Mexican agricultural frontier communities differ in forest dynamics with consequences for conservation and restoration

Madelon Lohbeck [1,2], Ben DeVries [3], Frans Bongers [1], Miguel Martinez-Ramos [4], Armando Navarrete-Segueda [4], Sergio Nicasio-Arzeta [4], Christina Siebe [5], Aline Pingarroni [4], Germán Wies [4], Mathieu Decuyper [1,2]

1. Wageningen University and Research, Wageningen, the Netherlands
2. World Agroforestry, Nairobi, Kenya
3. Department of Geography, Environment and Geomatics, University of Guelph, Canada
4. Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Morelia, Universidad Nacional Autónoma de Mexico, Mexico
5. Instituto de Geología, Universidad Nacional Autónoma de Mexico, Mexico City, Mexico

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Abstract

Forest regrowth is key to achieve restoration commitments, but we need to better understand under what circumstances it takes place and how long secondary forests persist. We studied a recently colonized agricultural frontier in southern Mexico. We quantified the spatiotemporal dynamics of forest loss and regrowth and tested how temporal variation in climate, and spatial variation in land availability, land quality and accessibility affect forest disturbance, regrowth and secondary forest persistence.

Marqués de Comillas consistently exhibits more forest loss than regrowth, resulting in a net decrease of 30% forest cover (1991-2016). Secondary forest cover remained relatively constant while secondary forest persistence increased, suggesting that farmers are moving away from shifting cultivation. Temporal variation in disturbance and regrowth were explained by the annual variation in the Oceanic El Niño index combined with dry season rainfall and key policy and market interventions.

Across communities the availability of high-quality soil overrules the effects of land availability and accessibility, but that at the pixel-level all three factors contributed to explaining forest conservation and restoration. Communities with more high-quality soils were able to spare land for forest conservation, and had less secondary forest that persisted for longer. Old forest and secondary forests were better represented on low-quality lands and on communal land. Both old and secondary forest were less common close to the main road, where secondary forests were also less persistent.

Forest conservation and restoration can be explained by a complex interplay of biophysical and social drivers across time, space and scale. We warrant that stimulating private land ownership may cause remaining forest patches to be lost and that conservation initiatives should benefit the whole community. Forest regrowth and secondary forest persistence competes with agricultural production and ensuring farmers can access restoration benefits is key to success.

keywords

secondary succession, Landsat, Marqués de Comillas, Mexico, Chiapas, natural regeneration, soil quality

Introduction

Increasing forest cover is central to achieving restoration commitments during the 2021-2030 decade of ecosystem restoration. The extent to which forest gains contribute to restoration depend on the characteristics of these new forests. Forests are often replaced by monoculture plantations (Rudel et al. 2016, Sloan et al. 2019) with limited restoration benefits, while secondary forest could make substantial contributions (Chazdon and Guariguata 2016). Secondary forests, or natural regeneration, is less costly and more effective than tree planting (Chazdon and Uriarte 2016, Crouzeilles et al. 2017). Secondary forests are resilient, capture large amounts of carbon (Chazdon et al. 2016, Poorter et al. 2016, Schwartz et al. 2017), are host many tree (Rozendaal et al. 2019) and animal species (Dent and Wright 2009) and provide multiple ecosystem services (Zeng et al. 2019). However, the extent to which secondary forests contribute to the recovery of ecological and societal benefits depend on how long these forests persist. Secondary forests are commonly ephemeral (van Breugel et al. 2013) like in the Brazilian Amazon where median persistence is about 5 years (Jakovac et al. 2017). Instead in Costa Rica median persistence was 20 years (Reid et al. 2018), allowing substantial benefits for restoration and conservation. To make use of natural regeneration for restoration we need to understand under what conditions regrowth occurs and how long secondary forests persist. Recent developments in remote sensing allow us to track continuous disturbance-regrowth dynamics using satellite image time series (Verbesselt et al. 2010, DeVries et al. 2015a) which enables to quantify the spatiotemporal forest dynamics and identify forest ages.

In addition, little is known about the drivers of forest dynamics (but see Carreiras et al. 2014, Schwartz et al. 2017). In this study we propose that forest conservation, forest regrowth and secondary forest persistence across communities are influenced by spatial variation in three key variables: land availability, land quality and accessibility that were shown to have a close connection to colonisation frontier development and forest transition theory (Richards 1996, Mather and Needle 1998). The early pioneer stage is characterized by rapid forest clearance for subsistence agriculture and where forest regrowth takes place as fallows in shifting cultivation systems. In the second stage agricultural concentration on high-quality land may give rise to forest regrowth on marginal lands, allowing for more persistent secondary forests (Mather and Needle 1998, Smith et al. 2001). During the third stage the a market develops which increases accessibility, and may further enforce agricultural concentration on high quality lands (Mather and Needle 1998) or decouple productivity from land quality because farmers get access to external inputs. During the fourth closing frontier stage no land is left to colonise and is characterized by urbanisation, land concentration and social differentiation (Richards 1996).

We assess how differences in societal and biophysical characteristics across time and space have shaped forest dynamics in agricultural frontier communities. We studied Marqués de Comillas region (MdC), a dynamic agricultural frontier located in the Mesoamerican biodiversity hotspot in the humid tropics of Mexico. MdC provides a suitable natural experiment of landscape change in a colonization context because colonization was recent (1970's-1980's), rapid, had big consequences for forest cover, and the region is representative of many such frontier areas in the tropics (Lepers et al. 2005). Specifically, we ask 1) how land availability, land quality, and accessibility affect the extent of conserved forest, the extent and persistence of secondary forest across communities, and 2) how annual changes in climate have shaped forest dynamics.
We hypothesized that: Land availability positively influences forest conservation and regrowth because land is only spared when basic food production needs are met. Land quality positively influences forest conservation because higher quality allows farmers to produce food more efficiently. Regrowth extent and persistence may be either decreased with land quality because of shorter fallow cycles, or it may be increased because agricultural concentration leads to land abandonment on marginal lands. Accessibility decreases forest cover as the pressure on land is higher with more market access. In addition, we expected a negative interaction between land quality and land availability since with high-quality lands, less land is needed to meet livelihood needs. Finally, we expected that with accessibility, farmers will have access to off-farm income and external inputs, decreasing the effects of land availability and land quality. We further expect that sudden climatic events may cause shocks in the more gradual processes predicted by colonisation theory. The results are discussed in the light of key policy interventions which may accelerate or slow down these transitions.

Methods

Study region

The study took place in the Marqués de Comillas region (about 2000 km^2) in Chiapas, Mexico (Fig. 1). It consists of two municipalities: Marqués de Comillas and Benemérito de las Américas and one community from the municipality of Ocosingo, and is enclosed by Guatemala and the Montes Azules Biosphere Reserve on the north-western side. The original vegetation is tropical rainforest. Close to 40 settler communities colonized the region from 1972 to 1986 rapidly converting forest into agricultural landscapes (de Vos 2003). Deforestation was significantly increased by settlement of Central American refugees in the 1980s (de Jong et al. 2000). Communities were organized in *ejidos*, which is a term for the agrarian collective use of the land. Farmers vary from subsistence smallholders to those that depend partly on markets (Montes de Oca et al. 2015) and poverty levels are high (CONEVAL 2015). The region is characterized by complex human-modified landscapes consisting of crop fields (mainly maize, beans), cattle ranches, forests and plantations (Martínez-Ramos et al. 2016).

For the spatial analysis the community is the unit of replication (n = 41), which is justified by the relatively unified colonisation history in which initial settlers usually arrived together and from the same region of origin (de Vos 2003). Most communities (n = 37) are indeed formally recognized as *ejidos*, four units are not (see Fig. 1).

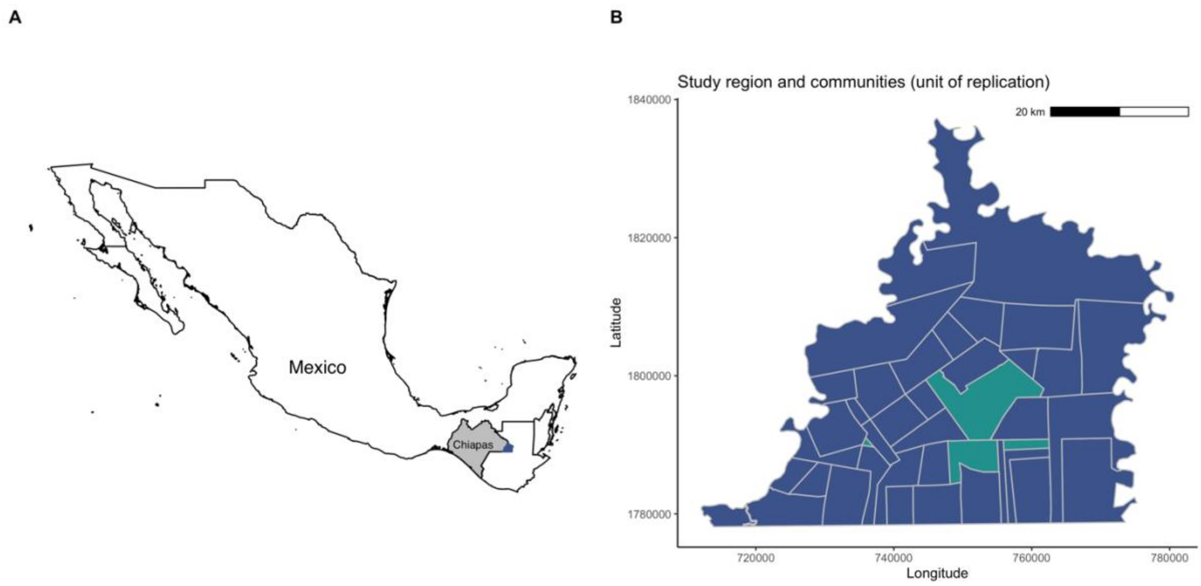

Figure 1. The 41 communities considered in this study. The dark blue units are formally recognized as *ejidos*, the green units are not. For the spatial analyses across communities only the dark blue communities (*ejidos*) were used.

Forest dynamics trajectories

To quantify forest landscape characteristics per community, we first characterized pizel-level forest dynamics trajectories using Landsat time series (1984-2016). An NDMI (Normalized Difference Moisture Index) raster stack was constructed and forest dynamics trajectories were created using on a mix of methods (detailed methods presented in Supplementary materials). A baseline was set in 1991, for which we produced a forest non-forest map using a maximum likelihood classifier applied in ArcGIS (ESRI 2012), which ensured sufficient historical data (1984-1991) as a historical reference. For pixels that were not forested in the baseline we instead used a spatial reference (DeVries et al. 2015a). To characterize disturbance-regrowth trajectories, we applied three sets of disturbance and regrowth algorithms to the monitoring period (1991-2017). Disturbances (forest to non-forest) was detected when the median NDMI anomaly exceeded -0.02 (cf. DeVries et al. 2015b). Regrowth (non-forest to forest) was detected using the *rgrowth* R package (DeVries 2015, DeVries et al. 2015a). Each method records the date at which a pixel undergoes the event and this iterative process results in six rasters representing the dates of first, second and third disturbance and regrowth dates for each pixel. Overall accuracies were 0.77 for disturbance (0.04 standard error) and 0.72 for regrowth (0.07 standard error).

Based on the baseline forest map (1991) and the pixel-level forest dynamics trajectories, we identified the state of each pixel. Old forest was forest in the baseline and no disturbance was identified during the monitoring period. This implies that old forest has been undisturbed for at least 26 years, and is not the same as old-growth forest. Secondary forest was not forested at some point in time, after which regrowth was detected and persisted until the year of interest. For pixels identified as regrowth we calculated the age (year of interest - year of regrowth). Since our monitoring period starts in 1991, the oldest secondary forest age that could be identified was 26 years (1991-2017). Secondary forest in this region rarely reach 26 years (van Breugel et al. 2006) so for the assessment of secondary forest extent and ages this is appropriate. The forest dynamics method was not designed to distinguish regrowth by secondary forest from plantations. Recent maps of oil palm were developed using Sentinel-2 imagery and an object-based image segmentation (SAGA-GIS) classification method (Fig. S2) and masked from the secondary forest and old forest maps.

Forest landscape characteristics

From the current (2017) state of each pixel, we calculated the four forest landscape characteristics at the level of the community. 1) Forest cover is the proportion of the land covered with forest. 2) Old forest cover is the proportion of the land covered with old forest. 3) Secondary forest is the proportion of the land covered with secondary forest. 4) Secondary forest age, estimated as the time (years) at which half of the forests survived (median survival) was calculated based on Kaplan-Meier survival analyses using the R-package *survival* (Therneau 2015). As one pixel may exhibit a maximum of three cycles of disturbance and regrowth, we only included the first cycle for any single pixel. Survival analyses were carried out for each community, and for the entire region. For three out of the 41 communities this value could not be estimated because the probability of survival remained higher than 0.5, in which case used 25 years as the median survival. We also split the dataset into two equal 10-year time periods (1994-2003 and 2004-2013) to evaluate shifts in median survival of secondary forests over time.

Community-level spatial drivers of forest landscape characteristics

We used six community-level indicators to quantify the drivers land availability, land quality and accessibility. *Land availability* is the access to land for farmers to produce food. For land availability we assessed the proportion of privately owned land and the proportion of communally owned land at the *ejido*-level (Registro Agrario Nacional 2020). Land available to individual landowners was quantified by dividing the privately owned land by the total number of landowners in the village (RAN; datos.gob.mx), expressed in hectares per farmer. Land available to the community was determined by the relative area of *ejido* land that is communally managed.

Land quality is the quality of the land and soil and determines what a farmer can do with the land. For land quality we used two indicators, one based on soil quality (see detailed methods in Supplementary materials), important for crop production, and one based on hydrological properties, important for cattle ranching. We calculated the median topsoil carbon based on the soil carbon contents (%) across each community and the proportion of the land covered with high productive soils (Fluvial terrace, Alluvial plain and the Karst Range of Limestone-Claystone; see Fig. S3). Hydrological properties were indicated by calculating the internal river length density (km of river length / km^2 of land area) for each community, based on data from the hydrographic network of INEGI (see Fig. S4). *Accessibility* is whether communities have access to infrastructure. With the opening of the road in 1994, the region was connected with nearby cities, but left some communities better connected than others. Accessibility of each *ejido* was included as the proportion of the land that falls within 1 km from the main road (see Fig. S5).

Temporal drivers of forest dynamics

We tested whether climatic variables explained annual variation in forest disturbance and regrowth across the region. The Oceanic Niño Index (ONI) reflects the El Niño-Southern Oscillation (ENSO). ENSO is a recurring climate pattern involving changes in the temperature of the central and eastern tropical Pacific Ocean where El Niño is a warming of the ocean surface (anomalies of 0.5 degrees or larger) and La Niña is a cooling of the ocean surface (anomalies of -0.5 degrees or larger; data derived from noaa.gov). This oscillation affects rainfall on land where Mexico receives less rain during El Niño events and more during La Niña events. As indicators of rainfall we used the total annual rainfall and the total rainfall in the dry season (February to April), as derived from the nearby Lacantún meteorological station (conagua.gob.mx).

Statistical analyses

For the spatial analyses we tested whether community-level forest landscape characteristics could be explained by drivers. Only communities formally recognized as '*ejidos*' could be included, for one *ejido* land ownership could not be estimated because it had no privately owned land, so this analysis relied on 36 communities. To test the most important drivers we used generalised linear models (glm) following a three-step approach. First, we tested a simple model without interactions, including all six community-level drivers. Second, we tested a model including all drivers and a two-way interaction between land availability and land quality. Third, we tested a model including all drivers and a three-way interaction between land availability, land quality and accessibility. The best model for each of the forest landscape characteristics was selected by first excluding models that were not significant, then excluding models for which none of the drivers were significant, we then selecting the best model based on the lowest Aikaike Information Criterion (Burnham and Anderson 2002). In case models did not differ ($\Delta AICc < 2$), we chose the simplest model. We also calculated pixel-level odd-ratios to get better understanding of the probabilities of forest to occur on land characterized by each of the drivers.

For the temporal analyses we used the year as the unit of replication ($n= 26$). For each year we used the total number of disturbance events detected and the total number of regrowth events detected. We tested whether the ONI index, the annual rainfall and the rainfall in the dry season (February to April) for that same year explained the disturbance and the regrowth. The best model was selected based on the criteria outlined above. Graphics were made in the *ggplot2* package (Wickham 2016), to estimate marginal effects we used the *ggeffects* package (Lüdecke 2018). All statistical analyses were carried out using R version 3.5.3 (R Development Core Team 2011).

Results

Forest landscape characteristics

The proportion of forest in 2017 in MdC was 0.63, of which 0.55 is old forest, 0.08 is secondary forest. Forest characteristics differ widely across communities (Figs 2, 3a)

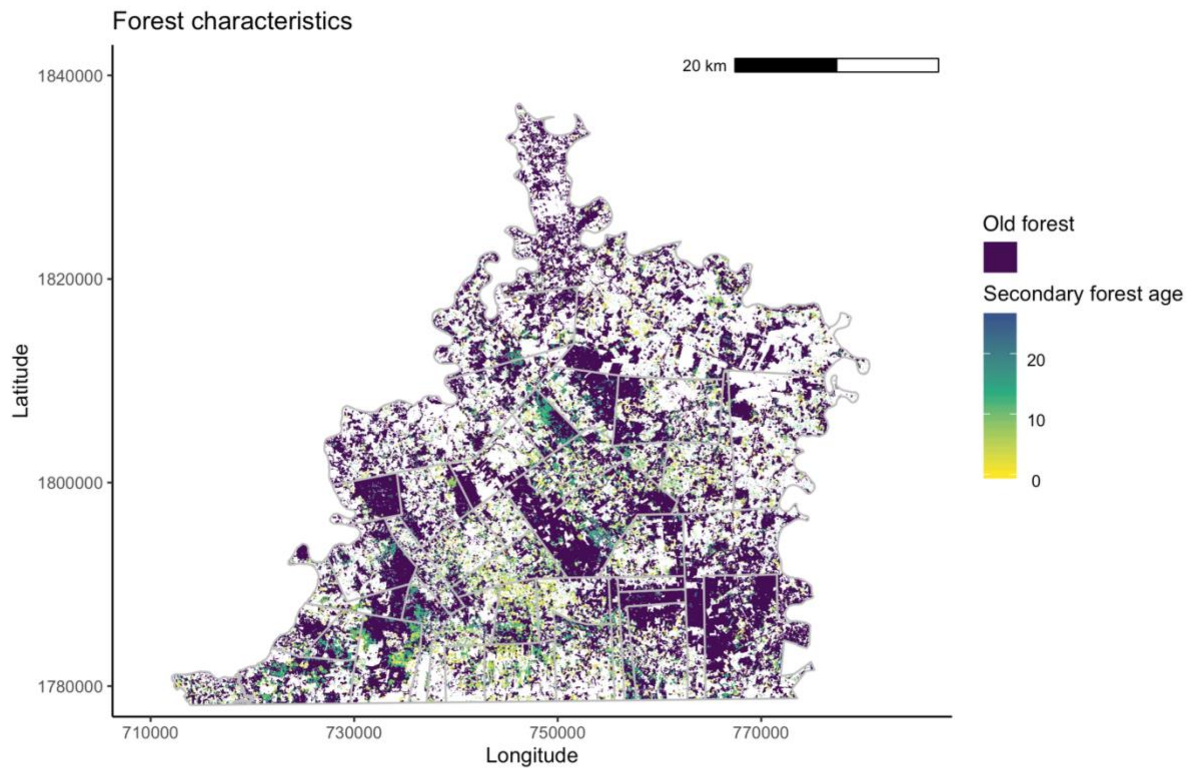

Figure 2. Map of the current (2017) forest landscape characteristics in Marqués de Comillas region, Mexico. Old forest is forest conserved for at least 26 years, blues, greens and yellows are secondary forests specified by their ages, no colour indicates no forest and can be pasture, maize field, oil palm or other land uses.

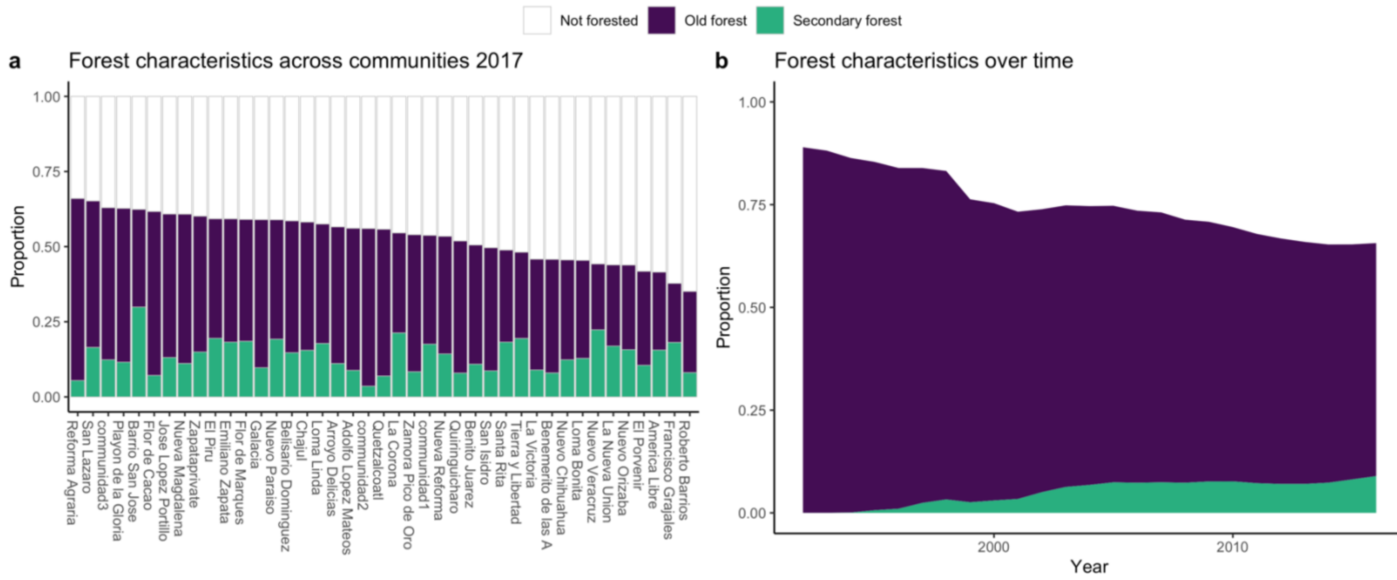

Figure 3. a) Current (2017) forest characteristics across Marqués de Comillas communities (see also Fig. 2). b) Trend in forest characteristics over time, for the entire study region. Colours indicate the proportion of old forest, secondary forest and not forested.

Marqués de Comillas consistently shows more forest loss than regrowth (Fig. 4), resulting in a net decrease of 30% in forest cover in the period 1991-2016 (Fig. 3b). A remarkable peak in forest disturbance in the year 1998 was found (Fig. 4) for which we assess its variation across communities (Fig. S6). Secondary forest cover has remained relatively constant since 2004 (7 - 8 % of land area; Fig. 3b), while secondary forest persistence has increased (Fig. 5b).

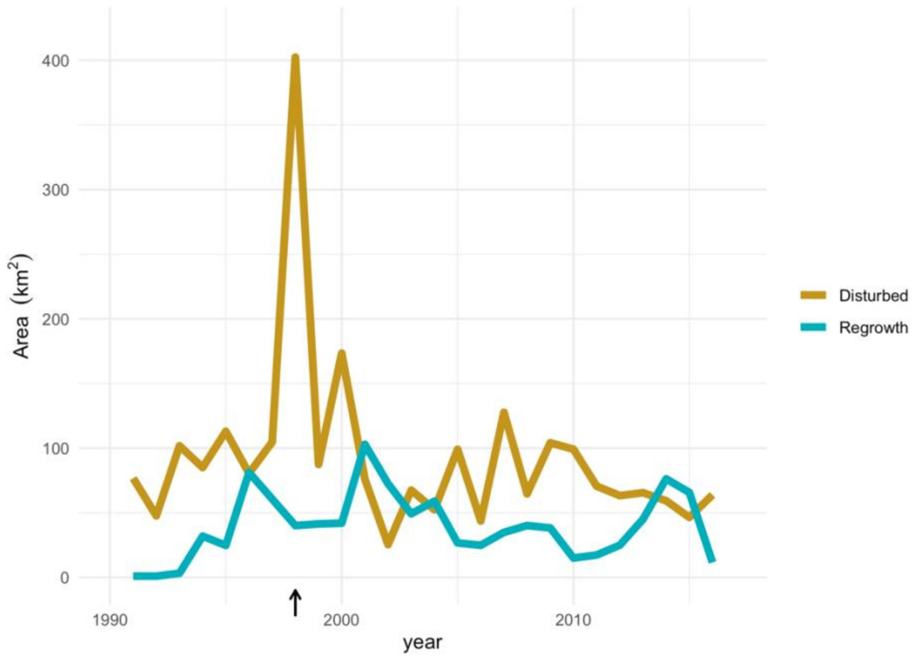

Figure 4. Total area of forest disturbed (pixels that changed from forest to non-forest) and of forest regrowth (pixels that changed from non-forest to forest) between 1991 and 2017. The year 1998 shows a remarkable peak in forest disturbance, which is also analysed for its spatial variation across communities (see Figs S6, 6).

Secondary forest in MdC reached a median age of 7 years (Fig. 5a), but values differ widely among communities (range: 3.5 - 21.4 years, mean: 8.1). Analysing the probability of surviving for two decades separately we found that there has been an increase in median secondary forest survival from 5.1 years in 1994-2003 to 7.9 years in 2004-2013 (Fig. 5b).

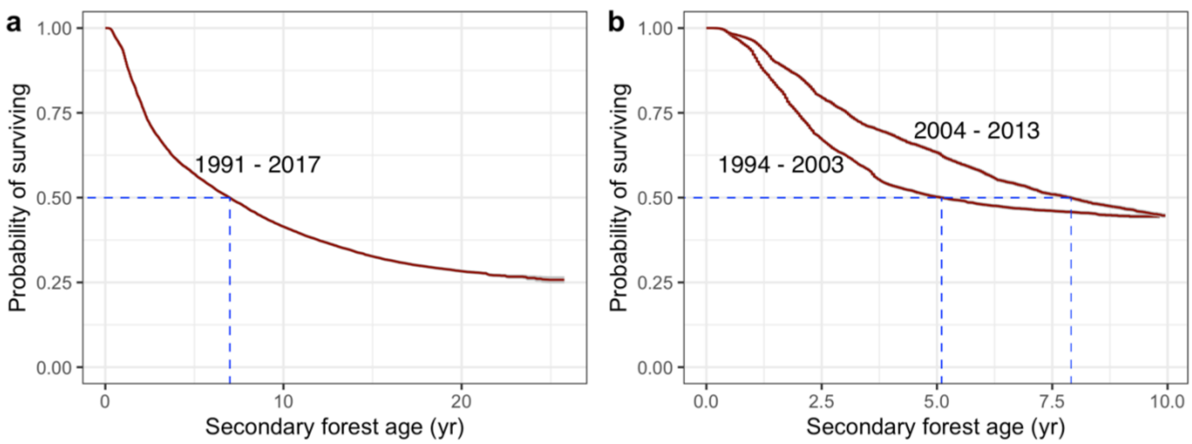

Figure 5. Survival of secondary forests across the Marqués de Comillas region as analysed with Kaplan-Meier survival analyses. Dashed lines indicate the median age (0.5 probability of surviving) of secondary forests. a) Including all years of study period 1991-2016, b) Separating data in two decades to evaluate changes in median survival over time.

Spatial drivers of forest landscape characteristics

From the four forest landscape characteristics plus the variation in area disturbed in 1998, the simple model (without interactions) best explained the data, except for secondary forest ages where the three-way interaction model fitted best (Table S2). Communities that had more land with high-quality soils tended to have more old forest (Fig. 6a), and less secondary forest (Fig. 6b) but these persisted for longer (Fig. 6c). The peak in disturbances in the year 1998 was particularly pronounced in communities that had less land with high productive potential (Fig. 6d).

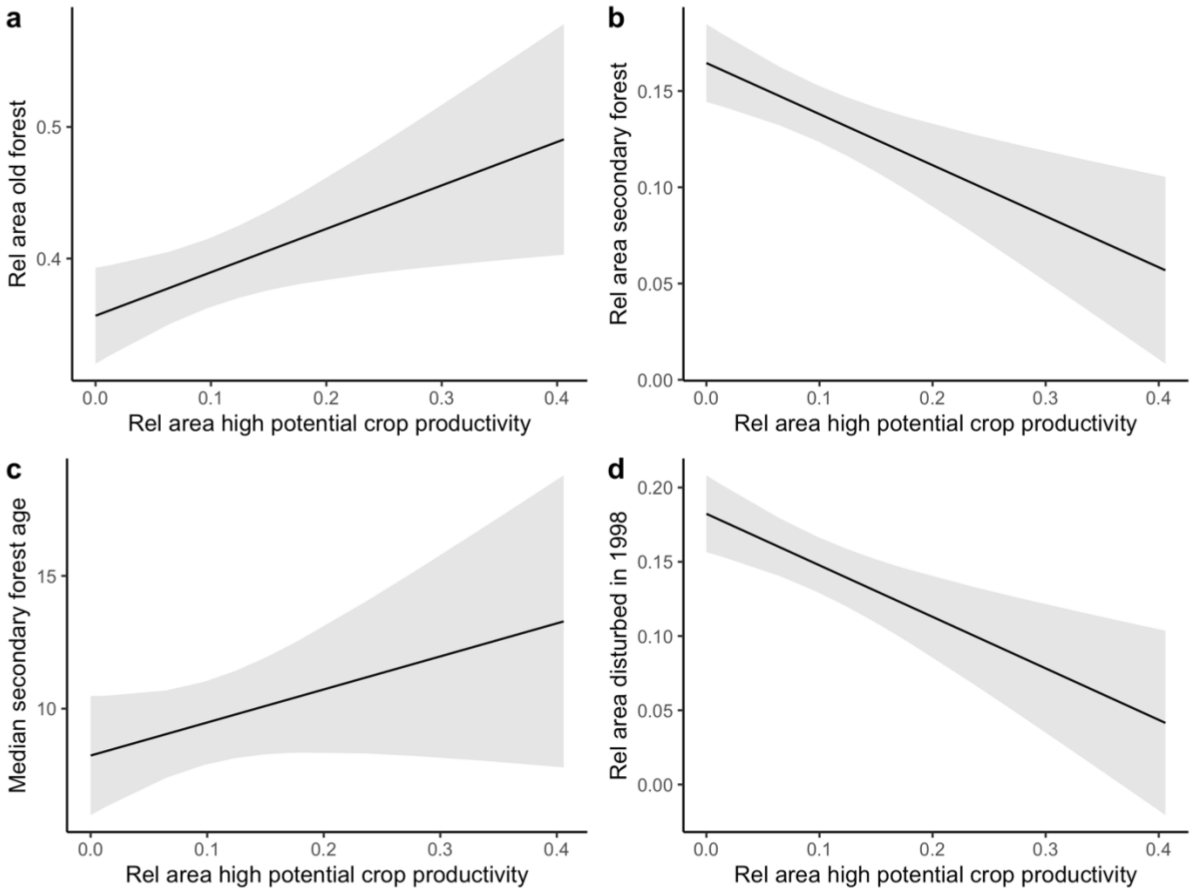

Figure 6. Results from the best fitted generalised linear model for each of the forest landscape characteristics. Given are the marginal effects of significant explanatory variables explaining differences across communities in: a) relative area covered by old forest, b)

relative area covered by secondary forest, c), median secondary forest age, d) relative area disturbed in 1998 (see Table S2 for test results).

At the pixel-level we found that all drivers contributed to explaining the probability of being covered with forest, old forest or secondary forest as well as secondary forest ages. In terms of land availability, it is more likely to find forest and old forest on communal land compared to private land and secondary forests tend to be older. In terms of land quality we found more forest and more secondary forest on low quality land, while no differences were found for old forest occurrence or for secondary forest ages. For accessibility we found all forest types to be less common inside the 1km buffer from the main road, and secondary forests tended to be younger close to the road (see Table 1).

Table 1. Odds ratios to evaluate the effect of land availability, land quality and accessibility on forest characteristics at the pixel-level. Given are the number of pixels covered with forest, old forest and secondary forest in given categories of land availability (on private or communal land), land quality (on high or low quality soil) and accessibility (within or outside the 1km-buffer of the road), the proportion of the forest type within each of the categories, and the odds ratio which indicates the ratio of the proportions of the forest type in the two categories. Odds ratios around 1 indicate the forest type is as likely to occur across the categories. Odds that differ from 1 indicate that the probability of that forest type to occur is different for the two categories, these are given in bold. The last row gives the median forest secondary forest age in each category, noteworthy differences are given in bold.

		Land availability			*Land quality*			*Accessibility*		
# pixels	total	private land	communal land	odds ratio	high quality soil	low quality soil	odds ratio	within 1 km buffer of road	outside buffer of road	odds ratio
total	2215790	1348171	677927		384495	1831295		381720	1834070	
forest	1065633	544851	406491		165526	900107		141325	924308	
proportion	0.481	**0.404**	**0.600**	**0.674**	**0.431**	**0.492**	**0.876**	**0.370**	**0.504**	**0.735**
old forest	828305	433854	345182		139477	688828		110377	717928	
proportion	0.374	**0.322**	**0.509**	**0.632**	0.363	0.376	0.964	**0.289**	**0.391**	**0.739**

secondary forest	237328	144192	71624		26049	211279		30948	206380	
proportion	0.107	0.107	0.106	1.012	**0.068**	**0.115**	**0.587**	**0.081**	**0.113**	**0.721**
median secondary forest age	10.67	**9.01**	**12.95**		10.59	10.67		**9.84**	**10.81**	

Temporal drivers of forest dynamics

Forest disturbance was best explained by an interaction between the rainfall in the dry season and the Oceanic Niño Index; El Niño years combined with lowered rainfall in the dry season led to peaks in forest clearance (Fig. 7a). Forest regrowth was best explained by rainfall in the dry season only, having a positive effect (Fig. 7b).

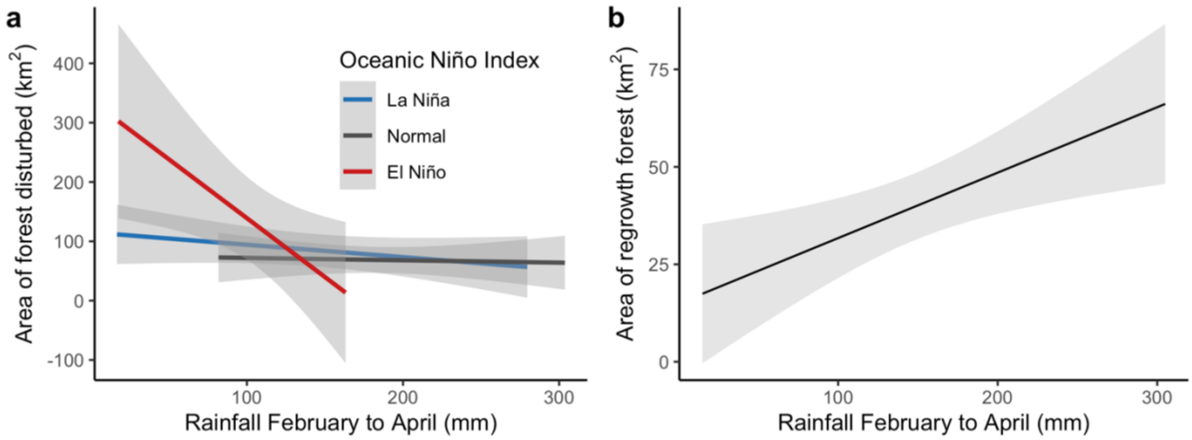

Figure 7. Climatic variation explaining the annually variation in forest dynamics (n= 26 years). a) Forest disturbance explained by the interactive effects of Oceanic Niño Index (La Niña, El Niño and normal years) and the rainfall in the dry season between February and April. b) Forest regrowth explained by the rainfall in the dry season between February and April (See Table S3 for test results).

Discussion

We quantified almost three decades of forest dynamics across in a recently colonized agricultural frontier in Mexico. Results show consistently more disturbance than regrowth and as such forest cover keeps decreasing, despite efforts to revert this. Secondary forest area has remained constant over the last decade though secondary forest persistence is increasing. We found large differences in forest characteristics among communities and these were explained only by differences in land quality. In contrast, when assessing impacts at the pixel-level, all drivers contributed to explaining forest characteristics. Forest dynamics over time was associated to climatic variation. Our results show that forest dynamics can be explained by a complex interplay of drivers across time, space and scale. Results give insights into agricultural frontier development and have consequences for conservation and restoration.

Continuous decline in forest cover

We found that forest disturbance consistently exceeds forest regrowth, resulting in a continuous decline in forest cover (Figs 3b, 4). This confirms Fernández-Montes de Oca et al. (2015) demonstrating that deforestation in the region was continuously high from 2000 to 2012, and Vaca et al (2012) who observed that forest cover continued to decline from 1990-2006. An older study covering the 1970's and 1990's already reported this forest cover decline and attributed it to policy support for agricultural expansion (de Jong et al. 2000). Although policy support for agriculture continues up to today, there seems to have been a shift from support for agricultural expansion (PROCAMPO since 1993, payments for arable fields on area basis) towards agricultural intensification (support for oil palm since 2007 and PROGAN support for cattle ranching on per-capita basis since 2008). The latter programmes, combined with those that aim to enhance conservation, such as the payments for ecosystem services programme (Costedoat et al. 2015), highlight efforts to halt deforestation and intensify agricultural production. This shift came into effect after international pressure, notably during the UN Summit of 1992, and coincided with signing the North Atlantic Free Trade Agreement (Tello et al. 2020). However, at least for MdC, these efforts have not resulted in halted or reverted deforestation.

Forest conservation

We found more old forest in communities that have more high-quality soils (Fig. 6a) though at pixel-level instead land availability and accessibility explained the probability of old forest to occur (Table 1). More conservation with better soils supports the land-sparing and agricultural intensification scenarios where agricultural production concentrates on high-quality soils and low-quality soils are spared for conservation (Mather and Needle 1998, Phalan et al. 2011). At the pixel-level, however, old forest was as likely to occur on high quality soils as it is on low quality soils. Possibly where forest is conserved is the result of two contrasting forces: on the one hand agricultural intensification favours old forest on poor soils, on the other hand, high-quality soils are often found near main rivers (see also Figs S3, S8) or in karst zones where agriculture is impractical or risky.

Odds-ratio analyses revealed that old forest is 1.5 times more likely to be present on communal land than it is on private land (Table 1), which goes against the conception that resources managed under the commons will eventually be overexploited, known as the tragedy of the commons (Hardin 1968). However this theory has been disputed by many studies (e.g. Feeny et al. 1990), and also in Mexico where communally owned coniferous forest had lower deforestation rates (Barsimantov and Kendall 2012). Other studies instead found no difference between communally and privately owned lands in Mexico, which was attributed to differences in community organisation and marginalisation (Bunge-Vivier and Martínez-Ballesté 2017, Ellis et al. 2017). These results warrant that the Neoliberal development allowing individuals to own and sell their land may accelerate forest loss in this region, as recently illustrated by a global analysis (Davis et al. 2020). It also suggests that programmes that aim to help conserve the remaining forests should ensure benefits for the entire community. Although accessibility of communities did not explain how much forest was conserved, at the pixel-level we do find that 35% more old forest occurs outside the buffer of the main road. This confirms that infrastructure determines the extent and ease in which farmers access markets, which increases land value and adversely affects forest cover (Putz and Romero 2014, Alamgir et al. 2017, Vaca et al. 2019).

Restoration: Forest regrowth and secondary forest persistence

Secondary forest covered only 8% of the land (Fig. 1), its cover remained relatively constant while median secondary forest ages increased over time (Figs 3b, 5b). This suggest a change from shifting cultivation to permanent cultivation, in line with forest transition theory and colonisation frontier development (Richards 1996, Mather and Needle 1998). Shifting cultivation was the main livelihood practice in the early pioneer stage (de Vos 2003), where secondary forests occur as part of fallows. De Jong et al (2000) estimated that secondary forests covered 17% in 1996. As agricultural frontiers increase access to markets, during the second and third stages of colonization development (Richards 1996), communities move towards more intensive land uses with cattle production and cash crops (van Vliet et al. 2012). Often this is characterized by agricultural concentration on high-quality lands allowing secondary forests to persist on marginal land (Richards 1996, Mather and Needle 1998, Smith et al. 2001). Drivers of the transition away from shifting cultivation are a mix of market development, population growth, policies and economic structures, increased land tenure security, government support for cash crops and/or cattle (van Vliet et al. 2012). In MdC similar developments have occurred: land could be owned individually since 1992 (Assies and Duhau 2009), government support shifted focus from agricultural expansion to agricultural intensification (Tello et al. 2020), and NAFTA marked the neoliberal discourse (Klepeis and Vance 2003) which caused farmers to change from crops (often in shifting cultivation) to (more permanent) cattle production (Speelman et al. 2014).

Across communities we found a large variation in secondary forest cover (4 to 30%, Fig. 3a) and in median secondary forest ages (3.5 to 25+ years). Differences across communities were explained by land quality only, while at the pixel-level all three factors mattered. Communities with more high-quality soils tended have less secondary forest that persisted for longer (Fig. 6c, d) which is explained by agricultural concentration on high-quality soils (Mather and Needle 1998). Indeed we found 70% more secondary forest on poor soils, though, surprisingly, soil did not explain differences in secondary forest ages (Table 1). Forest regrowth was also associated with poor soils in Costa Rica (Arroyo-Mora et al. 2005), though other studies found no link with soil quality (Sloan et al. 2016). Median secondary forest ages (up to 21 years) reach beyond what is expected in shifting cultivation, also confirming a change away from shifting cultivation. Results suggest that restoration is only an option in communities with access to high-fertile lands and that incentivising farmers may be needed to further increase the restoration potential of secondary forests (Rudel et al. 2016, Chazdon et al. 2020). The current PES programme, however, effectively excludes secondary forests due to the programme’s minimal area requirements. We found more persistent secondary forests on communal land, reflecting a similar pattern to old forests. Secondary forest was 30% less likely to be present within 1 km of the road where it was also less persistent, similar to findings from Peru (Schwartz et al. 2017).

Temporal drivers of forest dynamics

The method we employed allows a unique and detailed historical trajectory of disturbance and regrowth events, which is valuable to analyse drivers of variation in space and time. We found that variation in climatic conditions explained the variation in disturbance and regrowth over time. More forest is disturbed in El Niño years that had extreme drought in the dry season (Fig. 7a), which is driven particularly by the year 1998 that showed a four-fold increase in disturbance (Fig. 4) and had extreme socioeconomic consequences (Buizer et al. 2000). In MdC people combined it with deliberate forest fires to clear land for agriculture (Román-Cuesta et al. 2003, 2004). The proportion of area cleared in that year was negatively related to the proportion of land suitable for permanent cultivation (Fig. 6d), suggesting that 1998 was taken as an opportunity to easily clear lands with less potential. The price-changes resulting from NAFTA (Speelman et al. 2014), that made cattle ranching more popular, may have paved the way for the increased forest clearance. Forest regrowth instead was elevated in wetter years (Fig. 7b), similar to findings in the African Sahel and Southern India (Xiao and Moody 2005). Land use is the result of a complex interplay of drivers across scales, as illustrated by the 1998 disturbance peak which coincided with an El Niño event and followed changes in tenure security, government support programmes, and changing commodity prices. This is true also for forest regrowth, and similar to findings in the Sahel (Sendzimir et al. 2011).

Limitations of this study

Our method on pixel-level forest dynamics yielded good overall accuracies but probably overestimated the current amount of old forest and underestimated the area not forested and under secondary forest. While we found 55% old forest and 8% secondary forest, INEGI 2011 estimated 42% of forest cover, including both old growth and secondary forest (INEGI 2010). Estimates based on plot-data in the southwestern part of the region estimated 33% old-growth forest and 17% secondary forest (Zermeño-Hernández et al. 2016). Although definitions of old forest and of secondary forest may partially underlie this (in our case old is older than 26 years), we expect that model assumptions also played a role. Our method took a conservative approach to detecting disturbance or regrowth with thresholds that reduce commission errors but may increase omission errors. As a consequence some disturbances will go undetected (increasing old forest cover), and that some regrowth will go undetected (decreasing secondary forest cover). This may apply particularly to regrowth which remains hard to identify due to its gradual nature (DeVries et al. 2015a). Although we recognize this bias, such errors will apply homogenously to the whole region, and thus not affect our results in terms of the drivers across time and space.

Recommendations and conclusions

We found that forest conservation and regrowth can be explained by a complex interplay of drivers across time, space and scale. We warrant that further stimulating private land ownership will lead remaining forest patches on communal land to be lost and that initiatives geared towards enhancing forest conservation should benefit the community. To ensure that secondary forests contribute to restoration targets, forest regrowth and secondary forest persistence should be stimulated which requires incentivising farmers to set aside land for restoration (cf. Chazdon et al. 2020).

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Authors’ Contribution Statement

ML conceived the idea, carried out the statistical analyses and led the writing. MD and BdV performed the remote sensing analyses. ANS and CS have collected data for the soil properties and created the map on geomorphical units, SN and GW have created the oil palm map. All authors contributed to the writing and have approved the final version of this work.

The authors declare no conflict of interest

Please refer to the supplementary materials for:

Detailed methods on forest disturbance and regrowth identification

Detailed methods on soil properties across the geomorphic units

Figure S1. Illustrating the forest dynamics trajectory method and validation

Figure S2. Map of oil palm plantations in Marqués de Comillas, Mexico

Figure S3. Geomorphic land units across Marqués de Comillas and their values for high-productive potential and soil organic carbon

Figure S4. Internal rivers in Marqués de Comillas region

Figure S5. The main road (built in 1994) that connects communities in Marqués de Comillas region

Figure S6. Forest disturbance in year 1998 in Marqués de Comillas region

Figure S7. Map with formally registered lands under private and communal ownership across Marqués de Comillas region

Figure S8. The main rivers that border Marqués de Comillas region

Table S1. Soil sampling across the six main geomorphic units and across land uses

Table S2. Test statistics for the drivers of forest landscape characteristics across communities

Table S3. Test statistics for the drivers of dynamics over time

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