meanders. All human and naturally-induced bare ground gain land changes are distinct from agricultural or forestry land use practices that include ephemeral bare ground cover states. While an agricultural fallow or intensive tree harvest may in some cases result in an extended period of bare ground exposure, these cases are not included in the permanent or semi-permanent transformation of vegetated land covers to bare ground dominated land covers. We identified six bare ground gain land cover/land use outcomes, five of which are human-induced: resource extraction, infrastructure development, commercial/residential built-up, transitional bare gain and greenhouses. Natural bare ground gain dynamics were considered as a single dynamic. See Methodology Section 3.2 for the formal list of land cover/land use outcomes.

Recent developments in optical remote sensing hold tremendous promise for systematic monitoring of global bare ground cover and gain. Hansen et al. (2003) employed a regression tree model to produce the first global continuous fields of percent bare ground cover from Moderate Resolution Imaging Spectroradiometer (MODIS) data. The open access to the USGS Landsat data archive (Woodcock et al., 2008) enabled further improved thematic representation of bare ground cover and gain at Landsat-scale over the conterminous United States (CONUS) through Web-Enabled Landsat Data (WELD) (Hansen et al., 2014). Challenges to using Landsat data over large areas include unequal observation coverage due to cloud cover, scan-line corrector off (SLC-off) gaps, and variation in the number of Landsat acquisitions (Kovalskyy and Roy, 2013). Results for CONUS (Hansen et al., 2014) yielded a binary description (gain/no gain) of bare ground gain with user's and producer's accuracies of 62% and 75%, respectively, when adjacent errors were excluded. Common errors in bare ground gain for land use change mapping include commission errors over croplands with extended fallows and omission errors for developed areas within semi-arid landscapes (Hansen et al., 2014).

The study presented here characterizes bare ground gain using Landsat time-series inputs and employs the resulting maps to stratify the global land surface into areas of likely bare ground gain. A sample of over 5000 pixels was selected to assess map accuracy, estimate area of bare ground gain, and estimate the proportion of area gain attributable to different bare ground gain dynamics. Probability-based sampling methods are regularly used in forest inventories and in remote sensing applications for assessing map accuracy and estimating area (Olofsson et al., 2014). Due to inherent errors in land cover change maps derived from remotely sensed images, change areas obtained from pixel counting are likely biased (Olofsson et al., 2013). Instead, unbiased estimates of area of land cover change area may be produced using the sample and reference classification of change (Stehman, 2013). The map provides a way to target the sampling to a class of primary interest, in this case bare ground gain, via strata that provide sampling efficiencies greater than achieved by simple random or systematic approaches (Broich et al., 2009). For example, cities, towns and settlements account for < 1% of global land area (Schneider et al., 2010). Given the relative rarity of such land uses compared to the overall land surface, accurate area estimation is a challenge. Here, we are interested not only in mapping the class, but its increase over time, which is an even rarer land theme. To do so, we employ a change map of sufficient quality to construct strata that allow intensifying the sample into potential change areas. The mapped change strata serve to target the theme of interest and greatly reduce the standard error in providing unbiased estimates of change.

Another advantage of a sample based approach is the ability to determine additional contextual information such as land cover state prior to change, land use drivers and the timing of changes for the sampled pixels (Tyukavina et al., 2015). In the study of Tyukavina et al. (2015), forest cover loss was assessed, with all sample pixels interpreted for forest type (natural or managed), allowing for development of a more complete narrative of forest cover loss. We build on this approach in quantifying global bare ground gain dynamics. Specifically, we estimate the area of land converted to a non-vegetated state and attribute this dynamic to a set of bare ground gain land cover/land use outcomes.

2. Data

We employed Landsat mosaics from the research of global forest dynamics of Hansen et al. (2013) as inputs for mapping. In their study, 654,178 growing season Landsat 7 Enhanced Thematic Mapper Plus (ETM+) scenes from a total of 1.3 million stored in Google Earth Engine cloud platform were analyzed to form a global seamless composite dataset available annually from 1999 to 2012. Annual seamless composite images consist of Landsat 7 ETM+ per band median reflectance values of all cloud/shadow free growing season observations. Growing seasons were defined using MODIS phenology data and all Landsat observations processed therein. Cloud, shadow and water were screened for every pixel using a series of quality assessment models. Viable land observations were normalized to top of canopy reflectance for spectral ETM+ Red (0.631–0.692 μm), Near-Infrared (NIR 0.772–0.898 μm) and two Shortwave Infrared bands (SWIR 1.547–1.749 μm and 2.064–2.345 μm) (Potapov et al., 2012, 2015).

Two additional normalized difference band ratios were derived for their ability to facilitate the characterization of land conversion from vegetation cover to bare ground cover. Annual growing season minimum greenness (Normalized Difference Vegetation Index) values