CrossMark

ORIGINAL ARTICLE

Attributing changes in land cover using independent disturbance datasets: a case study of the Yucatan Peninsula, Mexico

Vanessa S. Mascorro · Nicholas C. Coops ·
Werner A. Kurz · Marcela Olguín

Abstract Detailed observations of natural and anthropogenic disturbance events that impact forest structure and the distribution of carbon are essential to estimate changes in terrestrial carbon pools and the associated emissions and removals of greenhouse gasses. Recent advances in remote sensing approaches have resulted in annual and decadal estimates of land-cover change derived from observations using broad-scale moderate resolution imaging spectroradiometer (MODIS) 250 m–1 km imagery. These land-use change estimates, however, are often not attributed directly to a cause or activity and are not well validated, especially in tropical areas. Knowledge of the type of disturbance that caused the observed land-cover changes is important, however, for the quantification of the associated impacts on ecosystem carbon stocks and fluxes. In this paper, we provide estimates of the amount of forest land-cover change in a Mexican forested region and propose an approach for attributing the cause of the observed changes to the underlying disturbance driver. To do so, we collate geospatial and remote sensing data from a variety of sources to summarize statistics about the major disturbances within the Yucatan Peninsula, an "early action" region for the reduction of emissions from deforestation and degradation, from 2005 to 2010. We combine the datasets to develop rules to estimate the likely disturbances that caused the observed land-cover changes based on their spatially explicit location. Finally, we compare our observed disturbance rates to those detected using classified land-cover data derived from MODIS.

Editor: Erica Smithwick.

V. S. Mascorro (✉) · N. C. Coops
Department of Forest Resources Management, Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada
e-mail: vanessa.mascorro@alumni.ubc.ca

N. C. Coops
e-mail: nicholas.coops@ubc.ca

W. A. Kurz
Canadian Forest Service, Natural Resources Canada, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada
e-mail: Werner.Kurz@NRCan.gc.ca

M. Olguín
Proyecto Mexico-Noruega, Comision Nacional Forestal, Col. del Carmen Coyoacán, CP 04100 Coyoacán, D.F., Mexico
e-mail: olguin.conafor@gmail.com

Introduction

Forested ecosystems are valuable, not only for ecosystem services provisioning (MEA 2005) and biodiversity conservation (Díaz et al. 2009), but also for their crucial role to mitigate climate change (Bosworth et al. 2008; Turner 2010; Kurz et al. 2009). Globally, forests contain one of the largest carbon sinks in the world (2.4 Pg C year^{-1}) (Pan et al. 2011). They have the ability to offset increasing atmospheric carbon (C) concentrations by sequestering large amounts of carbon and storing it in the vegetation and soils for long periods of time (Bosworth et al. 2008; Chapin et al. 2009; Kurz et al. 2009; Lorenz and Lal 2010). Hence, sustainable management of forested ecosystems is critical for both developed and developing countries to reduce net global carbon emissions and stabilize atmospheric carbon dioxide

concentrations to avoid "dangerous anthropogenic interference with the climate system" (UNFCCC 1992).

Forest disturbances play a critical role in the terrestrial carbon cycle. Natural and human-induced disturbances alter forest structure in a unique way, changing the size, composition and distribution of forest carbon pools, and transfer carbon into the atmosphere (Dale et al. 2001; Kurz et al. 2009; Spalding 2009; Lorenz and Lal 2010). They modify the stand age and succession dynamics, affecting the post-disturbance carbon dynamics (i.e., the living biomass and dead organic matter turnover rates, carbon emissions, and the rate of annual carbon storage) (Franklin et al. 2007; Lorenz and Lal 2010). After the burning of fossil fuels, permanent conversion of forested land to other land uses together with forest degradation are the second major cause of carbon emissions (DeFries et al. 2002; IPCC 2007; Spalding 2009; Houghton et al. 2012).

Based on the amount of vegetation removed, disturbances can be categorized as stand replacing or non-stand replacing (Oliver and Larson 1996). Stand-replacing disturbances, such as wildfires and land clearing for agricultural purposes, generally result in severe alteration or removal of the forest structure, killing or removing all the trees (Franklin et al. 2007). In the case of fire, significant amounts of carbon are transferred into the atmosphere from the combustion of biomass and dead organic matter, bringing the forest back to the initiation stage (Lorenz and Lal 2010). In this stage, the forest is a net carbon source because carbon emissions from dead organic matter and soil carbon pools exceed removals of the vegetation regeneration. Eventually, depending on the degree and speed of regrowth, the net carbon balance becomes positive once again and the forest becomes a carbon sink (see Fig. 1 in Kurz et al. 2013). Non-stand-replacing or minor disturbances (e.g., low-intensity fires, low-level insect, disease infestations, or selective logging) affect forested landscapes at a finer spatial scale, damaging or killing individual trees, or small groups of trees, reducing the overall forest productivity and growth, and thus carbon uptake.

Measuring and monitoring forest carbon stocks and stock changes remain a complex endeavor accompanied by high uncertainties (Chapin et al. 2006; Spalding 2009). Despite increasing efforts to assess gross forest cover loss at different spatial and temporal scales, attributing the forest cover loss to clear underlying causes remains an important challenge for carbon and ecosystem monitoring (DeFries et al. 2007; Hansen et al. 2010; Houghton et al. 2012; Potter et al. 2012). Until these causes and drivers of natural and human-induced forest cover change and the subsequent forest recovery and succession dynamics are understood, we cannot fully quantify specific contributions to the carbon balance (Spalding 2009; Kurz 2010; Masek et al. 2011; Schroeder et al. 2011). Knowledge of forest disturbance types is required to estimate

impacts on carbon stock changes and the associated greenhouse gas (GHG) emissions (Kurz et al. 2009; Spalding 2009). For example, land clearing with or without fire is associated with differences in the amounts, timing, and composition of CO_2 and non-CO_2 GHG emissions.

In Mexico, the government is conducting several initiatives to develop science-based decision support models and tools to improve ecosystem carbon reporting and to provide policy makers with information on the consequences of reducing emissions from deforestation and forest degradation (REDD+) strategies (SEMARNAT 2009; LGCC 2012). This includes a monitoring, reporting and verification (MRV) system for REDD+.

To fulfill Mexico's needs to meet numerous national and international commitments to reduce GHG emissions, quantifying forest disturbances is required by disturbance type. Current knowledge of the extent and impact of different disturbance types has serious gaps that can potentially be addressed using remote sensing land-cover change products (Coops et al. 2006; De Sy et al. 2012; Hayes and Cohen 2007; Hansen et al. 2008; Potapov et al. 2008; Wulder et al. 2010).

In this study, we developed a comprehensive approach, the multi-scale, multi-source disturbance (MS-D) assessment, to (1) spatially characterize type, extent, and location of major disturbances (natural and anthropogenic) for carbon modeling, (2) obtain land-cover change observations, and (3) attribute land-cover changes to their most likely disturbance driver. We first provide a brief background of the forest disturbances most likely to occur within Mexican forested ecosystems. Based on this review, we focus on dominant disturbance types, namely fires, hurricanes, settlement, harvesting, and agricultural activity. Annual spatially explicit layers were generated for major disturbance types from 2005 to 2010 for carbon modeling across the Yucatan Peninsula. Land-cover changes were then derived from moderate resolution imaging spectroradiometer (MODIS) satellite imagery from 2005 to 2010 and attributed by disturbance type. Finally, we conclude with recommendations on how these data can be used to quantify changes in carbon dynamics within carbon budget models to support climate change policy and decision making.

Natural and anthropogenic disturbances shaping the Mexican landscapes

Mexico has approximately 64.8 million hectares (ha) of forest (FRA FAO 2010), 49 % is temperate, 46 % tropical and subtropical, and 5 % other forest types (INFyS 2012a). Human activities are the major force that shape Mexican ecosystems (Ramírez-Marcial et al. 2001; Read and Lawrence 2003; Urquiza-Haas et al. 2007; Arredondo-León et al. 2008; Endara Agramont et al. 2012). Direct

consequences of human-induced disturbance include deforestation, fragmentation, degradation of habitats, and alterations to landscape dynamics (Ramírez-Marcial et al. 2001; Urquiza-Haas et al. 2007; Endara Agramont et al. 2012). This can lead to decreases in biomass and regeneration, and therefore have a negative impact of the net carbon balance (Ramírez-Marcial et al. 2001; Urquiza-Haas et al. 2007; Endara Agramont et al. 2012). Below we summarize the most common disturbance types occurring within the area.

Anthropogenic disturbances (Online resource 1) manifest through urban development, selective and clear-cut logging, shifting cultivation (known as milpa system), and extensive livestock grazing. In coniferous and deciduous forests in central Mexico, illegal logging and other extractive activities are one of the main causes of disturbance, resulting in large open gaps in the forest canopy that have a negative impact for natural regeneration and conservation (Endara Agramont et al. 2012). Dickinson et al. (2000) documented that selective logging for wood extraction activities also affected the tropical dry forests in the southern part of Mexico, reducing tree numbers, altering the understory vegetation, and promoting changes in the species composition during succession. Moreover, Ramírez-Marcial et al. (2001) found most forest logging in the southern mountain rainforest was driven by shifting agriculture where the forest was converted into "milpa" cultivation systems and livestock grazing. They found that grazing and trampling reduced the soil moisture, increased the probability of fire during the dry season, and reduced the ability of the forest to regenerate due to higher seedling mortality. Read and Lawrence (2003) reinforced these findings; shifting cultivation created large areas of secondary forest, reduced basal area, above ground biomass and tree densities, increased the number of stumps, and led to changes in diversity and species composition. While at fine spatial scales, local species richness and natural regeneration might benefit from the development of forest gaps (Sánchez-Gallén et al. 2010), these gaps also open the way for other disturbance types such as fire (Toledo-Aceves et al. 2009).

Studies of natural disturbances that affect Mexican ecosystems mainly focus on fires and hurricanes (Online resource 2). Fulé and Covington (1997, 1999) examined fire regimes in pine–oak forests in northern Mexico. They found that frequent, low-intensity fires were most common, burning forest understory vegetation, but rarely causing major damage to the forest canopy. While fires release carbon when burning organic matter, non-stand-replacing fires have become a forest management option to limit overall carbon losses by reducing the severity and frequency of large stand-replacing fires (Lorenz and Lal 2010). Consequently, large intensive stand-replacing fires

occur less often than in the past due to the short fire exclusion lengths, low accumulation of forest fuels, and burning of varying rates at different times (Fulé and Covington 1999; Drury 2006). In dry tropical forests, Vargas et al. (2008) found that frequent fires decreased the soil fertility, reducing the forest recovery and therefore carbon accumulation by limiting the nutrient provisioning. Furthermore, Skinner et al. (2008) reconstructed fire regime characteristics in mixed-conifer forests and found an increasing number of low-severity fires over a 209-year period. Their findings suggest that 5-year cycles of warm–wet conditions and low fire activity, tend to promote wildfires. In contrast, in the southeast tropical-montane-cloud forests, Asbjornsen et al. (2005) found that almost all vegetation cover was killed due to severe slow-burning ground fires. This was attributed to rapid water drainage from high-elevation karstic soils that are sensitive to extreme droughts. The resulting large severe fires turned the forest into an immediate net source of carbon and non-CO_2 GHG (methane and nitrous oxide).

"Hurricanes mainly affect tropical oceanic regions due to their proximity to the coast and warm temperatures (Foster et al. 1998). These storms mainly occur in the coastal areas of the Yucatan Peninsula, where the tropical forests are frequently altered by hurricanes of differing magnitude based on the Saffir–Simpson scales (Whigham et al. 2003; Rogan et al. 2011; Vandecar et al. 2011). Hurricanes tend to exhibit long-term impacts expressed by low tree mortality rates, high defoliation of the forest canopy, little changes in species composition, decreases in biomass of living trees, and opening gaps for subsequent fires (Whigham et al. 2003). Navarro-Martínez et al. (2012) found little changes in the forest composition and species diversity following hurricanes, but observed major impacts on the structural characteristics.

Materials and methods

Study area

The focus of this study is the Yucatan Peninsula (YP) that comprises three Mexican states: Yucatan, Campeche, and Quintana Roo, located in Southeastern Mexico, between the Gulf of Mexico and the Caribbean Sea (Fig. 1). The topography of the region is characterized by flat limestone areas and karst reliefs, where the dominant soil types are comprised of well-drained rendzinas, shallow rocky lithosols, and in some areas chromic luvisols, pellic vertisols, and gleysols (Urquiza-Haas el al. 2007). The region has a mean annual temperature of 25 °C, resulting in a tropical subhumid climate with precipitation ranging from 900 to 1,400 mm per year with dry winters and wet summers
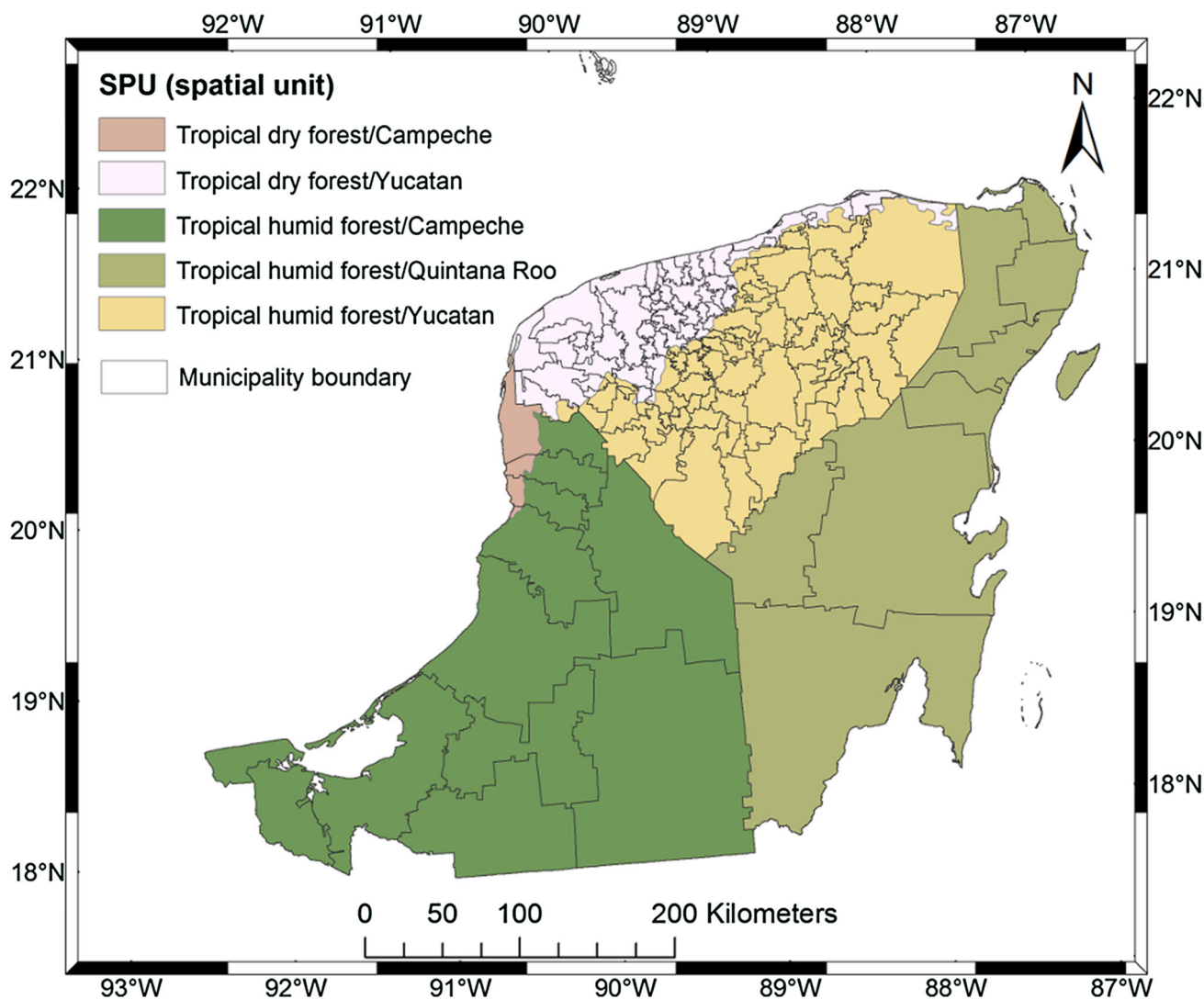
Fig. 1 Study area: the Yucatan Peninsula states and spatial stratification units. (Derived from INEGI's National geostatistic framework and CEC's ecological regions level 1)

(Vandecar et al. 2011). Accordingly, the vegetation of the region has been mainly classified as tropical forests that include semi-evergreen forest, semi-deciduous, deciduous forest, and mangrove forests (Urquiza-Haas et al. 2007).

Forest disturbance assessment

Forest disturbance ancillary data

Several datasets were compiled to map the location and severity of disturbances from 2005 to 2010: fires, hurricanes, and clearing for agricultural activity. These data are national statistics of forest disturbances recorded in Mexico for almost all the states and were collected and provided by the relevant national agencies (see description of the datasets below). Data were either spatially explicit:

where disturbance events contained information about their exact location in space, or spatially referenced: where the year and number of disturbances are recorded but not their detailed spatial location (most of them summarized at the municipality level) (Birdsey et al. 2013). Non-spatial disturbance data were associated with specific municipality polygons (the lowest level of geographic aggregation for which historical data were available). Two ecoregions of North America Level I (CEC 1997) were intersected with the three-state administrative boundaries of the YP (INEGI 2012) to provide a spatial stratification framework, comprised of five spatial units that will be used as a spatial framework for carbon budget analyses. Additionally, coverage of areas under forest management for the period was provided by Mexico's Forestry Commission (CONAFOR).

National statistics of wildfire information in Mexico have been recorded since 1970 for each state. Tabular data from the national database were provided by CONAFOR. Historical records include the number of fires and total hectares burned per year, aggregated by state. From 2005 onward, the database includes additional information: spatial coordinates of the fire central ignition point, cause of ignition, number of hectares burned, and type of ecosystem affected (temperate, tropical, arid) by municipality. Spatial layers were also available from the same database, from 2005 onward, containing the spatial coordinates of the central ignition point but not the polygon of the area burned. However, 39 % of the fire plots in tabular form (mostly from 2005, 2006, and 2009) did not include geographic coordinates and were not contained in these layers. These fires accounted for approximately 25 % of the total area burned over the period. As it was not possible to link the non-spatial fire events with the spatially explicit land-cover change information, we limited our analysis to the spatial datasets of the fire points with coordinates. Annual fire maps were then generated by buffering the ignition points with an area equal to the number of hectares burned per fire.

Information on the trajectories of tropical hurricanes from 2005 to 2010 that crossed the region was retrieved from the National Climatic Data Center (NCDC 2012; Fig. 2). For each hurricane, tabular data on the date, points of landfall, pressure, date, and wind speed for each storm were available. To assess the potential impact of the hurricanes beyond the storm trajectory, we buffered each track according to the disturbance severity associated with the Saffir–Simpson category (NHC 2013). To do so, we applied buffer distances derived from Skwira et al. (2005) rain-band width studies, with 15 km for major impact hurricanes categories (category IV or V), 10 km for category III and II, and 5 km for the remaining lower-impact storms.

Annual agricultural activity maps were generated using data from the Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food of Mexico known as SIACON (SAGARPA 2012). This program provides tabular data on the total area of annual cultivated land by state and municipality. Since the database lacked spatially explicit information, we referenced the cultivated area to the INEGI municipality polygon. Additional data on
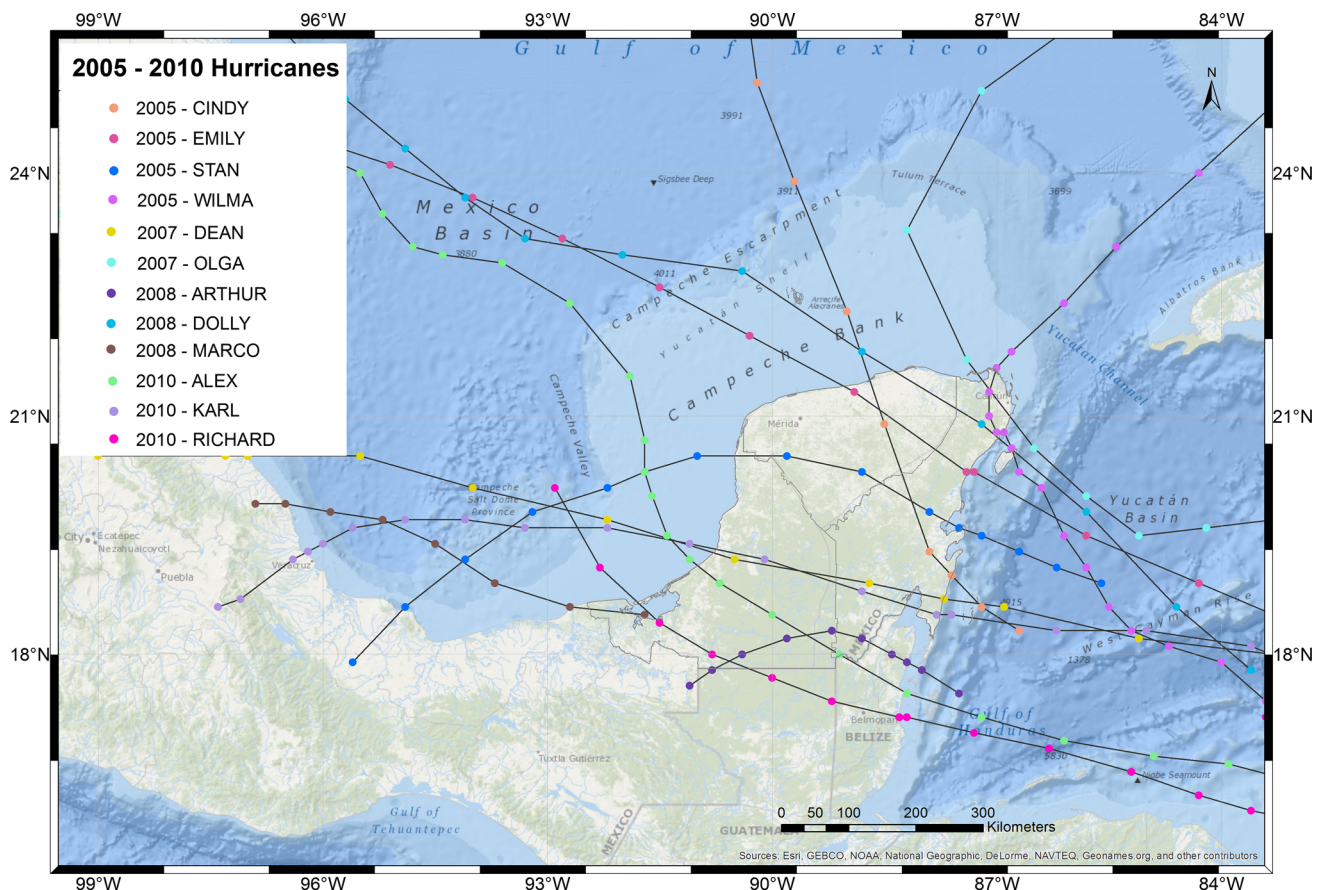

Fig. 2 Tracks of tropical hurricanes that crossed the Yucatan Peninsula from 2005 to 2010. (Derived from the National Climatic Data Center hurricane database)

agriculture were retrieved from INEGI's land use and vegetation series SIII and SIV, developed for 2003 and 2007, respectively (INEGI 2003, 2007). We used these datasets to differentiate permanent cultivation (PC) areas from the rest of the agricultural activities. Two masks were generated locating areas that fell under the status of PC (code "RP") and assign them a 100 % impact. Carbon budget models can be parameterized to represent these areas with a constant 100 % impact and simulate no forest regrowth. We first masked PC areas from SIII for 2005–2007, and second, filtered areas from SIV from 2008 onward. Annual maps were then produced for the YP, subtracting the hectares identified under PC by municipality from: (1) the cultivated hectares reported annually by municipality in the SIACON program and (2) the area of the municipality. The degree of impact was expressed as the percentage of total cultivated area by municipality.

National forest inventory

National Forest Inventory data are one of the primary sources used for forest carbon monitoring (Kurz et al. 2009; Birdsey et al. 2013). Throughout Mexico, ground plot data are routinely collected by the Mexican National Forest Inventory (INFyS, hereafter NFI) and available from CONAFOR. Two time periods of NFI measurement data were available for the assessment, the first sample cycle 2004–2009, and the re-measurement period 2009–2012 (with approximately 80 % of the plots revisited). Within the YP, 3,884 permanent sample plots were located, of which we used 3,633 and 2,544 plots, of the sampling and re-sampling cycles, respectively, discarding the un-sampled ones. Each plot is 1 ha in size and consists of a primary sampling unit, with four secondary sampling units (subsampling plots), of 400 m² each (INFyS 2012b). More than 150 variables are measured on a 5-year cycle, including attributes of the vegetation, soil, and environmental characteristics of the landscape. Forest gains and losses were estimated over the study period using the NFI ground plot data. We derived these estimates, by computing the difference in the mean basal area per hectare for each plot between the 2004–2009 and the 2009–2012 periods. For more details concerning the variables sampled in the NFI, as well as the sample design and the re-measurement framework, readers are referred to the NFI sampling manual (INFyS 2012b).

Remote sensing observations of land-cover change

Remotely sensed land-cover change observations were generated from the North American Land Change Monitoring System (NALCMS) developed as part of a collabo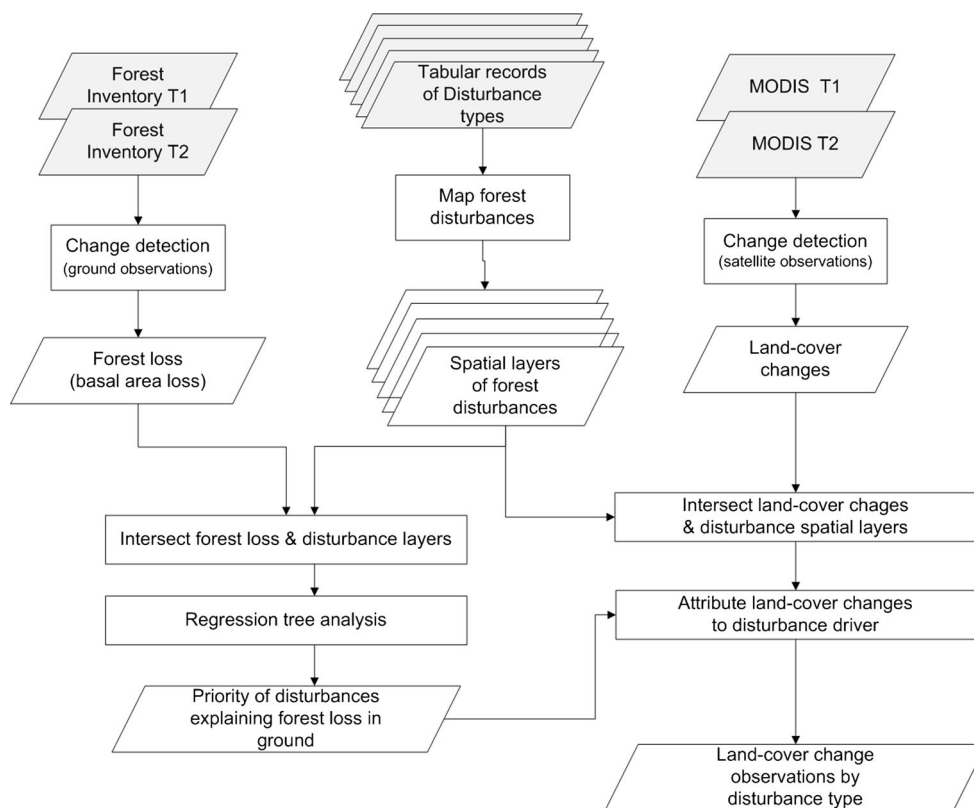rative effort between agencies from Canada, the USA, and Mexico coordinated by the Commission for Environmental Cooperation (CEC). The NALCMS provides land-cover information across the different ecosystems in North America, derived with 10-day MODIS composites at 250 m resolution (Latifovic et al. 2010). In the case of Mexico, land-cover classification maps embedded in the NALCMS were developed for 2005 and 2010 forming the basis of the comparison in this study; information on the classification approach is provided by Colditz et al. (2012). Fifteen land-cover classes were identified using multiple classifications (ensemble classifier) with decision trees and ancillary datasets including slope, aspect, temperature, precipitation, aerial photography, and high spatial resolution satellite images. The overall accuracy of the map was assessed with a disjoint set of sample data resulting in 82.5 % confidence (Kappa of 0.79). To assess the transition in the land-cover classes across the YP, we developed a change matrix, which calculates the number of pixels that changed land-cover class from 2005 to 2010.

Attributing land-cover changes to underlying disturbance types

Losses in basal area can be explained by tree mortality as the consequence of natural disturbances (e.g., fires, hurricanes) or as a result of tree removals due to harvesting activities (Healey et al. 2005). To assess the relative importance of fires, hurricanes, and forest management areas on the reduction in basal area in the NFI plots, a regression tree model was developed. Regression tree analysis is a flexible and robust method increasingly applied in ecological research for a number of reasons including the ability to deal with collinear datasets, to exclude non-significant variables, and to allow for asymmetrical distribution of samples (Quinlan 1986; De'ath and Fabricius 2000; De'ath 2002; Melendez et al. 2006; Schwalm et al. 2006). The technique automatically separates the response variable (reduction in basal area) into a series of choices that identifies the contribution of each constraining variable (i.e., fires, forest management areas and hurricanes). We made the explicit assumption that the remaining basal area loss was due to selective or clear-cut logging. Based on the relevance of the most likely variables explaining the basal area loss in the regression tree analysis, a final decision tree was developed attributing the MODIS land-cover change pixels to a disturbance type following that order.

To improve our understanding of the complexity of the different disturbance regimes across the YP, we developed the MS-D approach to characterize forest disturbances from 2005 to 2010 and attribute changes in forest cover to their underlying causes (Fig. 3). We first generated annual maps of major disturbance types. We then computed the

Fig. 3 Flowchart of the multi-scale, multi-source disturbance assessment (MS-D). The approach is based on a three-step implementation; (1) map type, extent, and location of forest disturbances, (2) derive land-cover change observations, and (3) attribute land-cover changes to their most likely disturbance driver

Results

Forest disturbances in the Yucatan Peninsula

An overview of fires that occurred in the YP from 2005 to 2010 is shown in Fig. 4a. In the study period, 97 % of the fires recorded burned an area equal or less than 1,000 ha. The remaining 3 % of wildfires burned a total of 80,905 ha, which corresponds to 63 % of the total area burned over the period, burning, on average, 3,852 ha per event. The largest fires occurred in the northeast Tropical humid forests of Quintana Roo, 58 % of the total fires registered in the period (Fig. 4b). On average, these fires burned 200 ha per event accounting for 77 % of the total area burned over the region from 2005 to 2010. The maximum area burned (13,240 ha) was registered in 2006, at the north of the YP. Across the region, the years with most severe fires were 2006 and 2009, burning 94,735 ha (75 % of total ha

burned). In contrast, 2007 registered the lowest fire regimes accounting for 2 % of the total area burned.

Estimates of hurricane disturbance derived from the NHDC across the region can be seen in Fig. 5. The years 2006 and 2009 were atypical for hurricanes with no tracks recorded in those years. In the north, the impact was dominated by larger and strong category V storms (Wilma and Emily), which struck the YP in 2005, and in the center by hurricane Dean (2007).The impact on the NFI plots due to Wilma and Emily was evident in the reduction in basal area. For the case of Dean, plots for the first sampling period in the area were first visited after the hurricane making an impact assessment not possible.

Annual maps of agricultural management lands across the YP are presented in Fig. 6a, b showing the initial and last year of the study (2005 and 2010). Areas under the permanent cultivation status obtained from INEGI SeriesIII (2003) can be observed in Fig. 6a depicted in red with a 100 % degree of impact. These areas are mainly located at the central-west of the YP, accounting for 35,509 ha. In 2007, areas under permanent cultivation increased by 15 % to 42,071 ha, shown in Fig. 6b. Additional areas extracted from the national agricultural database are represented by total cultivated land by municipality on an annual basis. Major areas of impact can be observed at the north of the YP, in the Yucatan state. Here, transitions in the degree of impact over the period can be seen, showing that some
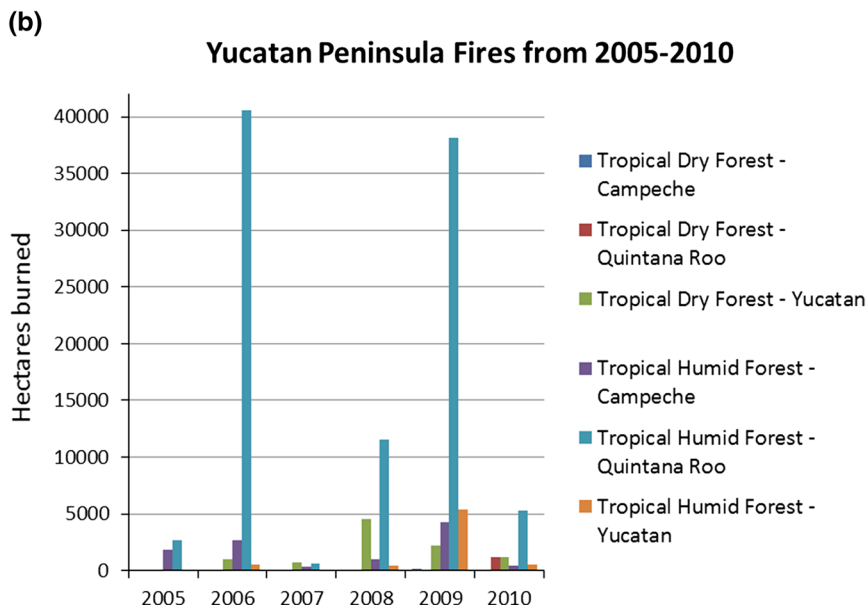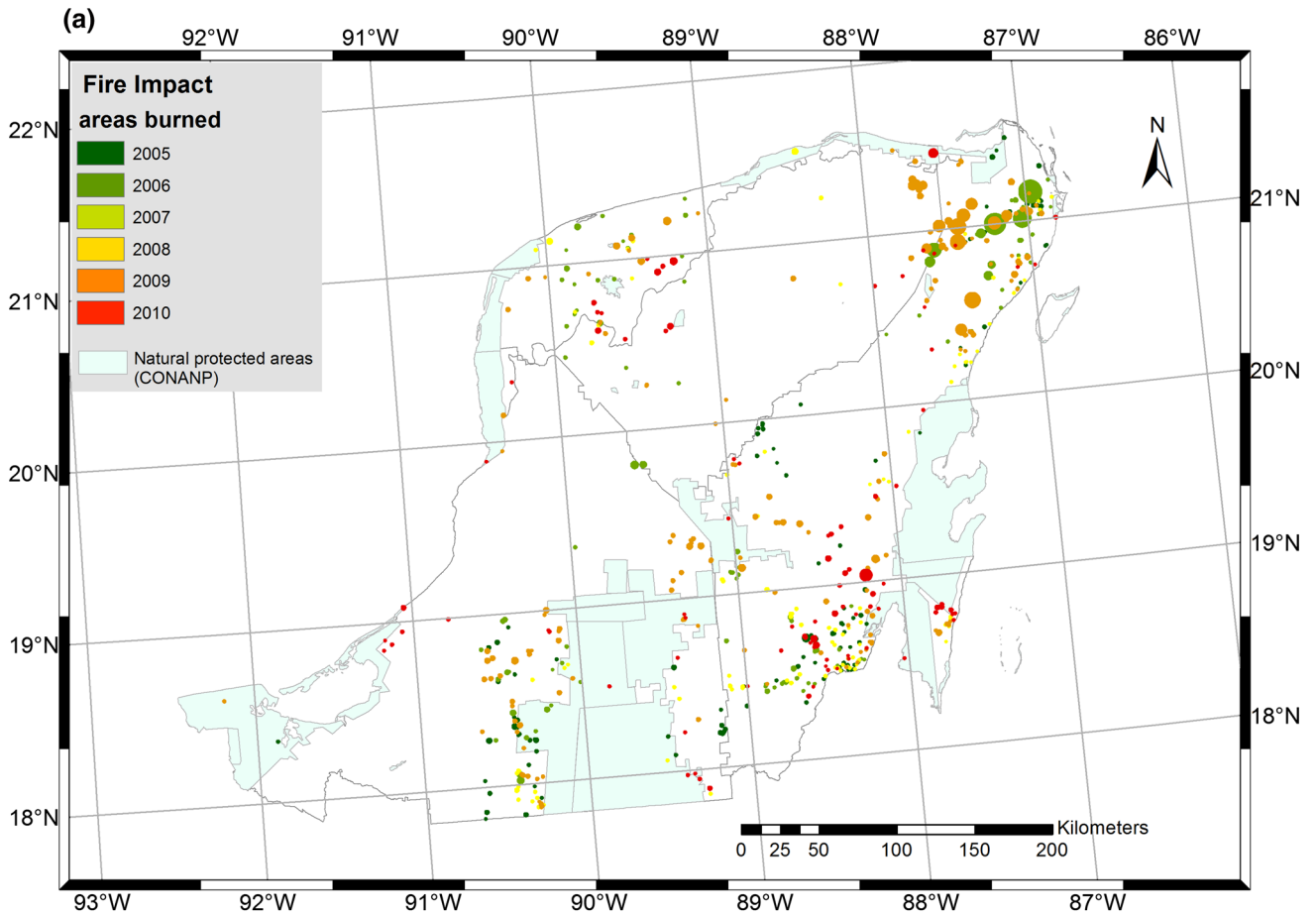
basal area loss observed in the ground plot data. Next, we compiled multiple disturbance datasets and used a regression tree analysis to identify the most likely underlying driver of change. Finally, we assessed the land-cover change from MODIS between 2005 and 2010 and using the results from the regression tree analysis attributed the change to the most likely disturbance driver.

(a)

(b)

Fig. 4 a, **b** Fires recorded throughout the Peninsula from 2005 to 2010

municipalities (unique areas depicted in red in 2005) went from 80 % of cultivated land that decreased drastically to 3 or 5 % in 2010. This was mainly due to a 13 % decrease in the amount of cultivated hectares reported in 2010 in the municipality records of the agricultural database of SAGARPA (SAGARPA 2012).
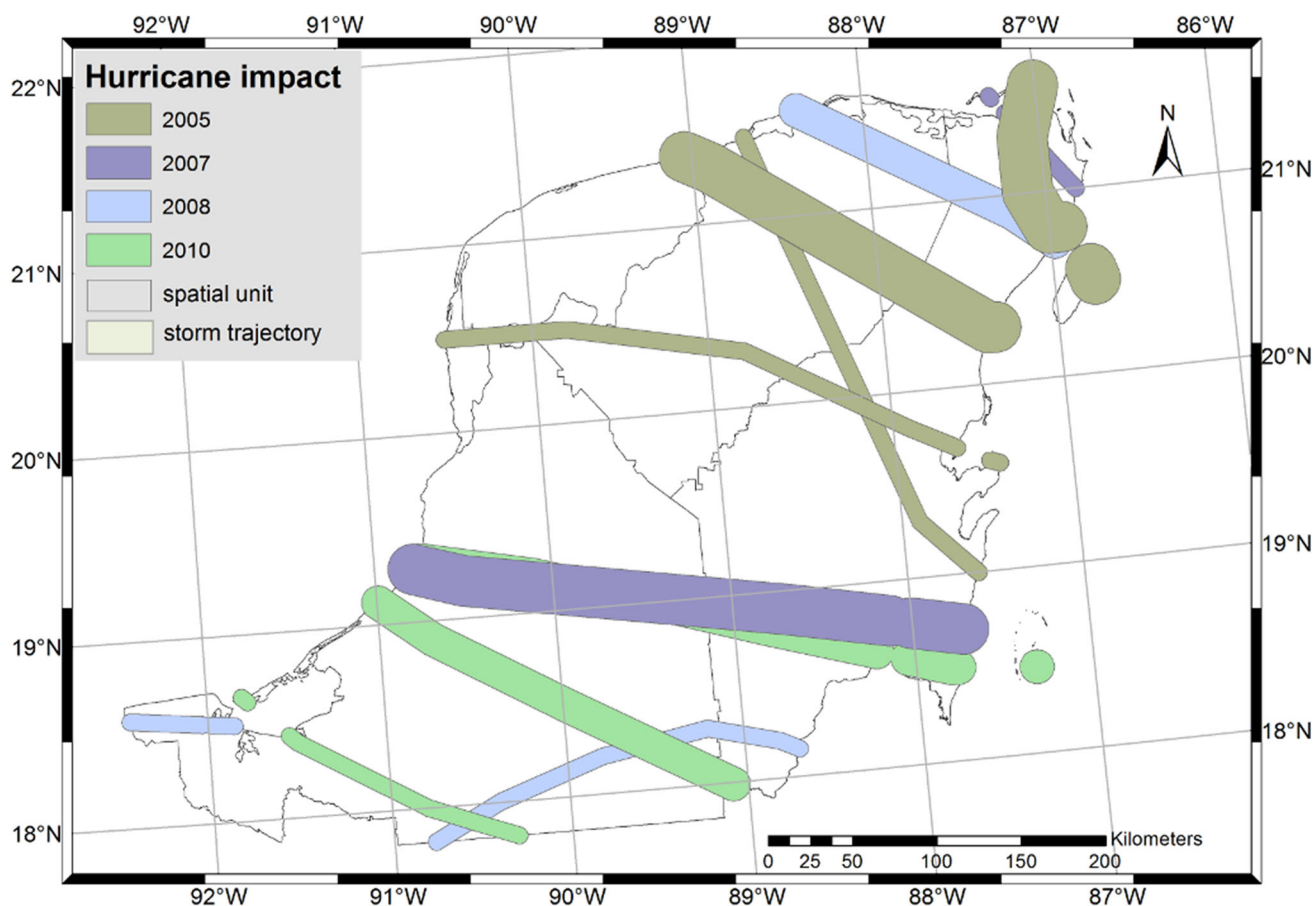
Fig. 5 Hurricanes disturbances recorded in the Yucatan Peninsula from 2005 to 2010

Ground plot observations of forest cover change

The amount of mean basal area change from the first measurement period (2004–2009) to the re-measurement (2009–2012) is shown in Online resource 3a–d. Overall 47 % of the plots had an average increase in basal area of 4.16 m^2 ha^{-1} between the two periods. Decreases in basal area were found in 20 % of the plots, with an overall mean reduction of 4.42 m^2 ha^{-1} and a maximum loss of 79.2 m^2 ha^{-1} registered in one plot in the tropical humid forests of Campeche. Clusters of plots with basal area loss can be observed in Online resource 3c, mainly at the tip and center of the YP, in the tropical humid forests of Quintana Roo, and some parts at the southwest of Campeche. The rest of the plots were either not sampled or inaccessible in the second period (30 %), or presented no change (3 %).

Remote sensing observations of land-cover change

From the land-cover change analysis derived with MODIS thematic maps, fourteen of the fifteen land-cover classes identified in Mexico by Colditz et al. (2012) were found in

the YP. Land-cover change from 2005 to 2010 totaled 7,281 ha. The most significant change was observed in the Tropical Evergreen forests with a net loss of 5,318 ha (73 % of the total forest area loss) mainly due to anthropogenic disturbances that changed forests into cropland and urban areas. Losses in cropland (5,368 ha) were offset by area gained from other classes (5,487 ha), showing a low net gain of 119 ha (2 %) in cropland area. The largest net area gain (5,218 ha, 71.7 %) took place in the Urban class, followed by gains in Barren land (10 %) and Tropical Grassland (8 %).

Drivers of change in the land-cover

Results from the regression tree analysis indicated that the area burned explained most of the variance in the reduction of basal area, with fires reducing an average of 5.38 m^2 ha^{-1} of basal area per plot across the YP (Fig. 7). With a 99 % confidence, the results from the regression tree analysis were highly statistically significant ($p < 0.001$) at predicting the mean basal area loss by each disturbance type (y). At plots which either did not intersect a fire or had no detected fire, forest management was the
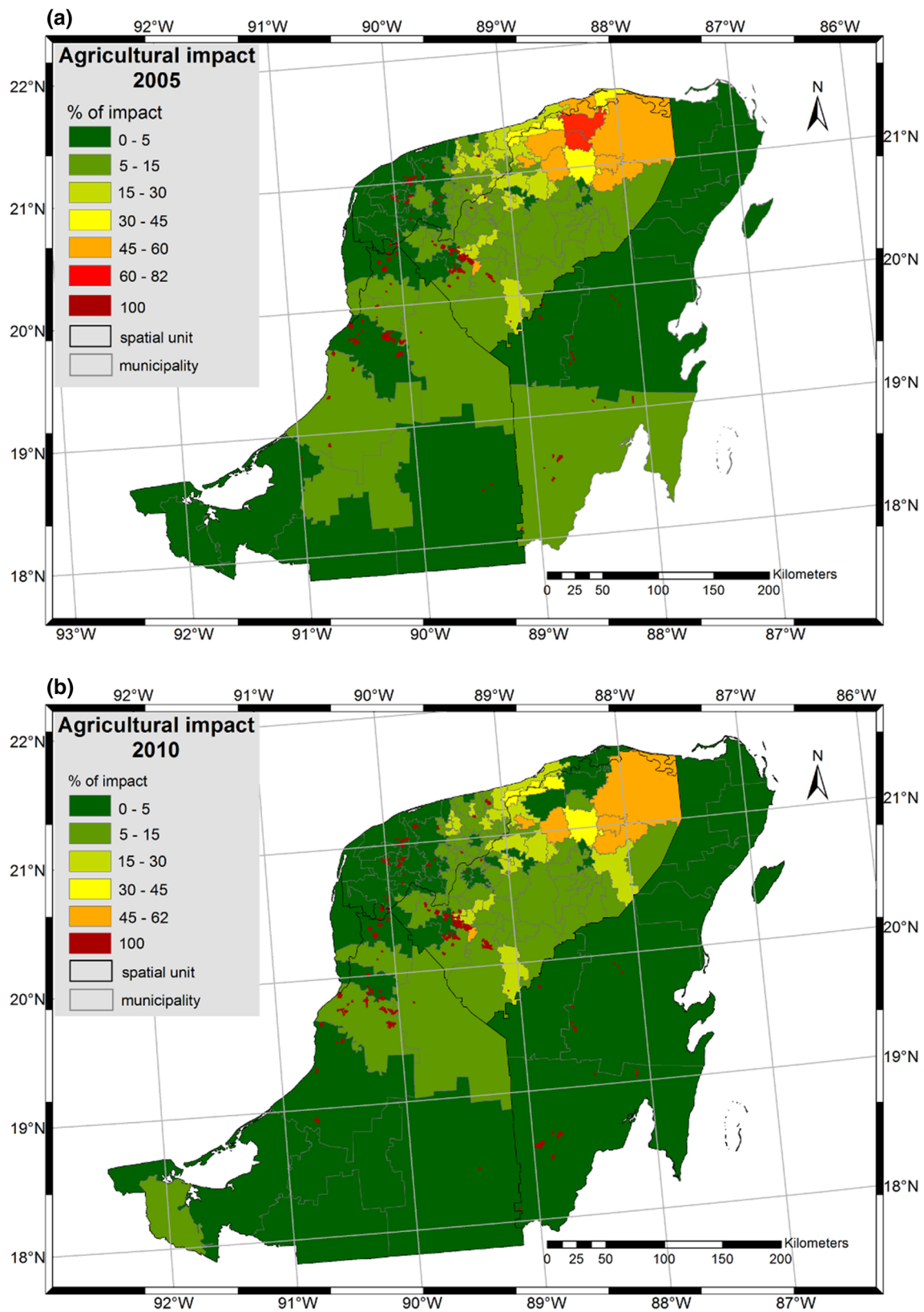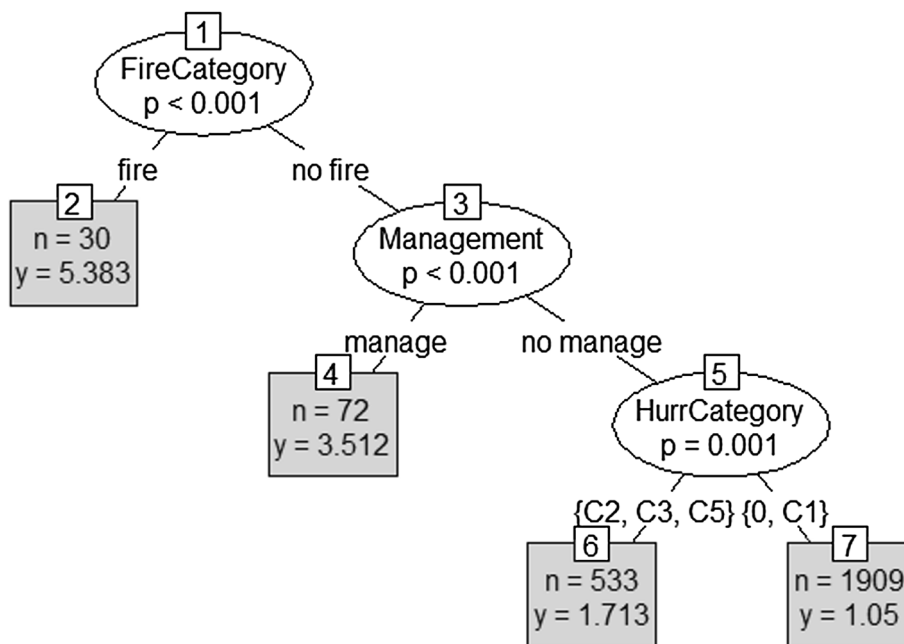
Fig. 6 a, b Percentage of cultivated area by municipality across the Yucatan Peninsula from 2005 to 2010

Fig. 7 Regression tree analysis of basal area loss explained by fire, forest management, and hurricanes

most significant variable followed by hurricanes, with lower categories reducing the basal area by a smaller amount (1.05 m^2 ha^{-1}) than severe hurricanes of higher categories (1.7 m^2 ha^{-1}).

Based on the results of the regression tree analysis, MODIS land-cover change pixels were attributed by disturbance type. First, MODIS land-cover change from non-urban in 2005 to urban in 2010 was attributed to settlement expansion. This is the largest percentage of change attributed over the YP (37 %). These disturbances match the locations close to major cities: Merida, Cancun, Chetumal, and Campeche. Fires were then attributed second, with 2 % of the change pixels overlaying burned areas, attributed to fire. Following, change pixels under forest management were assigned to harvest (3 %). Next, hurricanes were attributed to those land-cover change pixels which overlaid storm categories greater than level 1 and were not attributed to settlements, fire, or management. These changes comprise the second largest cause of disturbance in the region (26 %), following settlement. Agriculture was then attributed after the hurricanes to 18 % of the change pixels classified as non-cropland, but changed into cropland in 2010, and were yet not attributed. Lastly, any remaining change pixels for which we were not able to find corresponding disturbance data were assumed and attributed as harvest (14 %). The resulting map of MODIS land-cover change attributed by disturbance type is shown in Fig. 8a, b, including the percentage of each land-cover class attributed by disturbance type, the total area changed from 2005 to 2010, and the total pixels changed by class in the period.

Discussion and conclusion

This project was conducted in the context of a larger initiative aimed at developing a national MRV system for Mexico. We developed a new approach (MS-D) that allows for the attribution of observed land-cover changes to the underlying causes of disturbance. Knowledge of the cause of disturbance is critical for the accounting of GHG emissions and removals because different disturbance types have different impacts on carbon stocks, as well as direct and indirect emissions to the atmosphere (Kurz et al. 2009). The MS-D was successfully used to map major forest disturbance types and attribute them to changes in land cover over the ~1,37,605 km^2 region of the YP, an early action area for REDD+, for the period of 2005–2010.

Critical for the MS-D was the availability of NFI data to obtain basal area change. However, the time interval between successive measurements of the NFI (a rolling program of re-measurement in 5-year intervals) resulted in only two measurements between 2005 and 2010. We therefore treated the NFI data as a one-time change. Spatially explicit or spatially referenced data characterized by year are preferred to model forest carbon dynamics following disturbance as they allow assessment of inter-annual variability. Datasets of forest disturbance types by year would be desirable, but are difficult to obtain given the cost, efforts, and resources required.

We addressed the limitations of the multi-annual NFI data by compiling ancillary datasets available on an annual basis to fill some of the gaps. Improvements to this approach were possible due to the availability of national
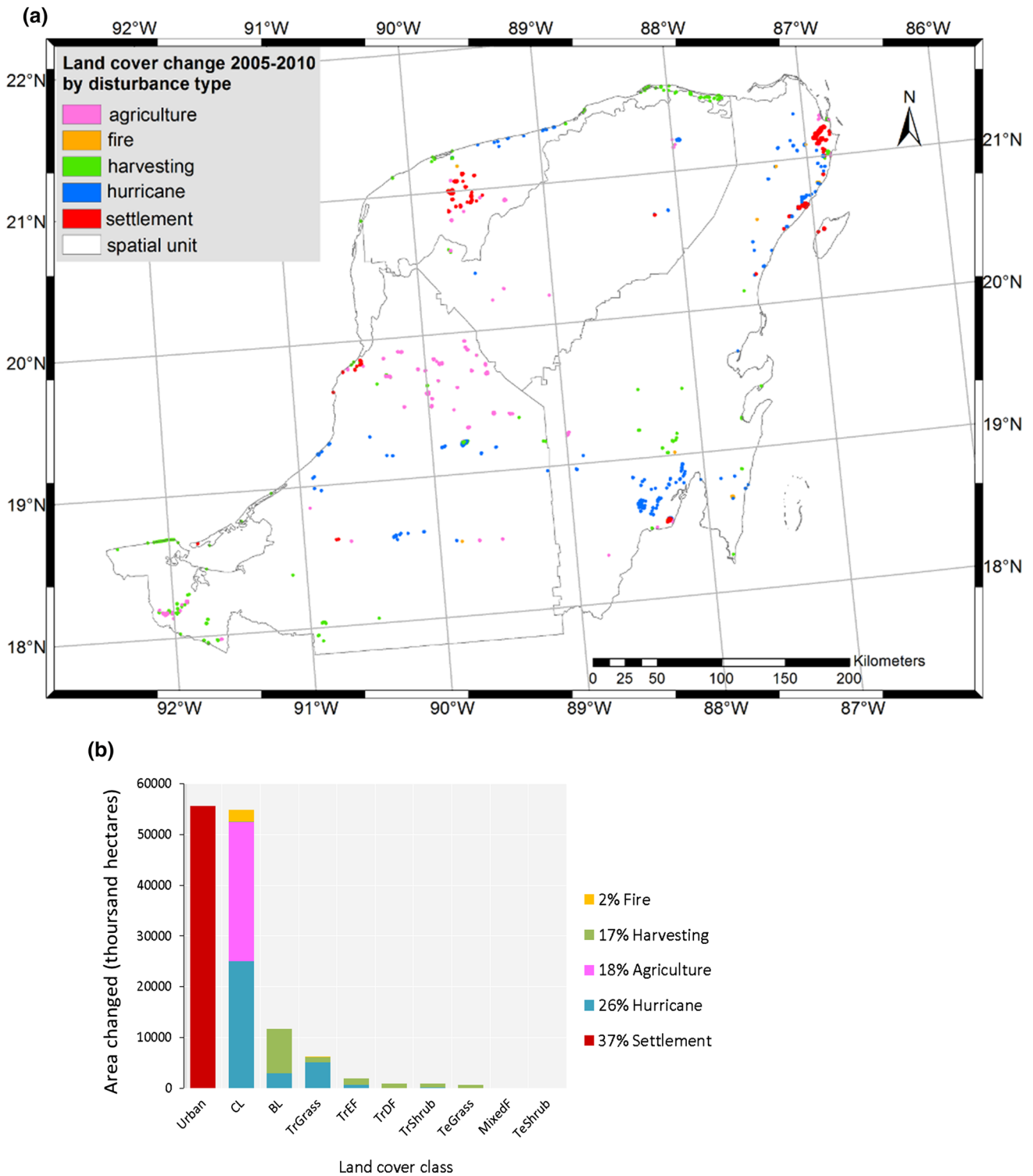
Fig. 8 MODIS Land-cover change pixels by disturbance type (**a**), land-cover changed area by disturbance type per class and percentage attributed by disturbance type (**b**). *TrEF* Tropical broadleaf evergreen forest, *TrDF* Tropical broadleaf deciduous forest, *MixedF* Mixed forest, *TrShrub* Tropical shrubland, *TeShrub* Temperate shrubland, *TrGrass* Tropical grassland, *TeGrass* Temperate grassland, *CL* Cropland, *BL* Barren land, Urban

statistics of different disturbances (i.e., fire, hurricane, and agriculture). While some of these historical records lacked spatially explicit data, they were successfully used to

produce annual layers of affected areas. In our analysis, we aggregated the data to the municipality level and allocated it to either all of the spatial unit or a specific group of

spatial units within the YP. This is convenient for countries like Mexico where historical records often lack spatial detail.

With respect to the land-cover change analysis, we utilized a simple change detection approach using two classification dates. However, the use of post-classification analysis has inaccuracies associated with image calibration, misclassification, and satellite sensor errors (Dai and Khorram 1999; Fuller et al. 2003). These inaccuracies can produce changes that did not actually occur and may not detect real changes that occurred. Despite these possible flaws, an extensive review of literature done by Lu et al. (2004) on major change detection techniques found that post-classification comparisons are one of the most common approaches used for change detection. Moreover, in Mexico, studies from Mas (1999) compared six change detection methods and concluded that post-classification was the most accurate procedure, including the benefit of providing the nature of the changes. While most of the land-cover change pixels (86 %) were successfully attributed with additional evidence of disturbance types, the 14 % of the changed pixels for which we were not able to find corresponding disturbance data, "false-positives", remain to be investigated. Further research on "false-positives" can also provide more insights for the attribution of the 25 % of fires with missing spatially explicit locations.

The change detection analysis performed using the MODIS imagery was able to determine that most of the conversion between the two time periods (2005–2010) was due to stand-replacing disturbances. For instance, areas of settlement impact observed in the MODIS changed pixels matched only with the location of major impacts, but not with subtle disturbances identified with the NFI plots. This is due to a number of factors. The first is the resolving capacity of the MODIS imagery itself. MODIS-based products can be useful to provide imagery suitable for regional and global applications with high-frequency observations, allowing users to keep track of the ecosystem dynamics with a coarse resolution at low cost (Coops et al. 2006; Wulder et al. 2010). Due to its low spatial resolution (250 m), it has limitations detecting forest disturbances occurring at finer scales. This broad spatial resolution along with the lack of land-cover observations on annual basis makes the identification of non-stand-replacing disturbances (e.g., low fires and selective logging) by year difficult.

Forest disturbance studies can be improved with the availability of remote sensing products derived on an annual basis at finer spatial scales, like Landsat satellite imagery. Landsat Thematic Mapper + and the new Landsat 8 OLI can improve the detection of medium and low-severity disturbances that result in subtle changes on the forest cover, providing more detailed information about the landscape (Cohen et al. 2010). However, the small coverage per scene along with the recurrent cloud coverage may sometimes limit its use (Hayes et al. 2008). Advances in technology are facilitating the processing and characterization of the Earth's surface with new super-computing systems. An example is Hansen et al. (2013), who developed a map of forest cover loss for the entire world from 2000 to 2012 with a 30-m spatial resolution based on Landsat data. This new map includes the spatially explicit characterization of forest loss and gain for the period, with annual loss distribution. Other examples include forest disturbance products derived with a new vegetation change tracker algorithm that efficiently processes Landsat time-series stacks to characterize forest cover change (Huang et al. 2010). Recently, Mexico acquired full coverage of RapidEye satellite imagery for the years of 2011, 2012, and 2013 with a 5-m spatial resolution that can help to characterize in more detail the current status of the forest cover. These remote sensing products can provide the means to enhance and expand the insights from this study.

The strength of this study is in its ability to create synergies between remote sensing products, ground truth data and ancillary datasets, thus taking advantage of the best available information acquired by other researchers/institutions. Mapping disturbances and attributing observed land-cover changes to the appropriate disturbance type with the MS-D approach provide a cost-effective solution to obtain activity data for carbon modeling and other ecological applications. Its flexibility allows a comprehensive integration of spatially referenced and/or spatially explicit data on an annual or multi-year basis to characterize forest disturbances by type and attribute changes in land cover to their underlying causes. Moreover, it provides a basis to replicate the study in other "early action" areas of Mexico for ecosystem carbon accounting and monitoring, and the development of an MRV system. This advance also allows other countries undertaking efforts to implement an MRV system for REDD+ (e.g., Ecuador, Peru) to explore the potential use of this approach using input data appropriate for their specific conditions.

distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

Arredondo-León C, Muñoz-Jimenez J, García-Romero A (2008) Recent changes in landscape-dynamics trends in tropical highlands, central Mexico. Interciencia 33(8):569–577

Asbjornsen H, Velazquez-Rosas N, García-Soriano R, Gallardo-Hernández C (2005) Deep ground fires cause massive above- and below-ground biomass losses in tropical montane cloud forests in Oaxaca, Mexico. J Trop Ecol 21:427–434. doi:10.1017/S0266467403002373

Birdsey R, Angeles-Perez G, Kurz WA, Lister A, Olguin M, Pan Y, Wayson C, Wilson B, Johnson K (2013) Approaches to monitoring changes in carbon stocks for REDD+. Carbon Manag 4(5):519–537. doi:10.4155/CMT.13.49

Bosworth D, Birdsey R, Joyce L, Millar C (2008) Climate change and the nation's forests: challenges and opportunities. J For 106(4):214–221

CEC (1997) Ecological regions of North America: toward a common perspective. Commission for Environmental Cooperation, Montreal

Chapa-Bezanilla D, Sosa-Ramirez J, de Alba-Avila A (2008) Multitemporal study on forest fragmentation in sierra fría, Aguascalientes, Mexico. Madera Y Bosques 14(1):37–51

Chapin FS, Woodwell GM, Randerson JT, Rastetter EB, Lovett GM, Baldocchi DD, Clark DA et al (2006) Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems 9(7):1041–1050. doi:10.1007/s10021-005-0105-7

Chapin FS, McFarland J, McGuire AD, Euskirchen ES, Ruess RW, Kielland K (2009) The changing global carbon cycle: linking plant–soil carbon dynamics to global consequences. J Ecol 97(5):840–850. doi:10.1111/j.1365-2745.2009.01529.x

Cohen WB, Yang Z, Kennedy R (2010) Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync—tools for calibration and validation. Remote Sens Environ 114(12):2911–2924. doi:10.1016/j.rse.2010.07.010

Colditz RR, López-Saldaña G, Maeda P, Espinoza JA, Tovar CM, Hernández AV, Benítez CZ et al (2012) Generation and analysis of the 2005 land cover map for Mexico using 250m MODIS data. Remote Sens Environ 123:541–552. doi:10.1016/j.rse.2012.04.021

Coops NC, White JC, Wulder MA (2006) Identifying and describing forest disturbance and spatial pattern. In: Wulder MA, Franklin SE (eds) Understanding forest disturbance and spatial pattern: remote sensing and gis approaches. CRC Taylor & Francis, New York, Boca Raton, FL, USA, p 246. doi:10.1201/9781420005189.ch2

Dai X, Khorram S (1999) Remotely sensed change detection based on artificial neural networks. Photogramm Eng Remote Sensing 65(10):1187–1194

Dale V, Joyce L, Mcnulty S, Neilson R, Ayres M, Flannigan M, Hanson P, Irland L, Lugo A, Peterson C, Simberloff D, Swanson F, Stocks B, Wotton B (2001) Climate change and forest disturbances. Bioscience 51(9):723–734. doi:10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2

De Sy V, Herold M, Achard F, Asner GP, Held A, Kellndorfer J, Verbesselt J (2012) Synergies of multiple remote sensing data sources for REDD+ monitoring. Curr Opin Environ Sustain 4(6):696–706. doi:10.1016/j.cosust.2012.09.013

De'ath G (2002) Multivariate regression trees: a new technique for modeling species-environment relationships. Ecology 83(4):1105–1117. doi:10.2307/3071917

De'ath G, Fabricius K (2000) Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81(11):3178–3192. doi:10.1890/0012-9658(2000)081[3178:CARTAP]2.0.CO;2

DeFries R, Houghton R, Hansen M, Field C, Skole D, Townshend J (2002) Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. Proc Natl Acad Sci USA 99(22):14256–14261. doi:10.1073/pnas.182560099

DeFries R, Achard F, Brown S, Herold M, Murdiyarso D, Schlamadinger B, de Souza C Jr (2007) Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environ Sci Policy 10(4):385–394. doi:10.1016/j.envsci.2007.01.010

Díaz S, Wardle DA, Hector A (2009) Incorporating biodiversity in climate change mitigation initiatives. In: Naeem S, Bunker DE, Hector A, Loreau M, Perrings C (eds) Biodiversity, Ecosystem Functioning and Human Wellbeing. Oxford University Press, Oxford. doi:10.1093/acprof:oso/9780199547951.003.0011

Dickinson M, Whigham D, Hermann S (2000) Tree regeneration in felling and natural treefall disturbances in a semideciduous tropical forest in Mexico. For Ecol Manag 134(1–3):137–151. doi:10.1016/S0378-1127(99)00252-2

Drury SA (2006). The effects of climate and disturbance on madrean pine–oak forests in Mexico's Sierra Madre Occidental. University of Colorado at Boulder. ProQuest dissertations and theses, pp 235–235. http://ezproxy.library.ubc.ca/login?url=http://search.proquest.com.ezproxy.library.ubc.ca/docview/305353918?accountid=14656

Endara Agramont AR, Franco Maass S, Nava Bernal G, Valdez Hernández JI, Fredericksen Todd S (2012) Effect of human disturbance on the structure and regeneration of forests in the Nevado de Toluca National Park Mexico. J For Res 23(1):39–44. doi:10.1007/s11676-012-0226-8

Food and Agriculture Organization (FAO), United Nations. (2010). The global forest resources assessment (FRA) 2010. Rome Retrieved from http://www.fao.org/docrep/013/i1757e/i1757e.pdf

Foster DR, Knight DH, Franklin JF (1998) Landscape patterns and legacies resulting from large, infrequent forest disturbances. Ecosystems 1(6):497–510. doi:10.1007/s100219900046

Franklin JF, Mitchell RJ, Palik B (2007). Natural disturbance and stand development principles for ecological forestry. USDA for Serv N Res. US Department of Agriculture, Forest service, Northern research station. Retrieved from http://courses.washington.edu/esrm315/pdfs/Franklinetal2007.pdf

Fulé PZ, Covington WW (1997). Fire regimes and forest structure in the Sierra Madre Occidental, Durango, Mexico. Acta Bot Mex 41:43–79

Fulé PZ, Covington WW (1999) Fire Regime Changes in La Michilía Biosphere Reserve, Durango, Mexico. Conserv Biol 13(3):640–652. doi:10.1046/j.1523-1739.1999.97512.x

Fuller RM, Smith GM, Devereux BJ (2003) The characterisation and measurement of land cover change through remote sensing: problems in operational applications? Int J Appl Earth Obs Geoinf 4(3):243–253. doi:10.1016/S0303-2434(03)00004-7

Hansen MC, Roy DP, Lindquist E, Adusei B, Justice CO, Altstatt A (2008) A method for integrating MODIS and Landsat data for systematic monitoring of forest cover and change in the Congo Basin. Remote Sens Environ 112(5):2495–2513. doi:10.1016/j.rse.2007.11.012

Hansen MC, Stehman SV, Potapov PV (2010) Quantification of global gross forest cover loss. Proc Natl Acad Sci USA 107(19):8650–8655. doi:10.1073/pnas.0912668107

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR,

Kommareddy A, Egorov A, Chini L, Justice CO, Townshend JRG (2013) High-resolution global maps of 21st-century forest cover change. Science 342(6160):850–853. doi:10.1126/science.1244693

Hayes DJ, Cohen WB (2007) Spatial, spectral and temporal patterns of tropical forest cover change as observed with multiple scales of optical satellite data. Remote Sens Environ 106(1):1–16. doi:10.1016/j.rse.2006.07.002

Hayes DJ, Cohen WB, Sader SA, Irwin DE (2008) Estimating proportional change in forest cover as a continuous variable from multi-year MODIS data. Remote Sens Environ 112(3):735–749. doi:10.1016/j.rse.2007.06.003

Healey S, Cohen W, Yang Z, Krankina O (2005) Comparison of tasseled cap-based landsat data structures for use in forest disturbance detection. Remote Sens Environ 97(3):301–310. doi:10.1016/j.rse.2005.05.009

Houghton RA, House JI, Pongratz J, van der Werf GR, DeFries RS, Hansen MC, Le Quéré C, Ramankutty N (2012) Carbon emissions from land use and land-cover change. Biogeosciences 9(12):5125–5142. doi:10.5194/bg-9-5125-2012

Huang C, Coward SN, Masek JG, Thomas N, Zhu Z, Vogelmann JE (2010) An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. Remote Sens Environ 114(1):183–198. doi:10.1016/j.rse.2009.08.017

INEGI (2003) Conjunto de datos vectoriales de la carta de uso del suelo y vegetación, Escala 1:250,000, Serie IV (CONTINUO NACIONAL). Aguascalientes, México, Instituto Nacional de Estadística y Geografía (INEGI)

INEGI (2007) Conjunto de datos vectoriales de la carta de uso del suelo y vegetación, Escala 1:250,000, Serie IV (CONTINUO NACIONAL). Aguascalientes, México, Instituto Nacional de Estadística y Geografía (INEGI)

INEGI (2012) Marco geoestadistico nacional (National geostatistic framework). Aguascalientes, México, Instituto Nacional de Estadistica y Geografia (INEGI)

INFyS (2012a) Inventario Nacional Forestal y de Suelos Informe 2004–2009 (National Forest and Soils Inventory report). Comisión Nacional Forestal (CONAFOR), México. Retrieved from http://www.ccmss.org.mx/wp-content/uploads/2014/10/Inventario_nacional_forestal_y_de_suelos_informe_2004_-_2009_.pdf

INFyS (2012b) Manual de muestreo del Inventario Nacional Forestal y de Suelos 2012 (National forest inventory sampling manual). Comisión Nacional Forestal (CONAFOR), México. Retrieved from http://www.cnf.gob.mx:8090/snif/portal/infys/temas/documentos-metodologicos

IPCC (2007) Climate change 2007: mitigation. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Contribution of working group III to the fourth assessment report. Cambridge University Press, Cambridge

Jardel-Peláez EJ, Morfín-Ríos JE, Vargas-Jaramillo S, Michel-Fuentes JM, Cuevas-Guzmán R, Castillo-Navarro F, Balcázar-Medina OE, Quiñónez, E (2006). Fire regime and fire effects on western mexico subtropical montane forest ecosystems. In: Fire regimes and fire effects in mexican ecosystems. Proceedings 3rd international fire ecology and management congress, San Diego, California

Kurz WA (2010) An ecosystem context for global gross forest cover loss estimates. Proc Natl Acad Sci USA 107(20):9025–9026. doi:10.1073/pnas.1004508107

Kurz WA, Dymond CC, White TM, Stinson G, Shaw CH, Rampley GJ, Smyth C, Simpson BN, Neilson ET, Trofymow JA, Metsaranta J, Apps MJ (2009) CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol Model 220(4):480–504. doi:10.1016/j.ecolmodel.2008.10.018

Kurz WA, Shaw CH, Boisvenue C, Stinson G, Metsaranta J, Leckie D, Dyk A, Smyth C, Neilson ET (2013) Carbon in Canada's boreal forest—a synthesis. Environ Rev 21:260–292. doi:10.1139/er-2013-0041

Latifovic R, Homer C, Ressl R, Pouliot D, Hossain SN, Colditz Colditz RR, Olthof I, Giri C, Victoria A (2010) North American land Change Monitoring System (NALCMS). In: Giri C (ed) Remote sensing of land use and land cover: principles and applications. CRC Press, Boca Raton

Ley General de Cambio Climatico (LGCC) (2012) General law of climate change. Camara de Diputados, Congreso de la Union

Lorenz K, Lal R (2010) Effects of disturbance, succession and management on carbon sequestration. Carbon sequestration in forest ecosystems. Springer, Berlin, pp 103–157. doi:10.1007/978-90-481-3266-9_3

Lu D, Mausel P, Brondízio E, Moran E (2004) Change detection techniques. Int J Remote Sens 25(12):2365–2401. doi:10.1080/0143116031000139863

Manzo-Delgado L, Sánchez-Colon S, Álvarez R (2009) Assessment of seasonal forest fire risk using NOAA-AVHRR: a case study in central Mexico. Int J Remote Sens 30(19):4991–5013. doi:10.1080/01431160902852796

Mas J (1999) Monitoring land-cover changes: a comparison of change detection techniques. Int J Remote Sens 20(1):139–152. doi:10.1080/014311699213659

Masek JG, Cohen WB, Leckie D, Wulder MA, Vargas R, de Jong B, Healey S, Law B, Birdsey R, Houghton RA, Mildrexler D, Goward S, Smith WB (2011) Recent rates of forest harvest and conversion in North America. J Geophys Res Biogeosci. doi:10.1029/2010JG001471

Melendez KV, Jones DL, Feng AS (2006) Classification of communication signals of the little brown bat. J Acoust Soc Am 120(2):1095–1102. doi:10.1121/1.2211488

Millennium Ecosystem Assessment (MEA) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington

National Climatic Data Center (NCDC) (2012) Global set of historical tropical cyclones data. National Climatic Data Center, National Oceanic and Atmospheric Administration (NOAA)

National Hurricane Center (NHC). (2013). Saffir-Simpson Hurricane Wind Scale. National Oceanic and Atmospheric Administration (NOAA), United States. Retrieved from http://www.nhc.noaa.gov/aboutsshws.php

Navarro-Martínez A, Durán-García R, Méndez-González M (2012). El impacto del huracán Dean sobre la estructura y composición arbórea de un bosque manejado en Quintana Roo, México. Madera y Bosques 18(1): 57–76. Retrieved from http://www.redalyc.org/articulo.oa?id=61724713005

Oliver CD, Larson BC (1996) Forest stand dynamics. Wiley, New York

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, Mcguire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333(6045):988–993. doi:10.1126/science.1201609

Potapov P, Hansen MC, Stehman SV, Loveland TR, Pittman K (2008) Combining MODIS and Landsat imagery to estimate and map boreal forest cover loss. Remote Sens Environ 112(9):3708–3719. doi:10.1016/j.rse.2008.05.006

Potter C, Klooster S, Genovese V, Hiatt C, Boriah S, Kumar V, Mithal V, Garg A (2012) Terrestrial ecosystem carbon fluxes predicted from MODIS satellite data and large-scale disturbance modeling. Int J Geosci 3(3):469–479. doi:10.4236/ijg.2012

Quinlan JR (1986) Induction of decision trees. Mach learn 1(1):81–106

Ramírez-Marcial N, González-Espinosa M, Williams-Linera G (2001) Anthropogenic disturbance and tree diversity in montane

rain forests in Chiapas, Mexico. For Ecol Manag 154(1–2):311–326. doi:10.1016/S0378-1127(00)00639-3

Read L, Lawrence D (2003) Recovery of biomass following shifting cultivation in dry tropical forests of the Yucatan. Ecol Appl 13(1):85–97

Rogan J, Schneider L, Christman Z, Millones M, Lawrence D, Schmook B (2011) Hurricane disturbance mapping using MODIS EVI data in the southeastern Yucatan, Mexico. Remote Sens Lett 2(3):259–267. doi:10.1080/01431161.2010.520344

SAGARPA (2012) Servicio de informacion agroalimentaria y de consulta 2010 (SIACON). Secretaria de Agricultura, Ganaderia

Sánchez-Gallén I, Javier Álvarez-Sánchez F, Benitez-Malvido J (2010) Structure of the advanced regeneration community in tropical rain forest fragments of Los Tuxtlas, Mexico. Biol Conserv 143(9):2111–2118. doi:10.1016/j.biocon.2010.05.021

Schroeder TA, Wulder MA, Healey SP, Moisen GG (2011) Mapping wildfire and clear-cut harvest disturbances in boreal forests with landsat time series data. Remote Sens Environ 115(6):1421–1433. doi:10.1016/j.rse.2011.01.022

Schwalm CR, Black TA, Amiro BD, Arain MA, Barr AG, Bourque CP, Dunn AL, Flanagan LB, Giasson M, Lafleur PM, Margolis HA, Mccaughey JH, Orchansky AL, Wofsy SC (2006) Photosynthetic light use efficiency of three biomes across an east–west continental-scale transect in Canada. Agric For Meteorol 140(1–4):269–286. doi:10.1016/j.agrformet.2006.06.010

SEMARNAT (2009). Special Program on Climate Change 2009–2012. Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), Mexico. Retrieved from http://www.semarnat.gob.mx/programas/Documents/PECC_DOF.pdf

Skinner CN, Burk JH, Barbour MG, Franco-Vizcaino E, Stephens SL (2008) Influences of climate on fire regimes in montane forests of north-western mexico. J Biogeogr 35(8):1436–1451. doi:10.1111/j.1365-2699.2008.01893.x

Skutsch M, De Los Rios E, Solis S, Riegelhaupt E, Hinojosa D, Gerfert S, Gao Y, Masera O (2011) Jatropha in Mexico: environmental and social impacts of an incipient biofuel program. Ecol Soc 16(4):11. doi:10.5751/ES-04448-160411

Skwira G, Schroeder J, Peterson R (2005) Surface observations of landfalling hurricane rainbands. Mon Weather Rev 133(2):454–465. doi:10.1175/MWR-2866.1

Spalding D (2009) The role of forests in global carbon budgeting. In: Tyrrell ML, Ashton MS, Spalding D, Gentry B (eds) Forests and carbon: a synthesis of science, management, and policy for carbon sequestration in forests. Yale Printing & Publishing Services, New Haven, p 535. Retrieved from http://environment.research.yale.edu/publication-series/5947

Toledo-Aceves T, Purata-Velarde S, Peters CM (2009) Regeneration of commercial tree species in a logged forest in the selva maya, Mexico. For Ecol Manag 258(11):2481–2489. doi:10.1016/j.foreco.2009.08.033

Turner MG (2010) Disturbance and landscape dynamics in a changing world. Ecology 91(10):2833–2849. doi:10.1890/10-0097.1

UNFCCC (1992). United nations framework convention on climate change. United Nations

Urquiza-Haas T, Dolman PM, Peres CA (2007) Regional scale variation in forest structure and biomass in the Yucatan Peninsula, Mexico: effects of forest disturbance. For Ecol Manag 247(1–3):80–90. doi:10.1016/j.foreco.2007.04.015

Vandecar KL, Lawrence D, Richards D, Schneider L, Rogan J, Schmook B, Wilbur H (2011) High mortality for rare species following hurricane disturbance in the southern Yucatan. Biotropica 43(6):676–684. doi:10.1111/j.1744-7429.2011.00756.x

Whigham DF, Olmsted I, Cano EC, Curtis AB (2003) Impacts of hurricanes on forests of Quintana Roo, Yucatan Peninsula, Mexico. In Gomez-Pompa A, Allen MF, Fedick SL, Jimenez-Osornio JJ (eds) The Lowland Maya Area: three millennia at the human-wildland interface. Haworth Press, Binghamton, pp 193–216

Wulder MA, White JC, Gillis MD, Walsworth N, Hansen MC, Potapov P (2010) Multiscale satellite and spatial information and analysis framework in support of a large-area forest monitoring and inventory update. Environ Monit Assess 170(1–4):417–433. doi:10.1007/s10661-009-1243-8