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Landsat time series analysis for temperate forest cover change detection in the Sierra Madre Occidental, Durango, Mexico

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A R T I C L E I N F O

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A B S T R A C T

The Sierra Madre Occidental (SMO) is the longest continuous mountain complex in Mexico and is characterised by high species diversity and a high proportion of endemism. The rate of deforestation is high in Mexico, as in other megadiverse countries, and protection of the country's biodiversity is a top priority. Quantification of changes in vegetation cover is essential for this purpose. Temporal information is required to enable classification of vegetation cover and change processes. In this study, the disturbances that occurred in the temperate forest of the SMO in the State of Durango (Mexico) during the period 1986–2012 were quantified using Landsat Time Series Stacks (LTSS) and the Vegetation Change Tracker (VCT) algorithm. The results obtained confirmed that land cover changes were detected with high overall accuracy (97.6%). In order to analyze the forest losses corresponding to the only official data available in Mexico, we retrieved land use and vegetation mapping (USV) data from the Mexican National Institute of Statistics and Geography (INEGI). The aridity index was established and fragmentation analysis was carried out in the study area, showing that forest pests and forest fires were the principal disturbance events in the SMO of Durango, and that the climate greatly influenced the occurrence of disturbances. The LTSS-VCT analysis revealed that for the period 1986–2012, about 34% of the temperate forest cover in the SMO in Durango was lost due to different types of disturbance, representing an annual rate of loss of forest cover of 1.3% and affecting 32,840 ha of land per year. The trend analysis of USV data showed very similar changes to those indicated by the LTSS-VCT analysis in terms of loss of temperate forest. However, differences were observed in regards to the absolute values of forest cover and vegetation loss, with analysis of the USV data indicating forest losses of 28% due to disturbances and an annual disturbance rate of 1%, affecting 49,940 ha of land per year. The LTSS-VCT approach proved efficient for mapping data on forest disturbance acquired by a medium spatial resolution (Landsat) sensor in the SMO in the State of Durango, providing satisfactory results and at low cost.

1. Introduction

Mexico is a megadiverse country that is home to extensive forest ecosystems. It is known as one of the 12 countries that harbour more than 10% of the total biodiversity of the planet (Sarukhán et al., 2012). Moreover, some 40% of the plant species and more than 17% of vertebrate species are endemic, leading the United Nations to consider the conservation of Mexican forests a top priority (SRNyMA-CONAFOR, 2007).

Forest harvesting is an important source of income and employment; however, forest production has decreased drastically in recent years, and the forest sector has suffered severe losses, leading to the degradation of natural forest resources (SRNyMA-CONAFOR, 2007). The deforestation rate is high (Williams-Linera and Alvarez-Aquino, 2010) and Mexico is one of seven countries in which the largest annual net loss of forest area occurred between 1990 and 2010 (FAO-CONAFOR, 2009). As in other megadiverse countries, the reduction in natural biodiversity is affecting ecosystem services such as timber production. Timber production levels are not sufficient to meet the national consumption needs, mainly due to the direct relationship

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between forest degradation and rural poverty in this sector and to the pressure due to gradual overexploitation, which has led to deforestation and soil degradation (SEMARNAT-CONAFOR, 2001a, b; SEMARNAT, 2013). Forest fires, changes in land use, intensive grazing and clandestine felling have also led to deterioration of the forests (SARH, 1994). Deforestation and degradation of forest lead to carbon release, thus minimizing the potential of Mexican ecosystems for carbon capture and hampering conservation of the resources and the search for other forms of income for the inhabitants of forest areas (FAO-CONAFOR, 2009).

Since 2000, Mexico has created diverse programs for the sustainable development of the forest sector in relation to climate change, deforestation and biodiversity, including The Climate Change Law (Ley General de Cambio Climático, 2012) and the Strategic Forest Plan for Mexico 2025 (*Programa Estratégico Forestal para México 2025*), which recognises the difficulty in quantifying the extent of deforestation, mainly due to the lack of reliable methods of estimating deforestation rates. The program also highlights the need to strengthen national forestry information systems, to make them reliable, transparent and helpful for decision-making in the sector (Lal, 2001). Studies of forest disturbance are therefore important and necessary in Mexico.

Forest disturbance (caused by e.g. insects, fire, cultivation, extraction of resources, and anthropogenic activities associated with settlement) and post-disturbance recovery are key processes in the development of forest ecosystems. These processes influence biomass level, biogeochemical cycling, productivity and resource availability across a broad range of spatial and temporal dimensions (Peterken, 2001; Hilker et al., 2009). Understanding the temporal and spatial aspects of these processes is crucial for modelling ecosystem characteristics, as well as for detecting changes in the terrestrial carbon cycle and mapping the quality and abundance of wildlife habitats (Hirsch et al., 2004; Law et al., 2004).

Ground-based measurements can provide accurate information on forest and biomass (Lopez-Serrano et al., 2016a, 2016b, 2016c, 2016d; Molinier et al., 2016; Lopez-Sanchez et al., 2017; Vargas-Larreta et al., 2017), but lack the spatial and temporal coverage capacity of remote sensing imagery. Remote sensing is well suited to monitoring land cover change, and a myriad of approaches have been developed for this purpose (Coppin et al., 2004; Hussain et al., 2013; Lu et al., 2004; SINGH, 1989; Tewkesbury et al., 2015).

Temporal information is essential for classifying vegetation cover and change processes (Stibig et al., 2014; Zhu and Woodcock, 2014; White et al., 2017). Time series of medium spatial resolution optical data have been shown to be capable of characterizing environmental phenomena, describing trends as well as discrete change events (Gomez et al., 2016). This type of data has been used to map forest disturbance (Kennedy et al., 2010) and surface water bodies (Tulbure and Broich, 2013), to characterize land cover change (Zhu and Woodcock, 2014), to identify the nature of land cover changes (Olthof and Fraser, 2014), and to model and estimate ecosystem structural variables, aboveground biomass (Gomez et al., 2014; Main-Knorn et al., 2013; Deo et al., 2017a,b), forest carbon sinks (Gomez et al., 2012), forest degradation (Shimabukuro et al., 2014) and forest disturbance (Schroeder et al., 2014). Strategies have been developed to deal with irregular and sparse time series of data (Gomez et al., 2011), and annual-time series have been found to be most appropriate for extracting information from vegetated ecosystems (Gomez et al., 2016; Zhu, 2017).

Many approaches to detecting change have been proposed in recent years, with the aim of improving the detection of forest disturbances from Landsat images (Hilker et al., 2009; Zhu et al., 2012; Verbesselt et al., 2012; Zhu et al., 2012; Xin et al., 2013; Reiche et al., 2015; Hamunyela et al., 2016; Hansen et al., 2016). Landsat Time Series Stacks (LTSS) provide a unique source of information for reconstructing forest disturbance history in many areas of the world. These collections can be analysed in order to document forest change, while the spatial resolution of the images from Landsat sensors provides the spatial details needed to classify many of the changes due to both natural and anthropogenic disturbance (Townshend and Justice, 1988).

Change detection methods based on annual Landsat time series (i.e. trajectory-based change detection methods) such as the Breaks For Additive Season and Trend (BFAST; Verbesselt et al., 2010), Continuous Change Detection and Classification (CCDC) (Zhu and Woodcock, 2014), Landsat-based detection of Trends in Disturbance and Recovery (LandTrendr by Kennedy et al., 2010) and the Vegetation Change Tracker (VCT) (Huang et al., 2010) make better use of the temporal depth of the Landsat archive to reconstruct forest disturbance histories with annual resolution and trends, such as forest regeneration and succession. The VCT has been used extensively to map forest disturbances in previous studies (Verbesselt et al., 2010; Masek et al., 2013). VCT is a change detection algorithm based on the spectral–temporal characteristics of land cover and forest change processes using LTSS (Zhao et al., 2015).

The State of Durango (with a forest area of about 4,900,000 ha) is the most important state in Mexico as regards the extent and economic value of its forest resources. Timber resources in the State of Durango amount to about one-quarter of the national resources of Mexico (SRNyMA, 2002; Wehenkel et al., 2011). Despite the economic importance of the Durango forests (SEMARNAT, 2013), multitemporal analysis of forest cover change has not yet been conducted. The objective of the present study was therefore to generate reliable information about the changes in forest cover in the state, thus contributing to the above-cited objectives of Mexican forest policies.

The overall aim of the study was to use LTSS and the VCT algorithm (Huang et al., 2010) to map the changes in forest cover in SMO in the State of Durango (Mexico) that occurred between 1986 and 2012, and to compare the results with those estimated by the INEGI's land use and vegetation maps (INEGI, 2013), the only official data source available in Mexico to characterize forest loss. The relevance of this study lies in the need to provide quality information for the monitoring disturbance trends in areas of particular importance for biodiversity and ecosystem services, in order to promote the implementation of reforestation programmes and policies that contribute to mitigating the effects of climate change.

2. Materials and Methods

2.1. Study area

The study area is part of the Sierra Madre Occidental (SMO) mountain range that runs through the State of Durango (Fig. 1), one of the main timber supplying regions in Mexico. The SMO is the longest continuous mountain complex in Mexico, extending from close to the US border to the north of Jalisco. It is of great economic and environmental value, partly because of the high diversity of species and the high proportion of endemism that it harbours. It is also an important biological corridor for boreal and tropical mountain species, as it is linked to the Colorado Plains and the Rocky Mountains to the north and connects to the south with the Trans-Mexican Volcanic Belt (González-Elizondo et al., 2012). Pine-oak forests harbour the highest level of floristic diversity in Mexico (Rzedowski, 1978), and this region is home to the greatest diversity of pines, oaks and strawberry trees worldwide (González-Elizondo et al., 2012).

The State of Durango occupies an area of 12.3 million hectares (6.3% of the total surface area of Mexico), and the forested area covers around 9.1 million hectares totalling 74.35% of the surface area of the state (Diario Oficial de la Federación, 2017), occupying 4th position as regards the national forest area. Some 44.67% of the area is occupied by temperate forests and rainforests, covering an area of 5.4 million hectares. The total afforested area of 4.9 million hectares (40.64% of the surface area of the state corresponds to temperate-cold forest and 495,020 ha (4.03% of the surface area of the state) to tropical rainforest (SRNyMA-CONAFOR, 2007), with arid zones, hydrophilous and