



Deforestation and secondary growth in Costa Rica along the path of development

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Abstract

Over the past 50 years, Costa Rica has experienced extensive landscape changes. It is, therefore, important to understand the historical changes that have occurred and how the forests will change in the future, which provides the objective of this study. To determine the historical deforestation trends and link them to the different biogeophysical and socioeconomic variables, forest maps from 1960 to 2013 were used in the Dinamica Environment for Geoprocessing Objects (Dinamica EGO) to create deforestation models for Costa Rica. The base model was built and analyzed for changes in landscape metrics such as patch size and distance between 1960 and 2013. After validation of the model's ability to replicate patterns, the landscape change was then projected to 2069. The historical model validated at 85% accuracy within 600 m for both the 2005–2013 and 1997–2005 iterations. All national future projections exhibited an increase in forest area, including the most extreme deforestation scenarios. Future projections are increasingly important given changes in the global socio-political structure, climatic change, and the ever-increasing globalization of capitalistic endeavors. The trajectory of the forest in Costa Rica can also serve as a way to track both these global pressures on the natural landscape, and as a proxy for how to manage deforestation in other similar political and geographic areas of the tropics.

Keywords Land cover change · Environmental modeling · Dinamica EGO · Deforestation trends · Environmental legislation

Introduction

In Costa Rica, the economic incentives for expanding the cattle industry began in the 1950s, with an increase in the international market price of meat driven by a majority of exports being directed towards the USA (McDade 1994). In the 1960s, pasture land expanded by 62%, with much of the growth located in Guanacaste (McDade 1994). By 1972, Guanacaste was the center of Costa Rican cattle ranching and was the site of over 40% of production in

this industry (Ibrahim et al. 2000), leading Costa Rica to have one of the highest deforestation rates globally (Sanchez-Azofeifa et al. 2001).

In the 1980s, there was a collapse of the meat market, leading to farm abandonment, and increased government interest in conservation in the latter part of the decade (Bender 2012; Sanchez-Azofeifa et al. 2003). This resulted in over 25% of the country belonging to protected areas, with only restricted uses allowed, and incentives introduced to diversify the economy (Bender 2012; Powell et al. 2002). The effectiveness of protected areas, however, continues to remain debated in the literature (Lopez-Carr and Burgdorfer 2013; Joppa and Pfaff 2010; Pfaff et al. 2017; Robalino et al. 2017). At a coarse scale, protected areas appear to increase the amount of forest that remains intact; however, at a fine scale, there is micro-fragmentation and degradation that persist (Barber et al. 2012). The effectiveness of both protected areas and local participation in forest management is largely considered site-specific. Regions directly adjacent to protected areas are also important to monitor for spillover effects and increased degradation (Andam et al. 2008; Robalino et al. 2017; Ferraro et al. 2012).

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Protected area status does not compare with soil, topography, remoteness, population growth, economic considerations, and infrastructure pressures for deforestation protection (Ellis and Porter-Bolland 2008; Porter-Bolland et al. 2012), making it essential to consider the economic pressures on current forest extent in Costa Rica. Recent economic endeavors include ecotourism, technology manufacturing, and payments for ecosystem services markets, but much of the GDP still comes from cash crops and cattle (Jones and Spadafora 2017; Le Coq et al. 2015). With projections of food shortages due to population growth, agricultural expansion may be required, leaving the future of the Costa Rica's non-protected forest in question (Mancosu et al. 2015).

Technology and methodology advancements over the past decade have enhanced the quality and quantity of land cover change (LCC) research in tropical environments (Fischer and Lindenmayer 2007; Kuenzer et al. 2014; Verburg et al. 2015). Cellular automata models use an algorithm to drive how different pixel changes migrate through multiple time steps, which makes the model highly applicable in time-series LCC analyses and project landscape changes into the future (Wolfram 1983; Mas et al. 2014). One such platform, Dinamica Environment for Geoprocessing Objects (EGO), combined this statistical power with the information-dense geographic information systems field (Soares-Filho et al. 2009). This created an open-source platform that has been increasingly used for Amazonian deforestation, urban studies, and policy assessment due to its high adaptability, communicability, and ability link inter-scale information (Soares-Filho et al. 2014; Leite et al. 2012; Nunes et al. 2012; Stan et al. 2015).

Despite these advances, there remain gaps in integrating biophysical, socio-economic, and legislative information in the LCC modeling field and with the variability of quality information in different study areas of Costa Rica, which provides motivation for this study. The objectives of this paper are, therefore, to (1) study the areal extent and spatial pattern of the Costa Rican forests between 1960 and 2013 and (2) determine how those changes will progress into the future (2013–2069). These changes will be based on modifying the historical rates and include the development of the protected areas legislation. Patch metrics and fragmentation will be included as a measure of connectivity. Both provincial and national boundaries will be used to find differences in socio-political areas across the country. The deforestation models will be constructed using the Dinamica EGO platform and will include biophysical, socio-economic, and legislative variables as change driver inputs.

Study area

This study was conducted in Costa Rica. The country's extent is estimated to be 51,100 km², with a population of 4.9 million people, and an estimated GDP of \$57.4 billion as of 2016

(World Bank Development Data Group 2017). There are two coastlines and two mountain ranges spanning the center of the country, the Cordillera Volcanica and the Cordillera de Talamanca (Stansifer et al. 2017), and the main forest types are montane forest, coastal mangroves, seasonally tropical dry forests, and an array of humid/rain forests, although these are not differentiated in this study (Holdridge 1967). Despite its small area, Costa Rica has one of the highest biodiversity index ratings globally due to its high number of species and endemic organisms (National Biodiversity Institute 2014; Global Environment Facility 2007). This biodiversity is balanced by cleared rangeland and agriculture areas which support farming, ranching, growing urban areas, and a dense network of roads to connect the country (Zahawi et al. 2015; Lopez 2003). The climate ranges from semi-arid to humid zones with a consistent temperature and a dry season ranging from 1 to 7 months (Enquist 2002) (Fig. 1).

Data

The Dinamica Environment for Geoprocessing Objects (Soares-Filho et al. 2009) requires at minimum two landscape maps. In this case, the historical landscape maps from 1960, 1979, 1986, 1997, 2005, 2010, and 2013, utilized in the historical analysis, were classified by Sanchez-Azofeifa (2015). The 1960 map was generated using aerial photographs from 1950 and 1965. The maps from 1979, 1986, 1997, 2005, and 2013 were all generated by Landsat images, while the 2010 map was generated using the SPOT satellite (Sanchez-Azofeifa 2015). The maps from 1997 to 2013 had 1500



Fig. 1 Costa Rica is located in Central America and divided into seven provinces

control points, were independently validated in the field, and had errors of 5–10% (Sanchez-Azofeifa 2015). The original images were pre-processed for relative humidity and aerosols (Sanchez-Azofeifa 2015), classified into forest/non-forest regions (Sanchez-Azofeifa 2015), and resampled to 240 m for modeling. This resolution was chosen to balance the original 30-m image resolution with the biogeophysical datasets which ranged between ~120 m and county-based resolution. The interest of the Costa Rican government and researchers has been on collecting forest data which leads to this forest/non-forest classification, instead of including other land covers such as agriculture and silviculture as has been done in other LCC models (Rosa et al. 2014).

Biophysical maps including geology, topography, slopes, river and water routes, biological corridors, geomorphology, and watershed delineation were used as supplementary information for the predictive models and scenarios (Fig. 2, Table 1). Legal boundaries of land, including protected areas, indigenous zones, and biological reserves, were included (Table 1). One final class of variables also inputted into the models was anthropogenic information on population change, road development, and land usability assessments (Table 1).

Methods

Using Dinamica EGO, the amount and pattern of forest cover in 1960, 1979, 1986, 1997, 2005, and 2013 were assessed for

the first study component. This long history of maps is important for understanding the entire picture of how the state of the current Costa Rican forest system has occurred and for consistency of analysis. The maps were analyzed for changes from forest to non-forest and non-forest to forest, by province and for the country. The images were assessed for both deforestation and regeneration to determine the overall trends and an inflection point of shifting trends. Additionally, patch numbers, sizes, and distances apart were calculated for forest and non-forest. Mean patch sizes and distances were assessed for the statistical difference between 1960, 2013, and the 2069 projections.

For the second component, using the historical changes from the past two decades (1997–2013) as a baseline, a Dinamica EGO model was built and validated. The 1997, 2005, and 2013 maps were chosen because of their consistency in classification techniques (from Landsat), validation against independent field measures, and the number of years between the calibration/validation (2005–2013) and transferability data (1997–2005). These features help to reduce non-systematic errors within the model and increase the model’s ability to replicate both quantity and patterns of change in the projected forests. The biophysical and socioeconomic variables were used as auxiliary data to create a cube map for comparing areas of deforestation and regrowth. The level of each variable is compared to the changes or stability in an area and assigned a weight of evidence using a Bayesian statistical algorithm (Soares-Filho et al. 2009; Ferreira et al. 2012; Maeda et al. 2010). These variable weights are then used on

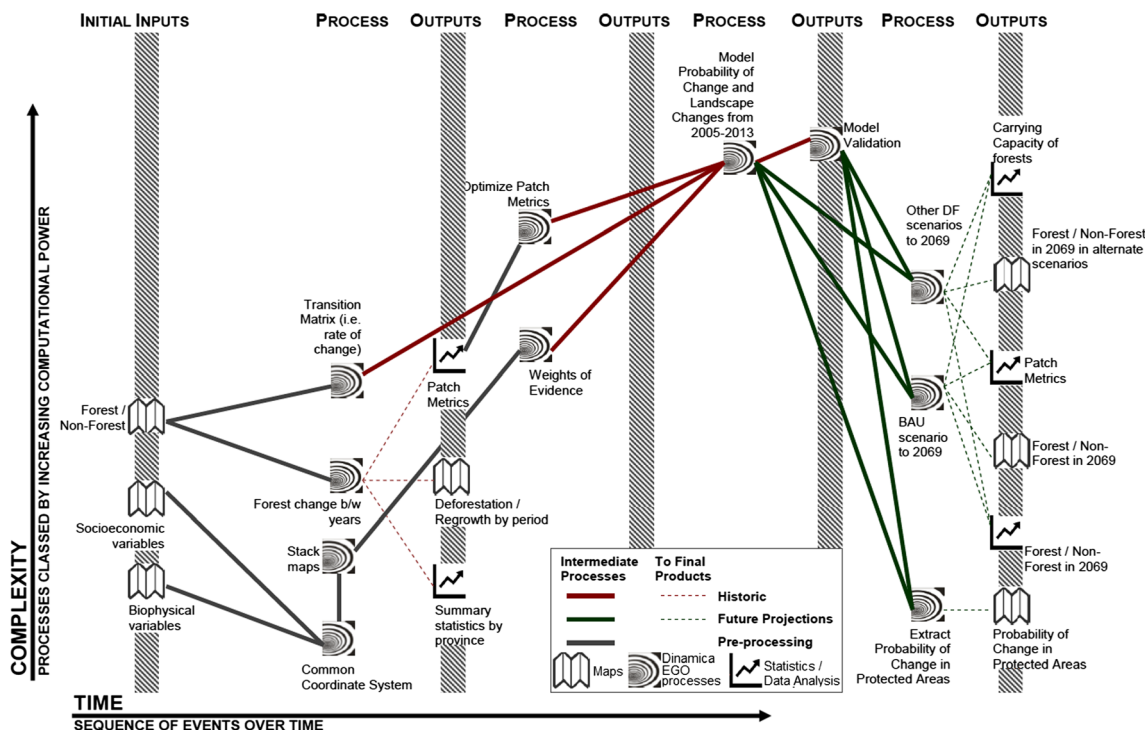


Fig. 2 The model workflow for Dinamica EGO

Table 1 The model training data including resolution, source, and year

Map name	Type/resolution	Source	Year
Biogeophysical variables			
Biologic corridors	Shapefile/min area = 18 km ²	Programa Corredores Biológicos SINAC 2009	2008
Biotic zones	Shapefile/min area = 2.5 km ²	Centro Científico Tropical (CCT)/Ministerio de Agricultura y Ganadería (MAG)	N/A
Digital elevation model	Raster/11 m	Proyecto Atlas Digital de Costa Rica	N/A
Fire risk	Shapefile/min area = 14 m ²	Part of Ana Irene Jimenez's work—Utilization of a Geographic Information System for the Determination of Risk Zones in order to Secure Forest Plantations	N/A
Geology	Shapefile/min area = 1643 m ²	José Alberto Fernández Solórzano	
Geomorphology	Shapefile/min area = 0.30 km ²	Unknown—Atlas of Costa Rica	
Rivers	Shapefile/line data	GEOTECNOLOGIAS S.A.	N/A
Slopes	Raster / 11 m	Derived from the DEM	N/A
Soils	Shapefile/min area = 1.5 km ²	MSc. Rafael Mata, Alban Rosales y Alexis Vásquez, D'Angelo Sandoval	2008
Watersheds	Shapefile/min area = 1124 m ²	Ing. Vladimir Jiménez	2008
Socioeconomic variables			
Distance to roads	Raster/240 m	Unknown—Atlas of Costa Rica	2008
Population change	Shapefile/district level data	GEOTECNOLOGIAS S.A.	1997–2000
Protected areas (including biological reserves)	Shapefile/min area = 23,143 m ²	SINAC	2008
Usability	Shapefile/mean area = 40.8 + 225 km ²	Unknown—Atlas of Costa Rica	2008

All vector data resampled to 240 m raster data. All data was compiled by the School of Forestry Engineering at TEC in Costa Rica to create the Atlas of Costa Rica

N/A not available

the initial map to create a probability map of how likely it is that each individual cell changes to another cover type (Soares-Filho et al. 2009; Ferreira et al. 2012). The complex topography and competing driving variables in various portions of the country made it essential to run the model by province and subsequently consolidate the national results. It is also important to note that the intraprovincial drivers have more impact compared to interprovincial drivers on the forest change. The impact of elevation dynamics with micro-meteorology, soil, and human factors varies across the study, impacting ecozones differentially. This was evident by the model's ability to replicate the historical change forest at a provincial level and not when combined into a generalized national model.

Two functors, a series of algorithms that perform a particular operation (Expander and Patcher; Soares-Filho et al. 2009), and the rate of change are utilized to project the landscape forward in time. The model's Expander and Patcher functions work complementarily (Soares-Filho et al. 2009) with Expander contracting or expanding existing patches using the historic metrics and Patcher using the fragmentation metrics to create new patches of an appropriate size, isometry, and isolation (Berberoglu et al. 2016; Soares-Filho et al. 2009; Maeda et al. 2010). The fragmentation metrics are optimized using the

historical data, to replicate the pattern of landscape development as the model is stepped into the future. The amount of land allocated to each functor is based on the rate of change and identification of the historical landscape changes in particular areas. For validation, Dinamica EGO compares the later time step map to the model simulation in an iterative manner, with a moving window size from 1 (the same pixel) to 13 pixels. The amount of deforestation is driven by the transition matrix, and the model validates the accuracy of the location of deforestation/regrowth. The model was validated at 85% within 2.5 pixels for the 2005–2013 time step and performed consistently (also 85% accurate within 2.5 pixels) for the 1997–2005 time step which was used to assess transferability between years. Moving into the future projections, it is essential that the time steps must be equivalent to those found in both the training and transferability data (i.e., 8 years).

The historical rates of change (1997–2013) were used to create a business-as-usual future scenario, and these rates were modified by province to increase deforestation by 1%, 2%, and 5%, and increase regrowth by 1%, 2%, and 5% (coded DF1, D2, DF5, RF1, RF2, and RF5, respectively). These rates provide an array of moderate and extreme scenarios and encompass the historical rates of change, even from the height of deforestation in the 1960s era (Sanchez-Azofeifa et al. 2007).

The changes in forest cover were assessed provincially and then aggregated to a national level, just as in the historical assessment. While transboundary impacts are important to consider, the historic model found that within province drivers outweigh the interprovincial effects.

To test the importance or relevance of protected areas, they were included and removed from a future BAU scenario model. The protected areas dataset is used in the models and to determine the effectiveness of this policy, and uses all protected areas designated by 2008, as the area set aside post 2000 is < 3%. The probability of each area being deforested was then assessed in a severity index. If the majority of the park had an average probability of deforestation at > 40%, it was multiplied by the potentially affected area to determine the “severity index” or the potential impact if the area was not protected.

Results

Historical model/business as usual

Between 1960 and 2013, there was a drop in the total amount of forest, with a high rate of deforestation from 1960 to 1986 (Figs. 3 and 4). Subsequently, there was an apparent reversal of the trend with net regrowth up until 2013 (Figs. 3 and 4); however, only half of the forest has been recovered. The Cartago, Guanacaste, and Puntarenas provinces have contributed the most to Costa Rican deforestation (70%; Fig. 4), with the 1960–1979 era contributing the most to the deforestation across all provinces with > 40% in the southern provinces, and

30–40% in the north. Regrowth has been more consistent across the time periods, but Guanacaste has seen the highest proportion of overall regrowth (Fig. 4). Overall, 69% of the total deforestation occurred between 1960 and 1986, and 66% of the regrowth occurred in the post-1986 era (Fig. 4).

T tests were used to establish changes in the patch sizes and showed a significant decrease in the mean ($p = 0.02$). In 1960, the average patch size was approximately 33 km², while in 2013, it was < 1 km², an ~ 100% drop (Table 2). There was an increase in the number of smaller non-forest patches, which drove a patch size decrease in the non-forest class, although it was not significant (mean 1960: 54.2 km²; mean 2013: 3.4 km²; $p = 0.15$). Patch distance was slightly different with significant decrease in distance between 1986 and 2013 for both forest (1960: 0.8 km; 2013: 0.5 km; $p < 0.0001$) and non-forest (1960: 1.0 km; 2013: 0.6 km; $p < 0.0001$). The greatest decrease in patch size occurred in 1960–1986, similarly to the highest deforestation rates (Fig. 5). After 1986, the patch sizes stabilized (Fig. 5).

Projections

The BAU scenario exhibited an expansion of forest to the 1960’s extent by 2040, and stabilization in 2062 at 32,314 km². The most extreme deforestation scenario (DF5) stabilized in 2068 at 27,156 km², a 2000 km² increase compared to present. The highest regrowth scenario, RF5, leveled in 2063 at 34,456 km² of forest. Mean patch size does not change significantly between 2013 and 2069 (Table 2) in any scenario, and there is a non-significant difference between the business as usual and largest regrowth scenario (BAU:

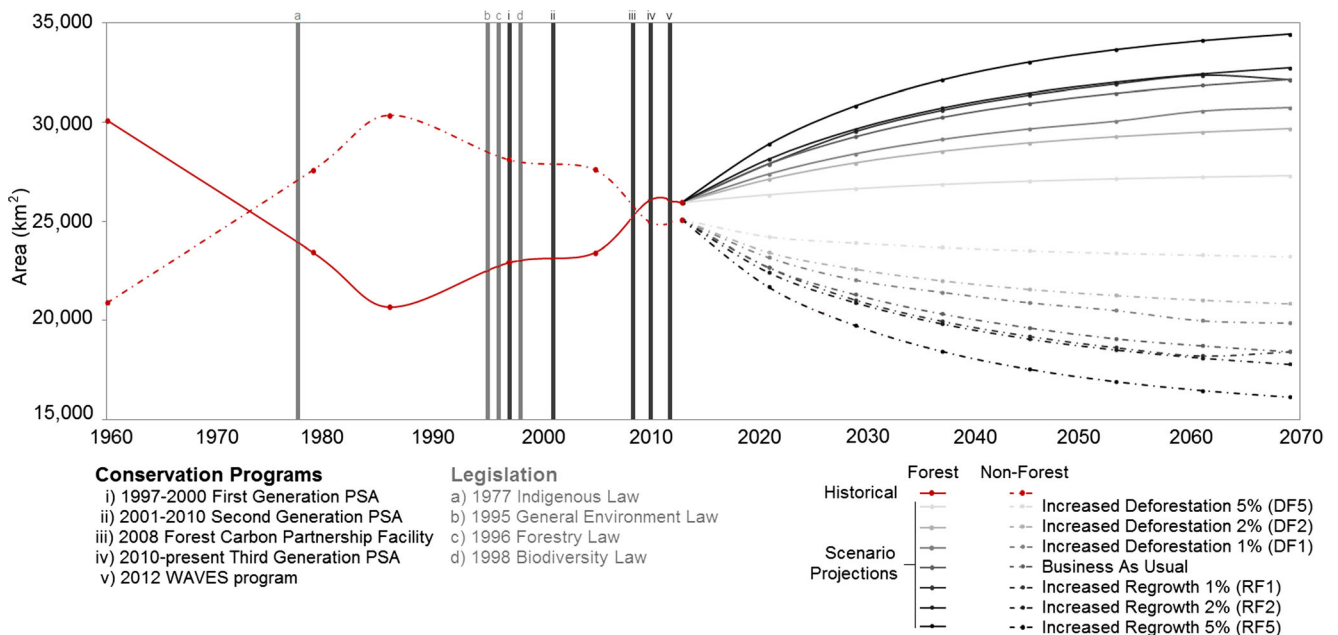


Fig. 3 The historic and future scenarios forest and non-forest areas

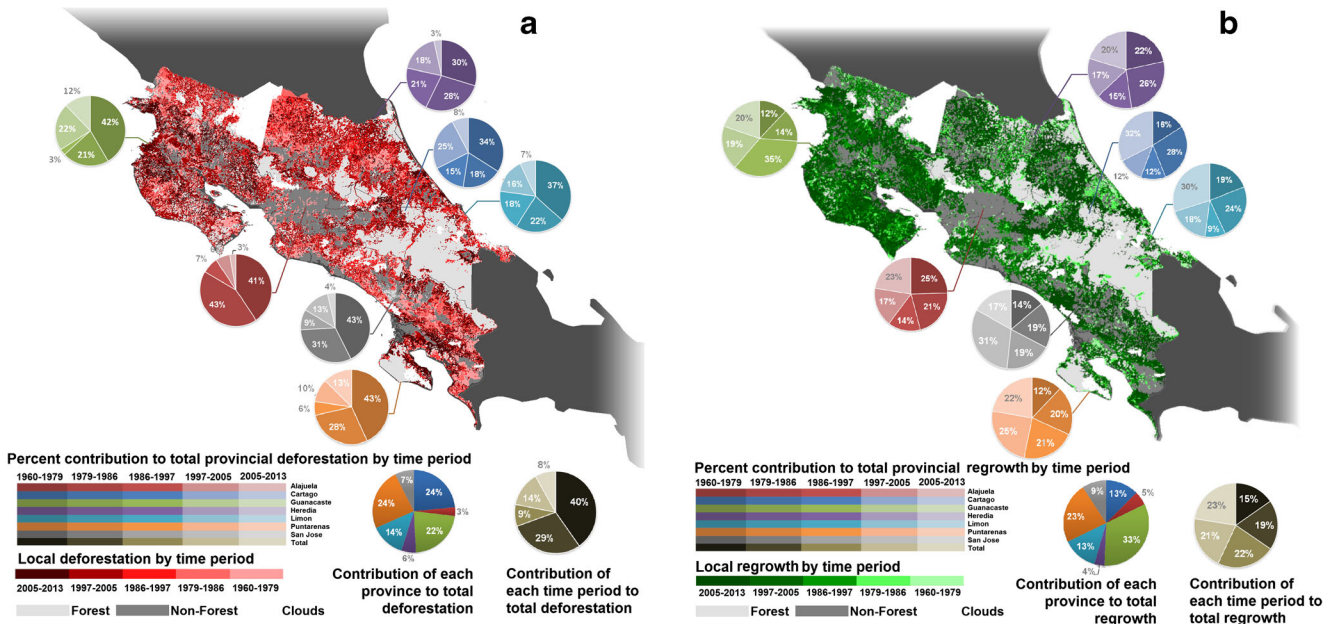


Fig. 4 The pattern of deforestation (a) and regrowth (b) between 1960 and 2013. Includes the contribution by time period to the total deforestation overall and by province. Also includes the total contribution by province to the total deforestation

4.4 km²; RF5: 16.0 km²; *p* = 0.19). This also applies for the non-forest, where there is a non-significant decrease in patch size between the BAU and regrowth scenarios (BAU: 3.8 km²; RF 5: 1.8 km²; *p* = 0.27).

Changes in forest extent are not equally distributed between all seven provinces of Costa Rica, though all experienced net regrowth in the BAU scenario. Deforestation centered in the Puntarenas and Guanacaste provinces, while the north and patches adjacent to large tracts of current forest experience regrowth (Fig. 6). In the most extreme deforestation scenario (DF5), the Puntarenas province experienced net deforestation, and Guanacaste had an approximately net zero change.

In the protected areas scenario, we found that there were 13 protected areas > 1 km² that an average probability of being deforested > 40% for > 50% of the park (Fig. 7). When multiplied by the potentially impacted area within the park, Golfo Dulce and Santa Rosa National Park would have the most severe impact on the environment if they were no longer protected areas.

Table 2 The mean patch size and change in patch size between 1960, 2013, and 2069

Mean forest patch size		
	Patch size (km ²)	Change in size (percent difference)
1960	33.5	
2013	0.9*	- 32.6 (- 98.8%)
2069 (BAU)	4.4	+ 3.5 (+ 389%)

**p* < 0.05

Discussion

Resistance is the forest’s ability to persist through change, and resilience is the system’s having the ability to recover to a state near its original (Duveneck and Scheller 2016). The future projections assess the Costa Rican forest’s resistance and resiliency under both extreme and moderate projection scenarios. Even the highest deforestation rates only produce forest loss in Puntarenas, with a net-zero change in Guanacaste. Puntarenas and Guanacaste are, therefore, the provinces to monitor closely for symptoms of change and increasing

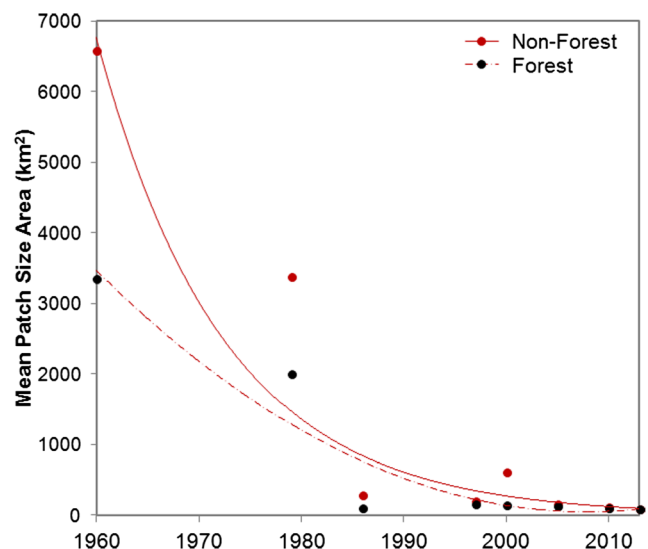


Fig. 5 The change in mean patch size each decade between 1960 and 2013

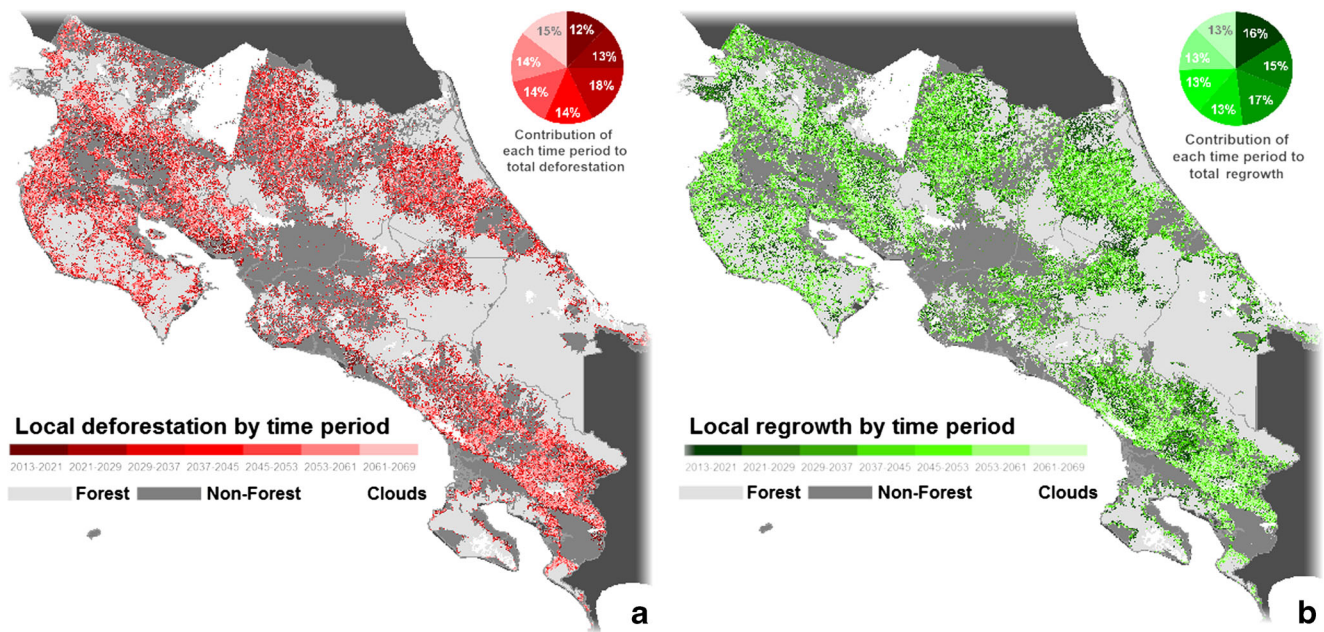
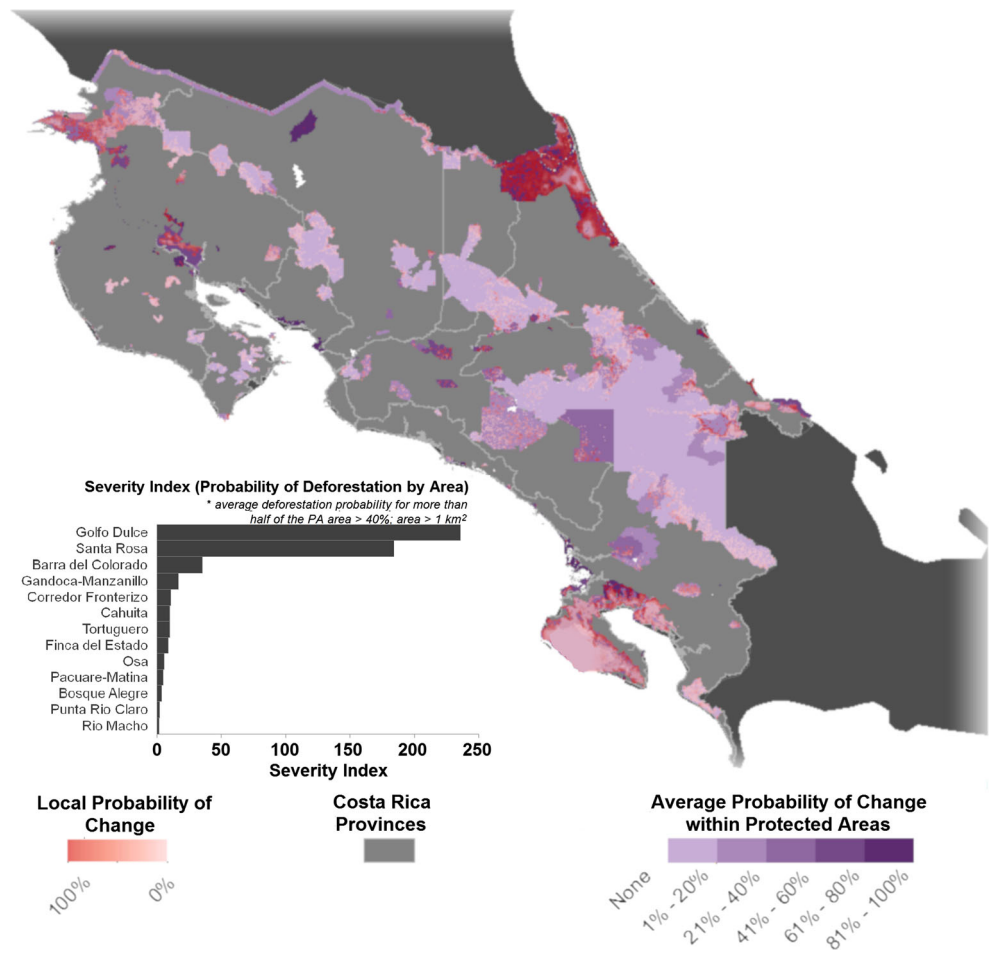


Fig. 6 The projected deforestation (a) and regrowth (b) by time period to 2069

deforestation and to implement pilot projects or community management techniques to avoid deforestation.

When looking at historical deforestation, especially from 1960 to 1986, economic factors drove forest loss, with

Fig. 7 The local and average park probability of deforestation within protected areas if they were no longer legally protected. Also includes a metric for the impact if the area was no longer protected. The severity index multiplies the probability of deforestation with the potentially impacted area



ranching as the primary driver during this time (Castillo et al. 2013; De Sy et al. 2015; Gasparri and Waroux 2015). Within that time period, there were five economic phases that have been identified: (i) 1950–1963—shifting from an agriculturally based to international trade economy; (ii) 1963–1973—expansion of internal regional agriculture trade markets; (iii) 1974–1978—industrial development and increased imports; (iv) 1978–1982—economic crisis; (v) 1983–1989—post-crisis recovery (Sanchez-Azofeifa 2000). In the post-1989 era, we have moved beyond this post-crisis recovery into the conservation-based, diversified economy. While reforestation efforts in the later 1970s were insufficient to reverse forest loss, carbon sequestration initiatives increased interest in environmental conservation (Sanchez-Azofeifa et al. 2001). Conservation areas initially reduced deforestation in localized areas, but over time, this was insufficient to balance agricultural expansion (Sanchez-Azofeifa et al. 2003), a finding echoed here. In period between the late 1980s and 1990s, Costa Rica experienced a great degree of diversification as well as several new government-driven reforestation policies (Sanchez-Azofeifa 2000). These changes on economic and conservation policies were also in tandem with the sale of their land by many rural farmers, who in turn migrated to the country's largest cities. With these changes in both migration, economic, and environmental policies, new environmental education programs were created to support elementary and high school education with the goal of building a collective sustainable conscience in the country (Castillo et al. 2013). This fundamental shift in how the human-environment interaction is framed in Costa Rica indicates that the regeneration seen in most recent decades is supported by a strong foundation of environmental conscientiousness. This interplay of government, economic, and cultural shifts supports the continuation of this trend into the future.

The regeneration of forest patches is a promising result, but its non-significance means additional measures are imperative for increasing forest connectivity. Fragmentation damages the diversity and quality of remaining forests, with the edges experiencing extreme temperature and water conditions (Ribeiro et al. 2009; Magnago et al. 2015). Road density and topographic features may permanently restrict patch sizes growth and ultimately reduce the total secondary forest connectivity. Road construction is typically precipitated by economic drivers that exacerbate environmental damage and degradation, i.e., logging, mineral extraction, or farmland (Laurance et al. 2014), further reducing ecosystem functioning and services (Lewis et al. 2015). Tree mortality and invasive species can impact patch interior vapor pressure deficit, temperature, and soil moisture content (Laurance 2008).

Costa Rica is considered one of the leaders in the Americas on environmental policy, due to its innovative environmental management and sustainable development projects. The areas protected by legislation increased greatly between 1950 and

1990 as did the number of foreign visitors to these areas with the rise of the Costa Rican ecotourism industry (Robalino et al. 2017). Even as early as the mid-1990s, Costa Rica had more conservation projects than its larger counterparts (Blum 2008). One of the central focuses of the initiatives was on education; however, there remains conflict about program effectiveness among educators, policymakers, and industry (Blum 2008).

Additionally, while the land tenure system in much of Central and South America is not well defined, and create increased complexity relating to the agriculture-forest interface, Costa Rica is unique in its definitions and subsequent restrictions relating to forest use. Costa Rica has very stringent and explicit land tenure considerations for both public and private lands which reduces the variability across the country, the former highly supported by a modernization of the national land registry where every parcel of land is registered, and information is publicly available. The 1995 7575 Forest Law redefined the forest use rights and set a precedent for sustainable management and conservation (Corbera et al. 2011). It restricted the access to public forests and the withdrawal of any forest resources. For private land, land ownership must be proved for 10 years before changes to reserve designation can be made, and finally, the indigenous rights are controlled by the Indigenous Integral Development Associations, restricting their access to commercial forest production (Corbera et al. 2011). This combination of factors results in a strict land tenure system where small landowners with no title and large commercial farms are not problems for deforestation dynamics like they would be in other countries which host the tropical dry forest.

In this paper, we investigated the relevance or effectiveness of a command and control policy, protected areas, which designates areas are not used for agriculture or industry (Lambin et al. 2014). Only 13 PAs, of the 25% of the country, have a high/medium probability of deforestation in the majority of the park. This is a relatively small portion of the country where deforestation is of concern without legal protection and is consistent with the 7–9% of the forests experiencing reduced deforestation after receiving the PA designation found in other studies (Andam et al. 2008; Sanchez-Azofeifa et al. 2007). This low percentage is indicative of the fact that historically many of the protected areas were located in high slope and undesirable areas where there was little initial deforestation (Pfaff et al. 2009). This reinforces the need to mindfully consider at-risk locations and ecosystems which could benefit from protection instead of the current practice of choosing areas unsuitable for human use and thus having a low deforestation rate and impact (Andam et al. 2008). The high-risk PAs found may be good places to invest money to enforce restrictions and work with the community to create a local management strategy (Porter-Bolland et al. 2012). With a more targeted funding, a more holistic approach can be

applied to hotspot areas to help balance the economic and environmental services pressures. In other areas, such as Brazil, it has been suggested that investing in the local economy and local businesses may be more sustainable than protected areas (Pfaff et al. 2014).

This targeted approach can extend into national management and monitoring programs. Forest inventories completed by SINAC have been a source of high-quality data but at high cost. While their pilot inventory in 2001 was conducted thoroughly by using a combination of aerial photography and in situ study for the entire country, this style of inventory is costly to repeat on an annual basis (Kleinn et al. 2001). With the identification of deforestation hotspots, it is economical to conduct detailed remote sensing monitoring in these locations but wall-to-wall estimations of forest cover are redundant assuming that social and environmental conditions continue based on our current understanding of the environmental and societal drivers. By the 2060s when the regrowth and deforestation rates stabilize in our model, it may be possible to further reduce the inventory requirements. This would free up capital to be invested in programs, such as payments for ecosystem services, which could use the additional funding to increase buy-in from industry.

A more targeted approach to mapping would also be of benefit when looking at the data that is needed to provide a more comprehensive modeling and land dynamics analysis approach. While this has historically not happened, the Costa Rican Central Bank, as part of its participation on the World Bank's Wealth Accounting and Valuation of Ecosystem Services (WAVES), is starting to generate more comprehensive land cover and land use map for 2017 and onwards. Wall-to-wall mapping and models in Costa Rica are also problematic because of the importance of intraprovincial drivers. Models, including the one utilized in this paper, have difficulty replicating patterns when it is run in a generalized national model. This is because of the presence of east-west and north-south variability on both bio-physical and socioeconomic factors driving land cover change; as such interactions associated with the estimation of forest cover change are not uniform across the entire country. Therefore, modeling the entire country at once leads to problematic results. By dividing this up by province or by hotspot, it largely controls for these differences in biosphere-hydrosphere-pedosphere-atmosphere-anthroposphere relationships.

When we look at other policies that have been implemented in Costa Rica, one of the most prevalent ones is the Reduction of Emission from Deforestation and Forest Degradation (REDD+) policy. REDD+ was designed to reduce emissions from deforestation and forest degradation by using positive incentives (Mbatu 2016). In Costa Rica, the first phase of REDD+ was implemented in 2008, and the Emission Reductions Payment Agreement phase was implemented for 2015–2020 (REDD CR 2018). There has been

research that shows stakeholder buy-in is considered imperative for REDD to be effective; however, many stakeholders are concerned about the transparency of the governing process (Cadman et al. 2017). It is interesting to note that the Costa Rican regeneration rates exceeded the deforestation rates long before the conceptualization of the REDD+ program and the implementation of the REDD+ program has not altered regeneration or deforestation rates, according to our study. As a result, it is unlikely that the REDD+ policy will have any additional impacts, positive or negative on the future forest in Costa Rica.

Conclusion

Costa Rica's deforestation history is divided up into two major sections, with the pre-1980 era heavily dominated by agriculture-/cattle-driven deforestation and post-1980 exhibiting a period of regrowth. This forest regeneration is projected to continue nationally until it stabilizes with a balance of deforestation and regrowth in the 2060s. Assuming climate change does not play a role, the forest extent is currently sustainable or projected to expand. The Puntarenas and Guanacaste provinces are projected to have the highest deforestation. protected areas still have some relevance, with nine of the regions experiencing more than a medium probability of deforestation without the legislation. These areas could provide an interesting case study to test how community style management and control style protection can work in concert moving forward.

Moving forward, a land classification which differentiates the types of land uses over the economic eras of Costa Rica and pasture lands for cattle from croplands, and allows for the explicit extraction of plantations through time, is needed. The dynamics of each land use on forest change is limited based on the available data, and to truly understand the system in Costa Rica, these explicit databases must be created for a more comprehensive understanding of the Costa Rican land system and how it impacts the change in forest cover through different eras in history.

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