Effect of land tenure on forest cover and the paradox of private titling in Panama

Kendra L. Walker[a,b]

[a]Environmental Markets and Solutions Lab, University of California at Santa Barbara

[b]Smithsonian Tropical Research Institute
Apartado 0843-03092, Balboa, Ancón, Panamá, República de Panamá

klwalker@umich.edu

Effect of land tenure on forest cover and the paradox of private titling in Panama

Abstract:

Meeting sustainable development goals requires policies that account for interrelatedness in social and environmental issues such as land tenure and deforestation. This work takes advantage of a nationwide titling campaign in Panama to explore the effect of private titling on forest cover across a heterogeneous landscape covering all stages of forest transition and diverse tenure arrangements. Situated in a broader matched analysis of the influence of zoning and tenure on forest cover, private management is estimated to have contributed to the deforestation of 1750-3650 km^2 of mature forest nationwide from 1990-2020 with an average marginal effect of 15.3%. Conversely, Protected Areas and Indigenous Comarcas are estimated to have protected 1700-3900km^2 and 500-1250 km^2 of mature forest, respectively. Private titling is associated with increased deforestation both during titling and years after, supporting observations that the titling process itself encourages speculative deforestation by title seekers and that private landholders value natural forests less than other land uses such as cattle. By disaggregating the data by region to highlight different stages of forest transition as well as by processes of deforestation and forest growth, this analysis shows that while private titling accelerates deforestation, it also encourages investment in reforestation. This presents a paradox for private titles and forests where agencies may perversely encourage speculative deforestation by creating stronger markets for forest-ready landscapes than for intact natural forests. In cases such as this one, where deforestation helps to secure a title, this paradox is confounded when having a title is set as a precondition for participation in a forest conservation program.

Keywords: Land-use zoning, tenure, protected areas, deforestation, Panama, private titles

1. Introduction

Tackling global sustainability challenges requires solutions that simultaneously address interrelated components of socio-ecological systems (Berkes et al., 2003; Folke et al., 2002; Sayer et al., 2013). Forests play a prominent role in sustainable development through critical ecosystem services, climate change mitigation and adaptation, biodiversity protection and human livelihood security (Katila et al., 2020; Timko et al., 2018; Seymour and Busch, 2016). Despite a growing collection of international agreements to conserve forests, however, deforestation has continued at an unsustainable pace (Baccini et al., 2017; Curtis et al., 2018; NYDF Assessment Partners, 2019; IPBES, 2019; WWF, 2018). Recent expansion of planted forests, primarily in temperate zones (Köhl et al., 2015), has caused a decline in net forest loss (Song et al., 2018; FAO, 2015), which may allow global forest trends to be framed in the optimistic terms of a forest transition (Song et al., 2018, Rudel et al., 2019; Meyfroidt and Lambin, 2011). Implications for sustainability and livelihoods, however, require nuanced examination of pathways of avoided deforestation and forest growth (Griscom et al., 2020; Naudts et al., 2016; WWF, 2018) as well as regional asymmetry in forest trends.

Curbing tropical deforestation is essential to achieving climate stability (Seymour and Busch, 2016) and protecting biodiversity (Bradshaw et al., 2009). However, due to large numbers of rural poor in forest-rich tropical countries (Wunder, 2001; Sunderlin et al., 2008) and the highest global rates of urbanization and development (Swamy et al., 2018), policy prescriptions for achieving sustainable development goals in the tropics often pit people against forests (Chomitz, 2007; Hartshorn, 1995). This is commonly the case in policies relating to tenure, or the institutions concerning who can access and benefit from resources (FAO, 2002). Tenure policies favoring forest conservation often exclude peoples' access to forests through protected areas (PAs). While PAs are generally effective in reducing deforestation (Busch and Ferretti-Gallon, 2017; Min-Venditti et al., 2017), to the point that they collectively reduced tropical carbon-based emissions by around 30% from 2000-2012 (Bebber and Butt, 2017), their exclusionary nature often negatively impacts the livelihoods of people around them (Oldekop et al., 2015). Alternative tenure arrangements such as communal management and private titling allow for people to garner economic benefits from forested lands, but have more varied success in conserving forests.

The literature on the effect of tenure arrangements on forest conservation is deep and varied, yet it usually relates to communal forest use and management. While not a panacea (Baynes et al., 2015; Ostrom and Cox 2010; Holland et al., 2017), communal management is generally found to benefit forest cover (Porter-Bolland et al., 2012; Min-Venditti et al., 2017), especially when the community is homogeneous with low immigration and high autonomy (Poteete and Ostrom, 2004; Agrawal and Chaatre, 2006; Chhatre and Agrawal, 2009). Since the mid-1980s, land tenure reform has dominated many international conservation and development policies. While such policies have focused largely on strengthening communal tenure arrangements, there are many situations where communities do not fit conservation-friendly prototypes or where poor land users do not belong to such communities. In these spaces, issues of individual tenure have been the focus of these policies in a simultaneous wave of private land-titling campaigns across the tropics. The area of tropical forest owned privately increased by 122% from 2002-2008 (ITTO, 2009). While similar to earlier land reforms in their primary goal of poverty reduction, these titling campaigns have differed in their general claim to underpin broader agendas of sustainability and forest conservation (Pacheco et al., 2011; Sunderlin, 2011).

Securing land and property rights is considered critical to achieving the Sustainable Development Goals (IEG, 2016) as a tool for reducing poverty and enhancing economic development. Development institutions that advocate for and facilitate private-titling campaigns generally maintain that private titling is likely to have a positive or neutral effect on forests (Keipi, 1995; FAO, 2012; Deininger, 2003), although long term effects remain understudied (Lawlor et al., 2020). Conservation literature suggests a more dubious relationship between private titling and forest conservation even in the short term, however. Recent meta-analyses of the effect of private land tenure on forest cover have found mixed results (Min-Venditti et al., 2017; Katila et al., 2020; Busch and Ferretti-Gallon, 2017). Clear ownership of forests can facilitate use of market mechanisms to manipulate incentives toward forest conservation or afforestation and is thus often a prerequisite for programs such as REDD+ and other Payment for Ecological Service (PES) programs. Whether such projects are successful depends both on context-specific cultural and economic factors as well as on the process of forest-cover change in question.

In cases where forests have already been degraded or deforested, secure private tenure can lead to greater forest cover if it provides landholders with incentives or means to invest in agroforestry or silviculture (Besley, 1995; Takahashi and Otsuka, 2016) or to intensify agricultural production and thus spare other lands for regeneration. Conversely, tree planting can be a means to demonstrate investment and thus enhance tenure security (Barbier and Tesfaw, 2013; Sjaastad and Bromley, 1997). If titled, degraded lands that no longer offer profitable agricultural returns can also be allowed to regenerate without fear of being taken by squatters or the government due to inactivity (Kaimowitz, 1996).

The mechanisms through which private titling might curb deforestation in existing forests are less straightforward. Secure private tenure can theoretically enhance forest conservation if it obviates motives to cut trees to prevent others from doing so first (Kaimowitz, 1996) or empowers landholders to prevent others from clearing forests (Alston et al., 2000). However, these mechanisms only work if landholders consider forests more valuable than other land uses, which is often not the case (Liscow, 2013; Angelsen and Kaimowitz, 1999; Angelsen, 2007; Robinson et al., 2017). Formal titles may also allow speculators to leave land idle without fear of invasion (Alston et al., 1996, Azevedo et al., 2017). However, in the context of development, such land speculation is generally not beneficial to poor smallholders (Fairhead et al., 2012). Largely for this reason, many governments have historically recognized claims to lands only when landholders can prove use, usually via clearing. When land clearing enhances one's claim to the land, private titling has a negative relationship with forest cover (Angelsen, 2007; Arnot et al., 2011; Araujo et al., 2009). One of the main reasons for titling private land advocated by development agencies is that such titles enhance landholders' access to credit and ability to invest (Feder and Feeny, 1991; Dorner, 1972; IEG, 2016). However, once provided the means, landholders may invest in deforestation (Rasmussen et al., 2017, Deininger and Minten, 1996). By entering forested lands into the market economy via formal titles, it is also more likely that they will eventually be sold to larger landholders such as ranchers (Schneider, 1994; Campbell, 2015). Empirical studies of efforts to establish or clarify private tenure in forested landscapes are rare but suggest it is risky for both people and forests (Robinson et al., 2014).

There have been few studies on the effect of private tenure on forest cover in Central America in the last decades (Min-Venditti et al., 2017) despite several large-scale land titling projects implemented in the same period (Keipi, 1999; Deere and Leon, 2002). From 2001-2010, the moist forests of Central America suffered net forest loss, although, as with global forests, this trend can be classified as an asymmetrical forest transition (Redo et al., 2012) as losses were partially offset by net gains in dry and coniferous forests. In Central America, land tenure is often secured by clearing forest (Ankersen and Ruppert, 2006; Liscow, 2013; Angelsen and Kaimowitz 1999; Jones, 1990). Land speculation by cattle ranchers is considered a principal cause of deforestation in Latin America (Roebeling and Hendrix, 2010), and there is evidence that recent land titling campaigns have fueled this speculative drive for land (Kaimowitz, 1996). While land policies and private tenure likely influence deforestation, they also influence forest recovery (Pacheco et al., 2011).

This work explores the effect of tenure on forest cover in the Central American nation of Panama and takes advantage of data from a large-scale private titling campaign to elucidate the effect of private tenure and titling on forest cover. Although a small nation of around 75,500 km^2, Panama presents an interesting microcosm of Central America with its diverse representation of land uses and tenure arrangements and simultaneous presence of all three forest transition stages, with “settled”, “frontier” and “remote” zones (Perz and Skole, 2003). Although some consider Panama to have already undergone a forest transition due to regrowth of forest in the settled region (Redo et al., 2012; Wright and Samaniego, 2008; Hosonuma et al., 2012; Sloan, 2015), deforestation has continued at a steady rate since 1990 in other regions (Walker, 2020). The national extent of the land titling campaign and other tenure arrangements amidst this mosaic of forest processes allows for insights into the effect of tenure and titling on forests to be broken down by processes of deforestation and forest growth. Such disaggregation is important to elucidate true impacts on forests and consequences for biodiversity and climate change mitigation.

The explicit goal of the titling program was to reduce rural poverty by increasing farmers' access to credit (IDB, 2014). A full review of whether this formal privatization of land and its insertion into the global market has had the intended effect of poverty reduction in Panama is beyond the scope of this paper (see Spalding, 2017). Here I focus on the environmental impact of titling and specifically on its effect on forest cover. Despite publishing a lucid report on the tenuous and often catastrophic relationship between private titling and forest cover in Central America (Jaramillo and Kelly, 1999) along with a long passage describing the history of deforestation to gain possession of land in the principal loan proposal itself (IDB, 2002), the InterAmerican Development Bank concluded in various loan documents that the titling program was expected to have positive or neutral effect on the environment. This work explores that relationship.

Exploration of effect of private titling on forest cover is first situated in a broader analysis of the influence of different zoning/tenure arrangements on forest cover in Panama. In assessing policy decisions such as zoning and titling on deforestation, the counterfactual, or what would have occurred in the absence of a given tenure arrangement, cannot be observed directly, and can only be approximated by controlling for environmental and social variables that influence treatment and outcome (Burivalova et al., 2019; Ferraro, 2009; Blackman, 2013). I controlled for such endogenous factors with propensity score matching, which balances the treatment and control groups by equalizing the probability of treatment based on a set of observed factors (Rosenbaum and Rubin 1983). I first estimated the effect of two restricted zones, PAs and Indigenous Comarcas, on deforestation from 1990-2020 across Panama and compared these to estimates for effect of private management and other Indigenous territories (where data allow) on deforestation using the same methods. I then examined the effect of private titles explicitly by asking 1) whether the PRONAT land-titling campaigns favored parcels with less forest and/or increased recent deforestation rates, and 2) whether deforestation or regeneration rates changed following attainment of a private title. Due to the relatively short amount of time since titling for many of the titles issued during the PRONAT campaign, I repeated this latter analysis for titles granted prior to the PRONAT campaign.

Methods

2.1 *Study area*

2.1.1 Regional disaggregation of forest-cover change processes

While more than 99.5% of Panama's land surface is naturally tropical forest (Holdridge and Budowski, 1956), 47-50% mature forest remained in 1990 (ANAM, 2003; Walker, 2020). Processes of forest-cover change under different tenure arrangements can best be elucidated by dividing Panama into three regions (Fig 1). The southern region (S), occurring along the western pacific coast, has been largely deforested since Spanish settlement in the 16th century (Heckadon Moreno, 2009) and is now potentially regaining some of its former forest (Caughlin et al., 2016; Metzel, 2010). This region represents the post-transitional stage described by Angelsen and Rudel (2013) or the "settled" zone described by Perz and Skole (2003). In contrast, the region east of the Panama Canal (E), can be considered the peak activity, or “frontier” zone, as rapid deforestation over the last few decades (Wali, 1993; Heckadon Moreno, 2009) has resulted in forest-agricultural mosaics as well as areas of rapid reforestation (Sloan, 2008). The Northwestern zone (NW) is also largely covered in forest-agricultural mosaic, but also contains a large “remote” zone, comprising mostly mature forests which are difficult to access and in economically impoverished areas (Wright and Samaniego, 2008), representative of the pre-decline stage of forest transition. The vast differences in the three regions in terms of their forest histories as well as timing and execution of titling campaigns precludes direct quantitative comparisons between regions. Nonetheless, these regions provide a firm framework for understanding the effect of tenure on forests cover when intersected with the key tenure regimes in Panama.

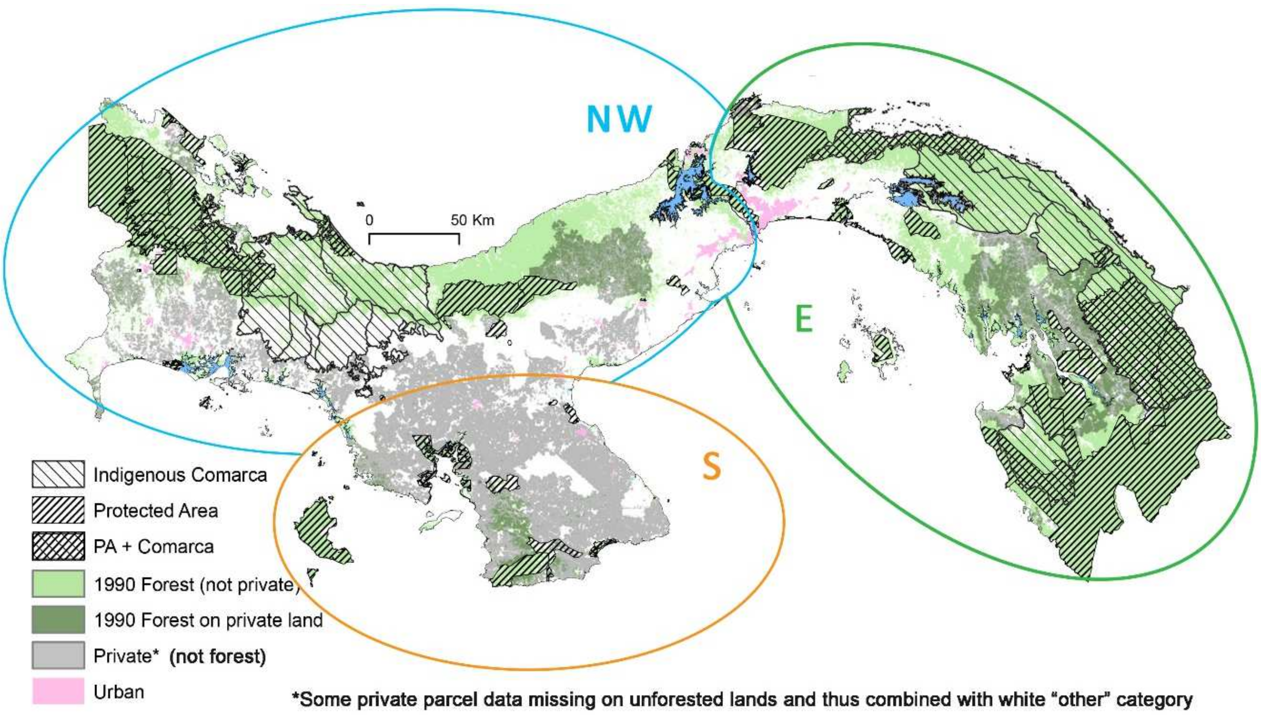

Figure 1. Map of Panama with 1990 forest extent, zoning data and model regions

2.1.2 Land zoning and tenure arrangements

A large percentage of Panama's forests are found within restricted zones in which use is prohibited for most of Panama's population. Protected Areas (PAs) covered 26% of Panama's land area and contained 50% of the nation's mature forest cover in 2000 (ANAM, 2010; Walker, 2020). While tree cutting is prohibited in most PAs, deforestation rates may be influenced by variances in funding and enforcement within each area (Oestreicher et al., 2009; ANAM, 2006). Comarcas, or formal indigenous territories, covered an additional 20-25% of Panama's land area and hosted an additional 20% of mature forest cover in 2000 (beyond that within the 26% of their area that overlapped PAs). Comarcas host nearly half of Panama's indigenous population, or 6% of its total population (INEC, 2010) and accord indigenous peoples some of the strongest constitutional rights in Latin America regarding land tenure (Roldan Ortiga, 2004; Recio, 2014). Contradictory laws regarding resources under and on the land have resulted in deforestation and conflict, however (Cansari and Gausset, 2013; Vergara-Aseno et al., 2017; Velásquez Runk, 2012; Tresierra, 1999).

The remaining 60% of Panama's land area and 30% of mature forest cover is a mosaic of land managed by the state, individuals, and indigenous groups with various levels of tenure security. At least 9% of national land outside the Comarcas is managed by indigenous groups as collective territories, with tenure rights informally recognized by the government but no formal titles as of 2010 (Vergara-Asenjo and Potvin, 2014). Most of this land overlaps with PAs, however. An additional 37% of Panama's land area was under cultivation or pasture in 2000, with around 60% of these lands lacking formal title (INEC and MIDA, 2001). Although lacking formal titles, most land users have held fairly secure tenure under arrangements known as *Derechos Posesorios* or Rights of Possession recognized by the government since the first Civil Code of 1917 (Spalding, 2017).

2.1.3 Private titles and the National Land Titling Program in Panama

Prior to the 1990s, formal private titles were infrequent in Panama; Of the 101,791 properties listed in the 1981 census, only 17% had formal titles (IDB, 2014). From 1996-2011, Panama received loans from the World Bank and InterAmerican Development Bank for a large land-titling program. The *Programa Nacional de Administración de Tierras* (PRONAT) was formed for this purpose and dissolved at the end of its mandate, with titling oversight passed to the larger National Land Administration Authority (ANATI). From 1999-2011, PRONAT surveyed 60% of the country, beginning in the NW region and including the S and, to a lesser extent, the E regions after 2002. Although most unrestricted lands were surveyed, 70% of parcels were not granted titles due to unspecified discrepancies and boundary disputes (Recio, 2011). The data provided by PRONAT on the 74,376 titles that were formalized in that period as well as those that were not can provide great insight into the effects of formal private titling.

2.2. Data

2.2.1 Restricted zones (PAs and Comarcas)

Protected area (PA) boundaries were provided by Panama's environmental ministry (ANAM until 2014, now MiAMBIENTE) in 2011 in accompaniment to documentation on the national system of protected areas (ANAM, 2006). Only protected areas established in or before 2001 were considered in this analysis. Boundaries for indigenous Comarcas were provided by Panama's census bureau in accompaniment to 2010 census data (INEC, 2011).

2.2.2 Unrestricted zones (Private, Indigenous Territory and Other)

Boundary data for private and state-managed property parcels were provided by PRONAT in 2011. These data include title status for privately managed properties (formal title issued prior to the PRONAT campaign, formal title issued during the PRONAT campaign, and no formal title issued by the end of the campaign). Where PRONAT did not issue a formal title, the status is marked as pending or in process, preventing distinction between titles outright denied and those that may be granted later by ANATI. Information on the precise year of titling is also missing for most of the titles granted. This dataset is geographically incomplete and notably excludes parcels in and around the most urban areas of Panama City and Colon. Most pertinent to this analysis, however, coverage of parcels in forested areas is likely nearly complete for 2011 (PRONAT, Pers. Comm). In areas surveyed by PRONAT, coverage is mostly wall-to-wall, delineating areas under government jurisdiction as well as cooperative private management. Parcels managed by a private owner or a private organization were included in the Private Title dataset, while all other management arrangements outside of restricted zones were considered “Other”. This category also includes all land not surveyed by PRONAT outside of restricted zones and identified Indigenous Territory. These unsurveyed lands are mostly managed by smallholders who do not possess a formal title but claim the land through traditional rights of possession.

An Indigenous territory (IT) category was included to identify areas outside of formal Comarcas but within territories managed by indigenous groups and under process of legalization as either new Comarcas or Collective Territories. This variable is informed by a map by Vergara-Asenjo and Potvin (2014) that was created to reflect the knowledge and claims of indigenous authorities and is not necessarily in agreement with government assessments.

2.2.3 Forest cover and change data

Forest cover and change was estimated from a 35-year dataset of national forest cover at 30m resolution based on Landsat imagery (Walker, 2021). Initial forest condition in 1990 was determined from the 1987-1991 composite map that forms the base of the time series, with mature forest defined as at least 80% canopy cover with trees at least 20 years old. This mature forest area was sampled with a random design stratified by region and tenure type, resulting in two percent coverage of large categories and at least 5000 pixels for small categories. These 1990 forest sample pixels were then assigned a dichotomous deforestation outcome based on whether they were ever observed as no or low vegetation in the subsequent 30 years of time-series data. Methods to minimize the effect of noise in the deforestation signal are discussed in detail in Walker 2020 and pixels with signals flagged as low confidence were excluded from the sample.

2.2.4 Control variables

Due to potential biases in application of zoning and tenure arrangements to areas more or less likely to be deforested, factors influencing ease of deforestation and attractiveness of other land uses need to be controlled for when estimating the effect of such arrangements on forests. Based on observed biases in zoning repeated throughout the literature (e.g. Joppa and Pfaff 2009), 14 cofounders were controlled for in matching analyses of effect of PAs, Comarcas, and Private management in general (Table 1). These include measures of local environmental conditions (forest type, climatic zone, elevation, and elevation squared), measures of forest accessibility (distance to forest edge, distance to any road, distance to water), measures of market access (distance to paved road, distance to urban area, population density), and measures of agricultural suitability (slope, slope squared, and distance to commercial agriculture in 1990).

Inclusion of environmental variables not only controls for the conditions themselves but helps adjust for other unobserved variables that are spatially autocorrelated. Forest type was extracted directly from the maps used for the forest-change analysis (Walker 2020) and was divided into two binary variables, mangrove and undisturbed, both observed to have strong negative correlations with deforestation and likely high zoning biases. Undisturbed pixels are defined as mature upland forest surrounded by eight forest neighbors and with no observed past disturbance. Climatic zone is also a binary variable and is based on a Köppen classification map provided by Empresa de Transmisión Eléctrica (ETESA) Panama. While most of Panama has a tropical monsoon climate with a short, distinct dry season, a large portion of the NW is wetter with almost no dry season, and a large portion of the S and E is drier with a longer dry season. The Koppen climate variable thus takes the form of Koppen_Wet for the NW and Koppen_Dry for the S and E regions. Elevation provides an additional estimate of environmental condition and agricultural suitability, although most effect occurs at extreme highs and lows, thus suggesting importance of an elevation squared term. Likewise, slope constrains agriculture mostly at the extreme levels and thus requires a square term. Elevation and slope were derived from 1-arc-second (approximately 30m) Shuttle Radar Topography Mission (SRTM) data acquired from the USGS EROS archive.

Population variables were derived from data provided from the Panamanian census bureau, both in published statistics (INEC, 1990; INEC, 2000; INEC, 2010) and GIS point and polygon data. To create a smooth surface to represent population data at a similar resolution as the other variables, rural populations were assigned to their corresponding “populated place” points and then redistributed across space using a kernel decay radius of one km, while urban populations were constrained within the boundaries of the urban polygons provided by INEC. These urban polygons also served as the basis from which the distance to urban center was derived. Road location and type was based on 2010 road network data provided by the Smithsonian Tropical Institute GIS Lab (STRI, 2011). Distance from roads reduces accessibility of forests to potential users but also reduces demand for the land and thus likelihood of being granted protected status. Distance to water, defined as navigable rivers and coasts, serves a similar role. Navigable rivers were considered to be rivers large enough to be visible in the 30m resolution Landsat images used to make the forest cover dataset and were digitized from such images. Two final variables, distance to forest edge and distance to commercial agricultural, serve not only as measures of accessibility but also controls for other unobserved variables related to forest loss and agricultural suitability. Distance to the forest edge was derived from the same 1990 forest-cover map from which the sample was taken. Commercial agriculture was derived from the 1992 Land use/Land cover map by Panama´s environmental ministry (ANAM, 1992).

For analyses of the effect of formal titling on deforestation within private parcels, factors expected to bias titling include geographic factors such as forest type and accessibility, as well as socio-economic variables that influence a landholder’s incentives to apply for a title and follow necessary protocol. The forest type variables mangrove and undisturbed were included in the matching procedures for these, as mangroves are

Table1. Variable definitions		Units	Base source
Dependent variable			
Deforest	Deforestation detected from 1990-2020	0/1	Walker 2021
Treatment variables			
Restricted zone			
COMARCA	within an Indigenous Comarca	0/1	INEC 2010
PA	within a Protected Area established before 2001	0/1	ANAM 2010
Unrestricted zone			
PRIVATE	within private parcel boundaries from PRONAT	0/1	PRONAT 2011
PrePRONAT	title issued before PRONAT campaign (before 2000)		
PRONAT	title issued during PRONAT campaign (2000-2011)		
pending	parcel surveyed by PRONAT, but no title issued		
IT	Indigenous Territory outside of a Comarca	0/1	Vergara-Asenjo 2014
Other			
Covariates used in matching for zoning analyses			
MANGROVE	1990 forest type is mangrove	0/1	Walker 2021
UNDISTURBED	1990 forest type is undisturbed upland	0/1	Walker 2021
ELEV, ELEV^2	Elevation and Elevation squared	m	SRTM 2015
SLOPE, SLOPE^2	Slope and Slope squared	deg.	SRTM 2015
KOPPEN	Wetter (for NW) or Drier (for E & S) hydrological zone	0/1	ETESA 2007
URBANdist	Distance to urban area	km	INEC 2013
AGDIST	Distance to commercial agriculture in 1992	km	ANAM 1992
RDDIST_Pvd	Distance to a paved road	100m	STRI GIS 2011
RDDIST_All	Distance to any type of road	100m	STRI GIS 2011
PDEN1990	1990 population density, interpolated	pers/km^2	INEC 1990
WTRDIST	Distance to any navigable river or coastline	100m	
additional Covariates used in matching for titling analyses			
CowsPerCap	*Corregimiento*-(borough-)level cows per capita in 2010	cow/pers	INEC&MIDA 2011
PCNG9010	Population density change 1990-2010, interpolated	pers/km2	INEC 1900 & 2010

generally protected regardless of zoning status and undisturbed forest suggests forest that is both more difficult to clear and less likely to already be part of a managed system. Distance from forest edge and distance from any road were included as accessibility factors likely to affect agents' access during the titling process as well as general market accessibility. Distance to urban area, distance to a paved road and distance to commercial agriculture were also included as indicators of market access and agricultural suitability. Population change and cattle densities were selected as indicators of demand for titled land. Population change was based on interpolated 1990 and 2010 population datasets from INEC and methods discussed above. Cattle densities were obtained from the 2010 agricultural census at the level of the *corregimiento* (borough) (INEC, 2011). A set of district-level poverty indices were also tested but found to have an insignificant effect on titling propensity beyond other included variables. Ideally, parcel-level data would be used to control for socioeconomic factors; however, such detailed data are not available. Use of neighborhood-level variables serve as a proxy and help control for other unobserved variables that are spatially autocorrelated.

2.3 Propensity-score matching

Treatment pixels were matched to statistically similar control pixels with the MatchIt package in R (Ho et al., 2011) using one-to-one nearest neighbor matching and a propensity-score caliper of 0.2 to exclude pixels with poor matching potential. Exact matches on mangrove were required due to the very strong influence of mangrove in predicting treatment. Given the relatively large sample size and number of covariates, simple one-to-one propensity score matching with a tight caliper was found to provide sufficient area of common support and adequately reduce bias among covariates with minimal computational load. Balance was considered good if the standardized difference in means between the treatment and control groups did not exceed 0.15 for any covariate and 0.1 for the majority. The average treatment effect on the treated (ATT), in this case the difference between deforestation within and outside of treatment zones, was calculated based on the matched pixels. Cluster-robust standard errors were estimated using the Sandwich package in R (Zeileis 2004, Zeileis and Graham 2020). For a dually robust estimation of treatment effect (Imbens and Wooldridge, 2009; Blackman and Viet, 2018), a logistic regression model was fit to the matched dataset and the average marginal effect of the treatment (AME) was estimated using the R margins package (Leeper, 2016). Hybrid matched-trend analyses incorporating methods such as differences-in-differences can help overcome bias due to omitted variables (e.g. Brandt et. al, 2015). However, due to the hypothesized influence of anticipated titling on deforestation and thus possible conflation of treatment-outcome during even the baseline period of this study, such methods are not possible here. Instead, Rosenbaum bounds were used to test the sensitivity of results to unobserved confounding factors (Rosenbaum 2002, Blackman & Viet, 2018).

2.4 Effect of land zoning and tenure on deforestation

To estimate the effect of PAs on deforestation, I matched sampled forest pixels within PAs to forest pixels outside of restricted zones (PAs and Comarcas) within each region. Likewise, to estimate the effect of Comarcas on deforestation, I matched sampled forest pixels within Comarcas to forest pixels outside of restricted zones within each region. To estimate the effect of private management on deforestation, sampled forest pixels within known private parcels with any titling status (PrePRONAT, PRONAT or Pending) were matched to forest pixels outside of the private parcel boundaries in each region. It is assumed that these registered parcels are all under private management although many have not received a formal title. Indigenous Territories were assessed in the same way, with simple inside/outside matching.

Private parcels were then disaggregated by title group to estimate the effect of the titling process itself on deforestation. Forested pixels within the subset of parcels titled by PRONAT were randomly sampled and matched to forested pixels in other unrestricted zones within each region. Deforestation was also disaggregated by timestep, to allow for consideration of different processes before and after titling. For insight into longer-term post-titling deforestation rates, a similar matching analysis was conducted with the subset of parcels titled prior to 2000.

2.5 Parcel-level analyses of afforestation and net forest-cover change in private lands

To gain insight into parcel-level titling and forest-change processes in privately managed land, an additional dataset was created with data aggregated at the parcel level. The data from PRONAT were first cleaned to remove duplicate entries, registration errors and overlaps. All parcels less than $1000m^2$ (slightly larger than a single Landsat pixel) were excluded from analysis to further reduce errors created by registration overlaps. This resulted in the removal of many true parcels in urban areas, however, it is unlikely to have much effect on parcels where forest-cover change occurs.

To analyze whether tilting was biased toward deforested lands, or whether parcels with less forest cover had a higher likelihood of receiving a title, parcels receiving a title during the PRONAT campaign were compared with surveyed parcels that were not granted a title as of 2011 using logistic regression models. To analyze forest-cover trends in titled parcels over time, the PrePRONAT set of parcels receiving titles prior to 2000 was compared to the pending parcels that were surveyed but not granted a title as of 2011. By aggregating land cover data within the parcels, more nuanced patterns of net forest-cover change could be examined, combining both deforestation and regrowth. Afforestation was estimated as the percent gain in forest from 1990-2020, while net growth was estimated as the percent gain in both forest and high vegetation. Neither distinguishes between processes of natural regeneration and active planting of trees or forest plantations. For parcel-level analyses, generalized mixed models were fit to control for district-level variation within each region. All covariates in Table 1 were included as possible controlling factors in these analyses.

Results

3.1. Naïve (unmatched) deforestation rates in land zoning units

Privately managed parcels lost 45% of their forest cover from 1990-2020, while indigenous territories in the process of formalization lost 17%, formal Indigenous Comarcas lost 11%, and PAs lost 6% (Table 2). Based on naïve case-control assessment of deforestation, both PAs and Comarcas seem to be very effective in reducing deforestation in Panama and private management appears to contribute to accelerated deforestation.

While overall deforestation rates are lower in PAs than in Comarcas, this may be driven by a few very large and remote PAs. When data are examined at the level of the individual PA or Comarca, the average deforestation rate for Comarcas is slightly lower than for PAs (Fig 2). Unit-level aggregation also reveals that while most PAs have low deforestation rates, high forest loss has occurred in some PAs.

Table 2 Panama forest cover and deforestation by tenure type and region

Tenure	% of 1990 Forest				Deforested 1990-2020			
	All	NW	E	S	**All**	NW	E	S
All Restricted	**70%**	24%	43%	3%	**7%**	10%	5%	2%
PA only	**21%**	8%	10%	3%	**6%**	8%	6%	2%
+ Comarca	**13%**	3%	10%	na	**6%**	11%	4%	na
+ other IT	**15%**	5%	10%	na	**3%**	3%	3%	na
Comarca only	**20%**	8%	12%	na	**11%**	16%	7%	na
All Unrestricted	**30%**	14%	14%	2%	**27%**	23%	33%	14%
Private*	**8%**	3%	4%	1%	**45%**	38%	62%	17%
IT (outside PA)	**3%**	1%	2%	na	**17%**	19%	17%	na
Other*	**19%**	11%	8%	0%	**21%**	23%	24%	7%
All	**100%**	38%	57%	5%	**13%**	15%	12%	7%

* Private parcels missing from the data given by PRONAT are mixed in with Other

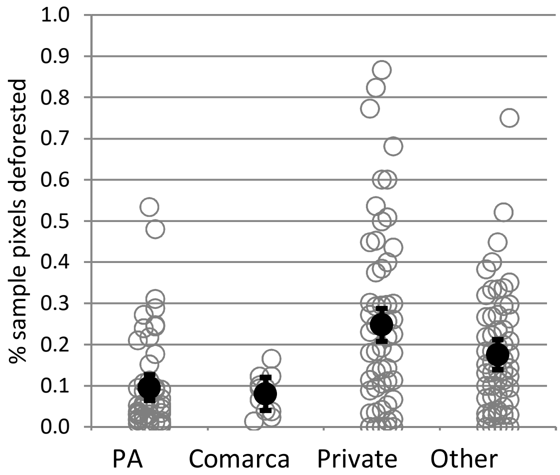

Figure 2. Deforestation by zoning type and unit. Hollow circles represent units, where PA is the whole protected area (N=52), Comarca is the Comarca-District (N=12), Private and Other are grouped by district (N=63). Black circles represent average unit values with 95% confidence intervals.

3.2. Drivers of deforestation

While tenure zoning and deforestation correlate strongly in all models, other variables have stronger correlations. When all covariates are set to a standardized scale with a mean of zero and a standard deviation of 0.5, the variables that emerge as the strongest predictors of deforestation are mangrove, distance from any road and distance from the forest edge, all with strong negative relationships with deforestation (Fig 3). Elevation is also a strong predictor of deforestation in the NW and E regions, with pixels at higher elevations less likely to be deforested. In the S region, pixels at higher elevations were more likely to be deforested, although this effect is weak, likely due to the low variation in elevation in the region. Other covariates including slope, 1990 population density, distance from agriculture, Köppen climatic zone, and distance from a paved road have significant but weak effects in most models. The relationship these covariates share with deforestation, coupled with their expected effects on zoning and titling decisions discussed in section 2.2.4, demonstrates the need for matching analysis in assessing the effect of zoning and titling on deforestation.

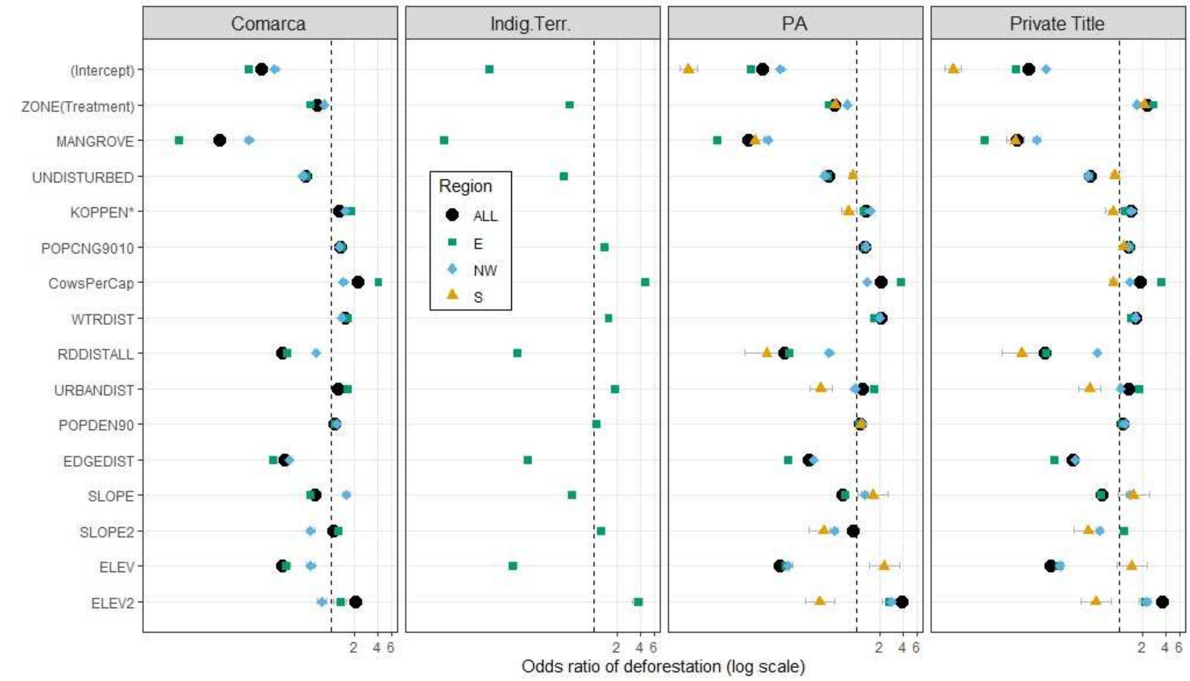

Figure 3. Effect of tenure zoning and covariates on 1990-2020 deforestation overall and by region. All variables are standardized to have a mean of zero and sd of 0.5, with dichotomous variables centered. All Zone (treatment) estimates are significantly different than no treatment at $p<.0001$

3.3. Biases in land zoning by tenure type

Naïve case-control figures ignore the possibility that factors that affect deforestation pressure may also affect zoning decisions. Such biases are evident upon inspection of the propensity of tenure assignment based on confounding variables (Fig. 4). A pixel is much more likely to be within a Comarca if it is farther from a road, an urban center, or the forest edge, especially in the E region. In the NW region, pixels at higher elevations, with steeper slopes and with wetter climates are also more likely to be within a Comarca. The same general biases apply to PAs, although pixels farthest from roads and from the forest edge are more likely to be within PAs than Comarcas in the NW region. In the S region, where there are no Comarcas, pixels farther from a road, commercial

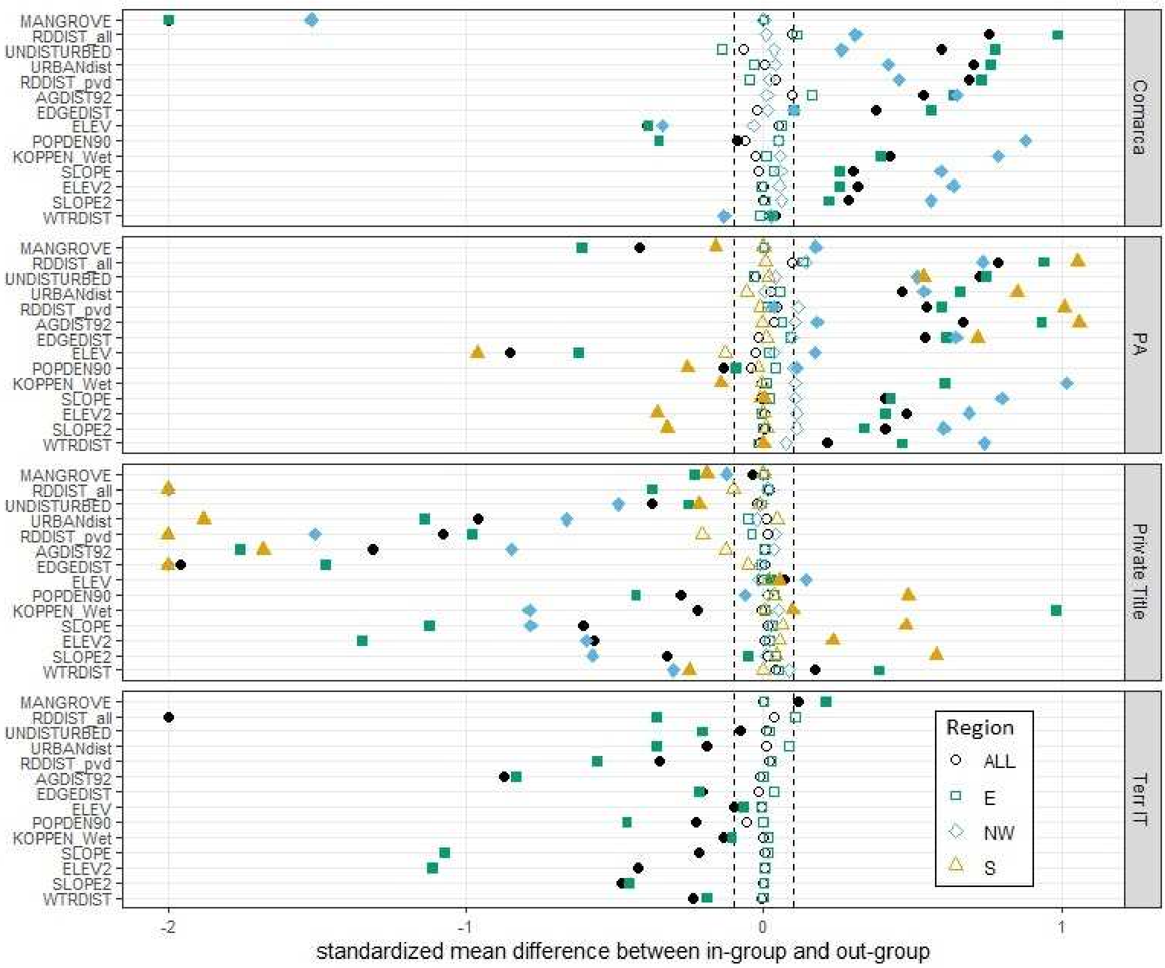

Figure 4. Covariate influence in propensity of zoning assignment for forest pixels
Before matching (filled) and after (hollow)

agriculture, or an urban center are much more likely to be within a PA. The opposite biases occur for private parcels in all regions. All noted biases were substantially reduced in the matching procedure, with the standardized mean difference between treatment and control below 0.1 for most covariates and below 0.15 for all covariates.

3.4. Effect of land zoning on deforestation

3.4.1. Average treatment effect on the treated (ATT) from matched samples

Based on the average effect of the treatment on the treated (ATT) calculated for the matched samples (Table 3), PAs reduced deforestation by 10.2% nationwide compared to unrestricted zones, with a greater effect of 10.4% in the E region and lesser effect of 3.9% and 3.0% reduction in the NW and S regions, respectively. Comarcas had a similar effect on deforestation rates nationwide, with 8.0 % reduction overall compared to unrestricted zones. However, this effect was much stronger in the E region than in the NW region. Pixels under private management had deforestation rates 15.6% higher than other zoning nationwide. This effect was much stronger in the E region, with 24.6% greater forest loss, and weaker in the S region, with only 6.2% greater forest loss compared to other zones.

Table 3: Effect of tenure type on 1990-2020 deforestation in Panama, nationwide and by region, based on three estimation models:
rawDM is difference of the means of the naïve (unmatched) data. ATT is Average Treatment effect on the Treated for matched data. AME is Average Marginal Effect of treatment based on a logistic regression model estimated post-matching. Numbers in parentheses are 95% Confidence Intervals.

		Panama (ALL)			E			NW			S		
	method	percentage point change		forest effect (km2)	percentage point change		forest effect (km2)	percentage point change		forest effect (km2)	percentage point change		forest effect (km2)
PA	rawDM	-22.0		3902	-39.0		3116	-16.0		934	-12.0		137
	ATT	-10.2	(-10.6 -9.8)	1809	-10.4	(-10.9, -10.0)	1117	-3.9	(-4.4, -3.3)	228	-3.0	(-4.0, -2.0)	34
	AME	-9.7	(-10.2, -9.2)	1720	9.3	(-9.7, -8.8)	999	-3.7	(-4.3, -3.2)	216	-3.6	(-4.6, -2.7)	41
COMARCA	rawDM	-18.0		1255	-27.0		941	-8.0		82			
	ATT	-8.0	(-8.4, -7.7)	558	-18.3	(-18.9, -17.8)	638	-2.7	(-2.3, -3.1)	28			
	AME	-7.3	(-7.6, -6.9)	509	-14.0	(-15.5, -14.)	488	-2.6	(-3.1, -2.0)	27			
other	raw DM	-11.0		101	-19.0		131						
Indig. Terr.	ATT	-11.7	(-12.6, -10.8)	107	-17.6	(-18.7, -16.5)	121						
	AME	-9.7	(-10.6, -8.9)	89	-14.6	(-14.5, -13.5)	100						
Private	raw DM	32.0		-3650	55.0		-2658	24.0		-1252	14.0		-817
	ATT	15.6	(15.2, 16.2)	-1780	24.6	(24.8, 26.5)	-1189	8.9	(7.9, 9.8)	-464	6.2	(5.7, 8.1)	-362
	AME	15.3	(15.8, 15.7)	-1745	24.1	(23.4, 24.8)	-1165	9.1	(8.3, 10.0)	-475	5.9	(5.2, 7.6)	-344

All estimates are significant $p < .0001$.

[editable table included as separate file]

3.4.2. Average marginal effects (AME) from post-matched models

The double-robust method of fitting logistic regression models to the matched data produced slightly lower but similar effect estimates for all treatments (Fig 4). The average marginal effect on 1990-2020 deforestation is -9.7% for PAs and -7.3% for Comarcas nationwide. Based on this most conservative estimate, PAs and Comarcas have contributed to the avoided deforestation of 1720 km^2 and 509 km^2 of mature forest from 1990-2020, respectively. Most of this conserved forest occurs in the E region, as this region had both the most mature forest and the most deforestation pressure during the study period. In this region, Indigenous Territories outside of Comarcas have as strong an effect as PAs on protecting forest cover per area of forest due to their co-occurrence with covariates associated with high deforestation pressure. In contrast to the protective nature of PAs and Indigenous lands, Private management has contributed to the deforestation of an estimated 1745 km^2 of mature forest nationwide.

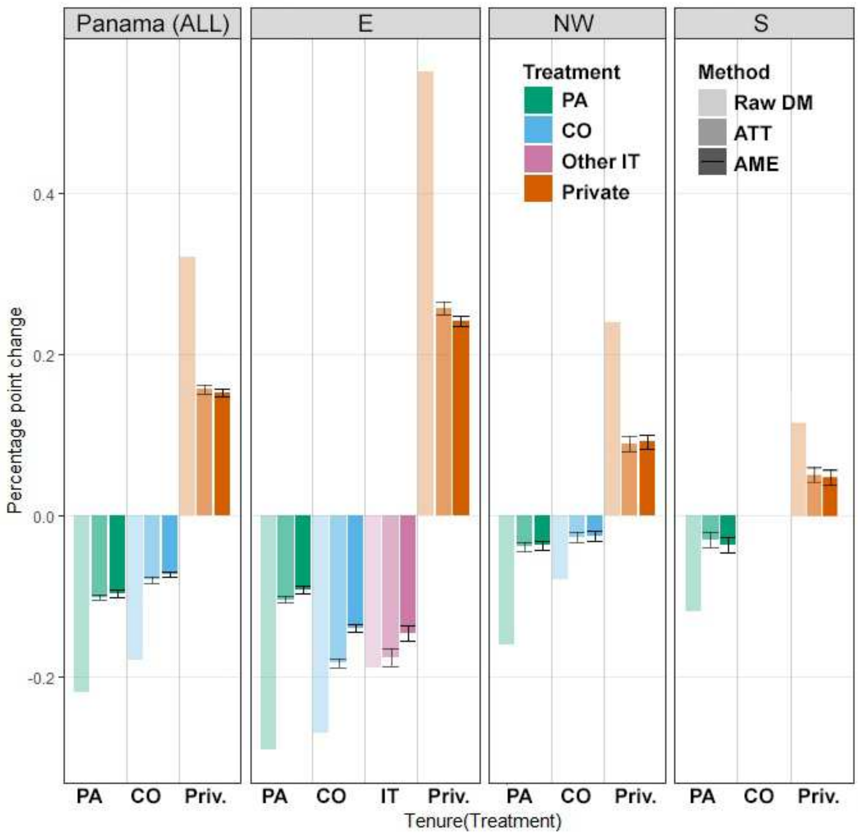

Figure 5. Effect of tenure zoning on 1990-2020 deforestation with three estimation methods

3.5. Titling of privatly managed parcels

3.5.1 Titling trends and factors affecting liklihood of receiving a title

For the 167038 private parcels >1000m^2 in the PRONAT dataset, average parcel size is 10.7 ha and median size is 2.3 ha. Of the 165176 parcels for which title status is clear, 18% were titled before 2000, 28% were titled during the PRONAT campaign, and 54% were still in process (not granted) when the campaign ended in 2011. Although some large urban areas were excluded from the dataset and small parcels <1000m^2 were removed, a large percentage of the parcels still occur in urban and suburban areas. Only 26% of parcels had any mature forest in 1990 (Table 4). Half as many parcels granted titles by PRONAT had mature forest in 1990 compared to parcels surveyed but not granted titles, suggesting a titling bias towards lands with less forest cover. This does not apply to the S region, however, where parcels with titles granted under PRONAT had more forest and less low vegetation than parcels not granted titles. Regression models confirm that the percent of the parcel covered by mature forest in 1990 and 2000 significantly decrease odds of receiving a title in the E and NW regions. Parcel area and distance from a paved road also decrease odds of a parcel receiving a title, while population density and the number of cows per capita in the area increases odds of receiving a title ($p < .001$ for all variables mentioned, models provided in A.1 – A.3).

Table 4. Private parcels >1000m^2 in PRONAT dataset by title status and region

	# parcels >1000m^2 in dataset				% of parcels with forest in 1990			
	All	E	NW	S	All	E	NW	S
titled prior to 2000	29073	3149	7700	18224	19%	28%	44%	6%
titled by PRONAT	46438	286	21520	24632	17%	46%	23%	11%
title not yet granted	89665	14061	52197	23407	34%	57%	37%	11%
ALL	165176	17496	81417	66263	26%	52%	34%	10%

3.5.2 Effect of titling on immediate deforestation

While the data on percent forest cover in parcels granted titles versus those with titles still pending suggest a bias toward granting titles to parcels with less forest, they do not on their own inform whether titling influences deforestation because they do not reveal the timing of the loss of forest. It is plausible that parcels settled and deforested long ago would be more eligible for titling due to longer occupancy, for example. However, comparison of deforestation rates of forested pixels in titled parcels with those in matched pixels in other unrestricted zones suggests that titling does elevate deforestation. In all regions, forest pixels in parcels titled during the PRONAT campaign had significantly higher 1990-2020 deforestation compared to matched pixels. Annual deforestation rates within parcels titled by PRONAT were significantly higher than outside in the period prior to titling (1990-2000) and peaked during the titling campaign (2000-2010), before falling to similar rates as outside following titling (Fig 6). Total average marginal effect of PRONAT titling on deforestation for 1990-2020, estimated with the doubly-robust propensity-score matching and regression models was 3.5±3% in the NW region, 9.1±5% in the S region, and 9.2±9% in the E region (Fig 7). The low confidence in the estimates for the E region is the result of low sample size caused by few titles issued by PRONAT in this region and lack of suitable data for matching.

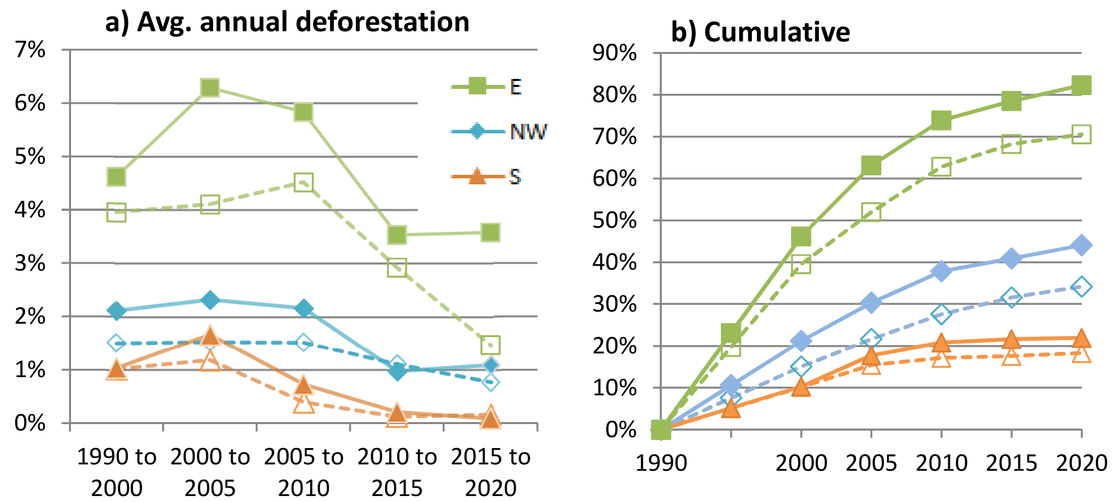

Figure 6: Deforestation of 1990 mature forests within parcels titled by PRONAT compared to other matched unprotected lands. Solid lines and markers represent pixels within parcels titled by PRONAT 2000-2010. Dashed lines and hollow markers represent matched pixels in other unprotected lands.

3.5.3 Effect of titling on longer-term deforestation and regrowth

To assess whether titling impacts deforestation over the longer term, titling prior to 2000 was used as the treatment in a similar analysis as with the PRONAT campaign. The average year of titling for these parcels was 1989 with a median of 1993. In all regions, parcels with titles issued prior to 2000 have higher deforestation compared to matched unrestricted lands (Fig 7), although the trend in the NW region is not significant after 2000. Total average marginal effect of titling on deforestation for 1990-2020 for titles issued prior to 2000 is 28±3% in the E region, 17±5% in the S region, and 3±3% in the NW region.

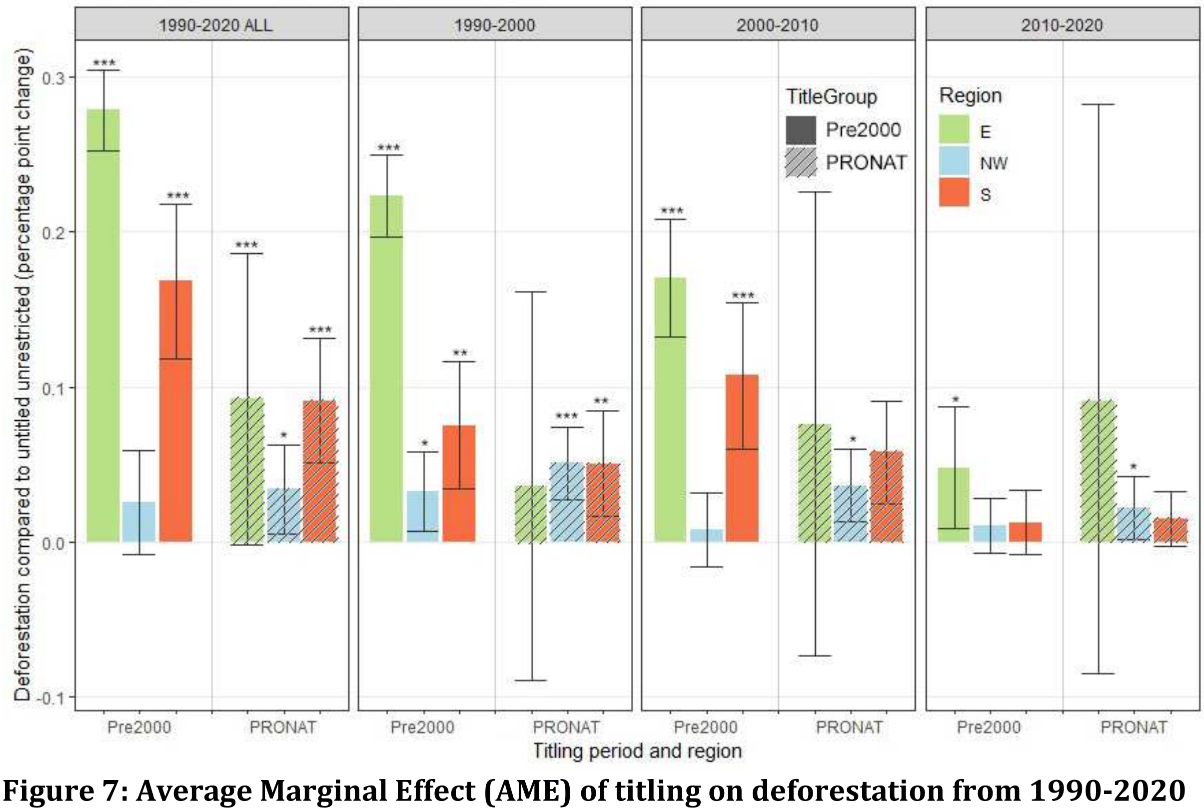

Figure 7: Average Marginal Effect (AME) of titling on deforestation from 1990-2020 disaggregated by time step, title period and region. Marginal effects are statistically different for titled parcels compared to matched pixels in unrestricted lands at *p<.05 **p<.01 ***p<.001.

While deforestation was accelerated in titles across all regions, regional distinctions become clear when net forest-cover change is examined instead of raw deforestation. In private parcels with some forest cover in 1990, net forest cover decreased by an average of 24.3% in the E region and 5.9% in the NW region, but increased by an average of 2.8% in the S region (Table 5). This difference can be explained by initial forest-cover conditions; forested private parcels were covered by an average of 48% forest in 1990 in the E region and 35% in the NW region but only 16% in the S region. In private parcels with no forest in 1990, afforestation rates were actually lowest in the S region (Table 5), but because far more parcels in the S region lacked forest in 1990 (Table 4), and average 1990 forest cover for all private parcels >1000m^2 was 1.5% in the S compared to 25% in the E and 12% in the NW, this relatively low rate of regrowth results in a perceivable trend of growth in the region (Walker, 2020; Wright and Samaniego, 2008).

To examine whether titling affects forest growth, either as forest plantations or regeneration, parcels without forest titled prior to 2000 were compared to those not yet titled as of 2011. In all regions, parcels with secure titles had significantly lower 1990-2020 growth of both forest and high vegetation than those with titles still in process in 2011, even when controlling for confounding variables such as parcel size as well as district-level variance (Table 5, full models in Appendix (A.4 to A.9)). The relationship between titling and regrowth is best explained in the form of a zero-inflated model, where untitled parcels have significantly higher odds of remaining completely deforested compared to titled parcels, but have a significantly greater extent of regrowth if any regrowth occurs. This suggests that private parcels are rarely completely abandoned once titled, yet they may be cleared and later abandoned if no title is secured.

Table 5: 1990-2020 Forest-Cover Change in private parcels >1000m² (average % parcel)

	Parcels with forest in 1990			Parcels with no forest in 1990					
	Net forest cover change			Afforestation			Net growth[a]		
Title status	E	NW	S	E	NW	S	E	NW	S
Titled prior to 2000	-24.1	-3.6	2.3	1.6*	1.4*	0.4*	0.3*	3.7*	1.6*
Titled by PRONAT (2000-2011)	-24.6	-6.3	2.6	1.3	2.3	1.0	3.8	4.7	3.1
Title still in process as of 2011	-24.8	-6.1	3.5	4.6*	4.5*	0.8*	4.7*	7.8*	2.6*
ALL	-24.3	-5.9	2.8	3.7	3.5	0.8	3.4	6.5	2.5

** difference between parcels with titles and still in process is significant at p<.01*

[a] Net change in high vegetation and forest combined

4 Discussion and Conclusions

4.1 Modelling limitations

This study is underpinned by a relatively robust 35-year vegetation-cover change dataset targeted specifically for Panama. While errors in this dataset are comparatively well assessed and documented for a forest-cover change analysis of this nature (Walker 2020), errors do still exist. Errors in missed and false deforestation are assumed to be distributed randomly across zoning and titling units, although this may be untrue especially in the case of deciduous trees, which are more dominant in agricultural areas. This bias, coupled with the fact that the 1990 base map only has five years of prior Landsat imagery to inform it, likely results in some activity related to re-clearing of fallow areas and planted trees being recorded as deforestation. Accounting for undisturbed forest and distance from forest edge in the matching analysis helps distribute any such bias evenly across the treatment units. For the titling analyses in particular, ground-based assessment of parcels and-or sample pixels would be useful to determine whether any bias remains.

Socioeconomic variables at the parcel level would also provide for a much stronger assessment of titling effect. Propensity-score matching was used to help reduce biases between lands more likely to receive titles, however the assumption of unconfoundness, or that all factors affecting the treatment that may also affect the outcome are observed and controlled for, may not be fully satisfied in this case. While socioeconomic factors were controlled for at the local level through variables known to correlate with poverty (Wright and Samaniego, 2008), individuals within these areas may still differ systematically. Poorer land users may be less likely to seek a title, for example because of tax expectations that may come with it, and less likely to receive a title because they have a harder time providing evidence for their presence on the land. The significant differences observed in deforestation rates between titled and untitled parcels were found to be fairly robust to unobserved covariates, with Rosenbaum gamma coefficients around two, indicating that a variable would need to double the odds of treatment for differences to be rendered insignificant. Nonetheless, it is possible that individual socioeconomic circumstances could affect titling odds in such a way. The question remains whether those less likely to request or receive a title due to socioeconomic conditions are also less likely to deforest land regardless of titling status. The theoretical and geographic framework provided here could be strengthened with groundwork including parcel visits and interviews with titleholders/seekers.

4.2 Main policy findings

4.2.1 PAs and Indigenous Comarcas reduce deforestation

This analysis supports the findings of others that restricted zones reduce deforestation in Panama, with PAs and Comarcas having the strongest and second-strongest effect, respectively, on avoided deforestation in all regions. While forests in lands designated as PAs or Comarcas have lower deforestation at the aggregate level, they are not a panacea in and of themselves. High levels of deforestation have occurred in a small percentage of PAs and in some locations within Comarcas, particularly within Ngäbe-Buglé in the NW region. While indigenous people are certainly responsible for some deforestation within these areas (Smith et al., 2017), they have also defended their forests from invasions by mining companies and developers (Jordan, 2018; Cansari and Gausset, 2013) and lost a large swath to a government-sponsored hydroelectric project (Velásquez Runk, 2012; Jordan 2018).

The role indigenous populations and environmental activists play in defending forests against large-scale land invasions and development projects can be obscured by analyses such as the one presented here. To estimate the effect of a policy without observing what would have occurred without the policy, variables that bias policy implementation, such as proximity to roads, must be controlled for. If PAs are established mostly in areas far from roads, they will naturally have lower deforestation pressure and thus less deforestation. After controlling for such variables in an econometric analysis, Nelson et al., (2001) concludes that PAs such as Darien National Park in the E region of Panama have made little difference in deforestation compared to what would have happened in their absence. While the data presented here suggest differently, even with the most conservative model, it is difficult to provide a precise effect estimate due to difficulty in separating accessibility variables from the treatment over the long term. For example, while a PA is more likely to be established in an area farther from roads, later roads are less likely to be built in a PA. Darien National Park is a clear example of this inseparability, where conservation activists have, to date, effectively blocked the completion of the Transamerica highway through the Darien in the name of the PA (Miller, 2014). Comarcas present a similar difficulty with treatment bias and effect over the long term, as roads and other development projects are often actively resisted by their populations (Cansari and Gausset, 2013; Savener, 2013). For these reasons, I provide three estimates of effect for each treatment. The actual effect of PA and Comarca on deforestation likely lies somewhere between the naïve case-control estimates and the most conservative AME estimates. Regardless of the conservativeness of the model, the results show a clear beneficiary effect of PAs and Comarcas on forest cover across Panama.

4.2.2 Indigenous territories reduce deforestation despite insecure tenure

Lands under customary management by indigenous groups but not yet formally titled or designated as a Comarca have higher deforestation rates relative to restricted zones. These lands, however, are also in areas with higher deforestation pressure due to proximity to roads and urban centers. When accessibility variables are controlled for in the E region, land outside of Comarcas and PAs under indigenous management have deforestation rates as low or lower than PAs. Effect could not be evaluated in the NW region due to deficiency of data for matching. Nonetheless, this result supports that reported by Vergara-Asenjo and Potvin (2014) who found around 7% reduced deforestation in all indigenous territories from 1992-2008 using different mapping methods. This strong reduction in deforestation is especially notable in that it occurs despite vulnerability of these territories to invasions and deforestation caused by outsiders (Vergara-Asenjo, 2017; Holmes et al., 2017).

4.2.3 High deforestation in private parcels is likely increased with titling

Land titling is viewed as an effective tool to reduce poverty, as evidenced by Panama´s pledge for 100% of its adult population to have secure tenure through a private or collective title by 2030 to meet the sustainable development goals (CCND, 2017). For land titling to have the full intended effect of reducing poverty, however, care needs to be taken to prevent deforestation and environmental degradation that would disproportionally affect the same land dwellers (Rasmussen et al., 2017; Wali, 1993, Heckadon Moreno 1985; IDIAP, 2010). The analysis of effect of titling on deforestation presented here reveals the threat that granting private titles poses to remaining forests across Panama. The observed bias in issuing titles to parcels with less forest, along with the higher deforestation observed in titled parcels during the titling process, supports the observation of many that the act of deforestation is itself an investment in more secure rights (Arnot et al., 2011; Heckadon Moreno, 2009; Wali, 1993; Peterson St.-Laurent et al., 2013; Velazquez Runk, 2017) as elsewhere in Latin America (Ankersen and Ruppert, 2006). Despite an extensive note of this historical tendency of the agrarian code to encourage deforestation in the process of formalizing tenure, the loan proposal for the large-scale titling PRONAT project concluded with the expectation that the project would "not result in significant or foreseeable adverse environmental impact" (IDB, 2002). This analysis highlights such adverse environmental impact so it may be foreseen in future projects.

4.3 Perverse incentives of reforestation

As a signatory to the New York declaration of forests, Panama's government has professed commitment to halving natural deforestation by 2020 and ending it by 2030. REDD+ preparations have also been ongoing since 2009 (UN-REDD, 2016). However, rather than modify laws and institutions to better promote sustainable use of existing forests, the general environmental strategy in Panama is trending towards reforestation efforts, such as the pledge of the Alliance for Reforesting One Million Hecatres to restore 13% of Panama's land area by 2030 as part of the global Bonn Challenge (FCPF, 2017; Miambiente, 2019). Such efforts can help explain the regeneration in the S region of Panama and fit within a larger context of forest transitions across Latin America, where landholders allow tree cover to expand on their lands if they receive economic benefits for doing so (Rudel et al., 2016; Kaimowicz, 1996) or simply no longer benefit from agriculture.

For a forest transition via reforestation or regrowth to be beneficial, however, mature natural forest must already be depleted. This is true in the S region, but not in the other regions of Panama. In areas with remaining natural forest, a paradox occurs when economic benefits of forests to landholders are more heavily associated with reforestation than with conservation. The case presented here is similar to that in Nicaragua (Liscow, 2013), where titled land has higher deforestation rates, but also greater extent of planted forest. Speculative deforestation occurs as a cost of creating better markets for land and tree planting without creating markets for the positive externalities provided by mature forests. The perverse incentives of land titling and reforestation projects echo current debate of zero net deforestation policies that allow for reforestation to offset deforestation (Garrett et al., 2019) as well as early critiques the Clean Development Mechanism providing disproportionate value to international afforestation and reforestation projects compared to protection of intact forests (Murray, 2000; Nieston et al., 2002).

A system that encourages deforestation and promises rewards for subsequent reforestation is not only inefficient but detrimental to biodiversity (Gibson et al., 2011) and climate change initiatives (Watson et al., 2018) and can have negative consequences on livelihoods (Uriarte and Chazdon, 2016; Lazos-Chavero et al., 2016). Restoring forests does not offset deforestation, particularly of primary forests, because it takes over a decade (Griscom and Ashton, 2011) to even a century (NYDF Assessment Partners 2019; Bechara et al., 2016) to recover lost ecosystem function and services. Passive regeneration often never recovers original forest diversity (Griscom and Ashton, 2011), while monoculture forest plantations offer neither the biodiversity nor the ecosystem services of natural forests (Hooper, 2008; Hall et al., 2011; Meyfroidt and Lambin, 2011). Even the most ardent advocates for forest regeneration in Latin America acknowledge that curbing deforestation of existing tropical forests yields the most benefits to the carbon budget and that regeneration projects must be supplementary to such efforts (Chazdon et al., 2016).

4.4 Path forward: coherent landscape approach

Despite declaring a new era of forestry policy focused on integrating forests in sustainable economic development (World Bank, 2004; Chomitz, 2007), the World Bank continues to advocate that “due to their complexity, land projects are best handled as stand-alone operations rather than as part of multi-sectoral operations” (IEG, 2016). Tendencies toward tackling tenure and titling lands before addressing environmental issues on those lands may seem practical but can further unsustainable forces (Bastos Lima et al., 2017), as seen here in the case of Panama. To meet ecological, economic and livelihood goals, multilateral and national institutions need to commit to coherent policies that acknowledge the interdependence of these goals (Ribot et al., 2006; IPBES, 2019) as well as heterogeneity of the landscape (Sayer et al., 2013). Such tailored management requires institutional coordination that may take many years to develop but can provide promising results over the long term in Latin America (Estrada-Carmona et al., 2014). In the absence of such coordination, private titling fuels the already powerful and fundamental forces of business-as-usual neoliberalism, which commoditize and exploit forests to the primary benefit of wealthy elites (Alston et al., 1996; Fairhead et al., 2012).

Panama's strong network of PAs and ongoing work on Indigenous lands provides a foundational sketch that can be refined for robust management of its forests. In the agricultural mosaics between PAs and Comarcas, there is opportunity to address development issues while simultaneously conserving and connecting forests if strategies are tailored to the landscape as well as socio-political context (Chomitz et al., 2006; Agrawal et al. 2014). This work highlights the need to disaggregate national strategies by forest transition zone and history to avoid creating stronger markets for reforestation than conservation where native forests exist. In the S. region of Panama that has been largely deforested historically, a "restore" pathway focused on efforts to help farmers enhance live fences, riparian corridors, and other strategic tree cover on their lands might be most effective (Garen et al., 2011; Garen et al., 2009; Metzel and Montagnini, 2014). In the frontier and forested regions, however, there is still great need for incentive-based policies such as REDD+ to encourage tree conservation on private lands. Although the effect of titling by PRONAT could not be fully analyzed in the E province due to the campaign's inability to issue the targeted number of titles, trends from past titling in the region show the drastic impact that private titling can have on forests frontier zones.

Market opportunities for incentive-based forest conservation mechanisms may exist (Duke et al., 2014, Coomes et al., 2008), yet more contemplation is needed regarding the often-required prerequisite of clear and irreversible land tenure (UN-REDD, 2017; Mateo-Vega et al., 2018; Wunder, 2013). This work highlights a paradox for private titles and forest conservation where titling land as a necessary condition for participation in forest conservation programs may result in loss of forest cover at least in the period before the conservation programs come into play.

Acknowledgements

I thank the government employees at PRONAT and INEC who provided detailed parcel and population datasets. The availability of Landsat images from USGS and higher-level processing through the ESPA interface is also always greatly appreciated. J. Wright at the Smithsonian Tropical Research institute provided insightful feedback on early versions of this work. The comments of three anonymous reviewers also resulted in substantial improvements to this manuscript. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

AGRAWAL, A., and A. CHHATRE. 2006. Explaining success on the commons: Community forest governance in the Indian Himalaya. World Development 34: 149-166.

AGRAWAL, A., E. WOLLENBERG, and L. PERSHA. 2014. Governing agriculture-forest landscapes to achieve climate change mitigation. Global Environmental Change 29: 270-280.

ALSTON, L. J., G. D. LIBECAP, and R. SCHNEIDER. 1996. The determinants and impact of property rights: Land titles on the Brazilian frontier. The Journal of Law, Economics, and Organization 12: 25-61.

ALSTON, L. J., G. D. LIBECAP, and B. MUELLER. 2000. Land reform policies, the sources of violent conflict, and implications for deforestation in the Brazilian Amazon. Journal of Environmental Economics and Management 39: 162-188.

ANAM. 1992. Mapa de la cobertura boscoso de Panamá de 1992. Autoridad Nacional del Ambiente, Panamá.

ANAM. 2003. Informe final de resultados de la cobertura boscosa y uso del suelo de la República de Panamá: 1992-2000. Autoridad Nacional del Ambiente, Panamá, República de Panamá.

ANAM. 2006. Informe el Sistema Nacional de Áreas Protegidas. ANAM, Panamá.

ANAM. 2010. Compendio Estadístico Ambiental 2009. p. 185. Autoridad Nacional del Ambiente, Panamá.

ANGELSEN, A. 2007. Forest Cover Change in Space and Time: Combining the von Thünen and Forest Transition Theories. World Bank Policy Research Working Paper, p. 43. The World Bank, Washington, D.C.

ANGELSEN, A., and D. KAIMOWITZ. 1999. Rethinking the causes of deforestation: Lessons from economic models. World Bank Research Observer 14: 73-98.

ANGELSEN, A., and T. K. RUDEL. 2013. Designing and Implementing Effective REDD + Policies: A Forest Transition Approach. Review of Environmental Economics and Policy 7: 91-113.

ANKERSEN, T. T., and T. RUPPERT. 2006. Tierra y Libertad: The Social Function Doctrine and Land Reform in Latin America Tulane Environmental Law Journal 19: 69-120.

ARAUJO, C., C. ARAUJO BONJEAN, J.-L. COMBES, P. COMBES MOTEL, and E. J. REIS. 2009. Property rights and deforestation in the Brazilian Amazon. Ecological Economics 68: 2461-2468.

ARNOT, C. D., M. K. LUCKERT, and P. C. BOXALL. 2011. What Is Tenure Security? Conceptual Implications for Empirical Analysis. Land Economics 87: 297-311.

AZEVEDO, A. A., R. RAJAO, M. A. COSTA, M. C. C. STABILE, M. M. MACEDO, T. N. P. DOS REIS, A. ALENCAR, B. SOARES-FILHO, and R. PACHECO. 2017. Limits of Brazil's Forest Code as a means to end illegal deforestation. PNAS 114: 7653-7658.

BACCINI, A., W. WALKER, L. CARVALHO, M. FARINA, D. SULTA-MENASHE, and R. A. HOUGHTON. 2017. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. Science.

BARBIER, E. B., and A. T. TESFAW. 2013. Tenure Constraints and Carbon Forestry in Africa. American Journal of Agricultural Economics 95: 964-975.

BASTOS LIMA, M. G., G. KISSINGER, I. J. VISSEREN-HAMAKERS, and J. BRANA-VARELA. 2017. The sustainable development goals and REDD+: assessing institutional interactions and the pursuit of synergies. International Environmental Agreements 17: 589-606.

BAYNES, J., J. HERBOHN, C. SMITH, R. FISHER, and D. BRAY. 2015. Key factors which influence the success of community forestry in developing countries. Global Environmental Change 35: 226-238.

BEBBER, D. P., and N. BUTT. 2017. Tropical protected areas reduced deforestation carbon emissions by one third from 2000-2012. Scientific reports 7: 14005.

BECHARA, F. C., S. J. DICKENS, E. C. FARRER, L. LARIOS, E. N. SPOTSWOOD, P. MARIOTTE, and K. SUDING. 2016. Neotropical rainforest restoration: comparing passive, plantation and nucleation approaches. Biodiversity and Conservation 25.

BERKES, F., J. COLDING, and C. FOLKE. 2003. Navigating Social-Ecological Systems. Cambridge University Press, Cambridge.

BESLEY, T. 1995. Property rights and investment incentives: Theory and evidence from Ghana. Journal of Political Economy 103: 903-907.

BLACKMAN, A. 2013. Evaluating forest conservation policies in developing countries using remote sensing data: An introduction and practical guide. Forest Policy and Economics 34: 1-16.

BLACKMAN, A., and P. VEIT. 2018. Titled Amazon Indigenous Communities Cut Forest Carbon Emissions. Ecological Economics 153: 56-67.

BRADSHAW, C. J., N. S. SODHI, and B. W. BROOK. 2009. Tropical turmoil: a biodiversity tragedy in progress. Frontiers in Ecology and the Environment 7: 79-87.

BRANDT, J. S., B. S. VAN BUTSIC, T. KUEMMERLE, V. C. RADELOFF. 2015. The relative effectiveness of protected areas, a logging ban, and sacred areas for old-growth forest protection in southwest China. Biological Conservation. 118: 1-8.

BURIVALOVA, Z., D. MITEVA, N. SALAFSKY, R. A. BUTLER, and D. S. WILCOVE. 2019. Evidence Types and Trends in Tropical Forest Conservation Literature. Trends in Ecology & Evolution 34: 669-679.

BUSCH, J., and K. FERRETTI-GALLON. 2017. What Drives Deforestation and What Stops It? A Meta-Analysis. Review of Environmental Economics and Policy 11: 3-23.

CAMPBELL, J. M. 2015. Conjuring Property: Speculation and Environmental Futures in the Brazilian Amazon. University of Washington Press, Seattle, Washington.

CANSARI, R., and Q. GAUSSET. 2013. Along the road: the Ngäbe-Buglé struggle to protect environmental resources in Panama. International Indigenous Policy Journal 4: 1-15.

CAUGHLIN, T. T., S. W. RIFAI, S. J. GRAVES, G. P. ASNER, and S. A. BOHLMAN. 2016. Integrating LiDAR-derived tree height and Landsat satellite reflectance to estimate forest regrowth in a tropical agricultural landscape. Remote Sensing in Ecology and Conservation: 190-202.

CCND (CONSEJO DE LA CONCENTRACION NACIONAL PARA EL DESARROLLO). 2017. Plan Estratégico Nacional con Visión de Estado "Panamá 2030". p. 100. CCND y PNUD, Panama.

CHAZDON, R. L., E. N. BROADBENT, D. M. A. ROZENDAAL, F. BONGERS, A. M. ALMEYDA ZAMBRANO, T. M. AIDE, P. BALVANERA, J. M. BECKNELL, V. BOUKILI, P. H. S. BRANCALION, et al. 2016. Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. Science Advances 2.

CHHATRE, A., and A. AGRAWAL. 2009. Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. Proceedings of the National Academy of Sciences of the United States of America 106: 17667-17670.

CHOMITZ, K. M. 2007. At Loggerheads? Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests. The International Bank for Reconstruction and Development / The World Bank, Washington, D.C.

CHOMITZ, K. M., G. A. B. FONSECA, K. ALGER, D. M. STOMS, M. HONZAK, C. LANDAU, T. S. THOMAS, W. WAYT THOMAS, and F. DAVIS. 2006. Viable reserve networks arise from individual landholder responses to conservation incentives. Ecology and Society 11.

COOMES, O. T., F. GRIMARD, C. POTVIN, and P. SIMA. 2008. The fate of the tropical forest: Carbon or cattle? Ecological Economics 65: 207-212.

CURTIS, P. G., C. M. SLAY, N. L. HARRIS, A. TYUKAVINA, and M. C. HANSEN. 2018. Classifying drivers of global forest loss. Science 361: 1108-1111.

DEERE, C. D., and M. LEON. 2002. Who Owns the Land? Gender and Land-Titling Programmes in Latin America. Journal of Agrarian Change 1: 440-467.

DEININGER, K. 2003. Land policies for growth and poverty reduction. World Bank Group, Washington, D. C.

DEININGER, K., and B. MINTEN. 1996. Determinants of Forest Cover and the Economics of Protection: An Application to Mexico, Research Project on Social and Environmental Consequences of Growth-Oriented Policies. World Bank, Policy Research Department, Washington, D. C.

DORNER, P. 1972. Land reform and economic development. Penguin Books, Baltimore, Md.

DUKE, E. A., J. H. GOLDSTEIN, T. L. TEEL, R. FINCHUM, H. HUBER-STEARNS, J. PITTY, G. BEATRIZ RODRIGUEZ P, S. RODRIGUEZ, and L. OLMEDO SANCHEZ. 2014. Payments for ecosystem services and landowner interest: Informing program design trade-offs in Western Panama. Ecological Economics 103: 44-55.

ESTRADA-CARMONA, N., A. K. HART, F. DECLERCK, C. A. HARVEY, and J. C. MILDER. 2014. Integrated landscape management for agriculture, rural livelihoods, and ecosystem conservation: An assessment of experience from Latin America and the Caribbean. Landscape and Urban Planning: 1-11.

FAIRHEAD, J., M. LEACH, and I. SCOONES. 2012. Green Grabbing: a new appropriation of nature? Journal of Peasant Studies 39: 237-261.

FAO. 2002. Land tenure and rural development. FAO Land Tenure Studies 3. UN Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO. 2012. Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2015. Global forest resources assessment 2015 - Desk Reference. p. 245. Food and Agriculture Organization of the United Nations, Rome.

FCPF (FOREST CARBON PARTNERSHIP FACILITY), 2017. Mid-Term Progress Reporting for Country: Panama - Forest Carbon Partnership Facility (FCPF) Readiness Fund. REDD+ Panama, MiAMBIENTE & Government of Panama, Panama City, Panama.

FEDER, G., and D. FEENY. 1991. Land Tenure and Property Rights: Theory and Implications for Development Policy. World Bank Economic Review 5: 135-153.

FERRARO, P. J. 2009. Counterfactual thinking and impact evaluation in environmental policy. New Directions for Evaluation 122: 75-84.

FOLKE, C., S. R. CARPENTER, T. ELMQVIST, L. H. GUNDERSON, C. S. HOLLING, and B. H. WALKER. 2002. Resilience and sustainable development: Building adaptive capacity in a world of transformations. Ambio 31: 437-440.

GAREN, E. J., K. SALTONSTALL, J. L. SLUSSER, S. MATHAIS, M. S. ASHTON, and J. S. HALL. 2009. An evaluation of farmers' experiences planting native trees in rural Panama:

implications for reforestation with native species in agricultural landscapes. Agroforestry Systems 76: 219-236.

GAREN, E. J., K. SALTONSTALL, M. S. ASHTON, J. L. SLUSSER, S. MATHIAS, and J. S. HALL. 2011. The tree planting and protecting culture of cattle ranchers and small-scale agriculturalists in rural Panama: Opportunities for reforestation and land restoration. Forest Ecology and Management 261: 1684-1695.

GARRETT, R. D., S. LEVY, K. M. CARLSON, T. A. GARDNER, J. GODAR, J. CLAPP, P. DAUVERGNE, R. HEILMAYR, Y. LE POLAIN DE WAROUX, et al. 2019. Criteria for effective zero-deforestation commitments. Global Environmental Change 54: 135-147.

GIBSON, L., T. M. LEE, L. P. KOH, B. W. BROOK, T. A. GARDNER, J. BARLOW, C. A. PERES, C. J. A. BRADSHAW, W. F. LAURANCE, T. E. LOVEJOY, and N. S. SODHI. 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478: 378-383.

GRISCOM, H. P., and M. S. ASHTON. 2011. Restoration of dry tropical forests in Central America: A review of pattern and process. Forest Ecology and Management 261: 1564-1579.

GRISCOM, B. W., J. BUSCH, S. C. COOK-PATTON, P. W. ELLIS, J. FUNK, S. M. LEAVITT, G. LOMAX, W. R. TURNER, M. CHAPMAN, J. ENGELMANN, et al. 2020. National mitigation potential from natural climate solutions in the tropics. philosophical Transactions of the Royal Society B 375.

HALL, J. S., M. S. ASHTON, E. J. GAREN, and S. JOSE. 2011. The ecology and ecosystem services of native trees: Implications for reforestation and land restoration in Mesoamerica. Forest Ecology and Management 261: 1553-1557.

HARTSHORN, G. S. 1995. Ecological basis for sustainable development in tropical forests. Annual Review of Ecology and Systematics 26: 155-175.

HECKADON MORENO, S. 1985. La ganadería extensiva y la deforestación: los costos de una alternativa de desarrollo. In S. Heckadon Moreno and J. Espinosa González (Eds.). Agonía de la naturaleza: ensayos sobre el costo ambiental del desarrollo panameño. Instituto de Investigación Agropecuaria de Panamá & Smithsonian Tropical Research Institute, Panama.

HECKADON MORENO, S. 2009. De selvas a potreros: la colonización santeña en Panamá, 1850–1980. Exedra Books, Panama City, Panama.

HO, D. E., G. KING, K. IMAI, and E. STUART. 2011. MatchIt: Nonparametric Preprocessing for Parametric Causal Inference. Journal of Statistical Software 42.

HOLDRIDGE, L. R., and G. BUDOWSKI. 1956. Report of an ecological survey of the Republic of Panama. Caribbean Forester 17: 92-110.

HOLLAND, M. B., K. W. JONES, L. NAUGHTON-TREVES, J.-L. FREIRE, M. MORALES, and L. SUAREZ. 2017. Titling land to conserve forests: The case of Cuyabeno Reserve in Ecuador. Global Environmental Change-Human and Policy Dimensions 44: 27-38.

HOLMES, I., C. POTVIN, and O. T. COOMES. 2017. Early REDD plus Implementation: The Journey of an Indigenous Community in Eastern Panama. Forests 8.

HOOPER, E. R. 2008. Factors Affecting the Species Richness and Composition of Neotropical Secondary Succession: A Case Study of Abandoned Agricultural Land in Panama. Post-Agricultural Succession in the Neotropics, pp. 141-164.

HOSONUMA, N., M. HEROLD, V. DESY, R. S. DEFRIES, M. BROCKHAUS, L. VERCHOT, A. ANGELSEN, and E. ROMIJN. 2012. An assessment of deforestation and forest degradation drivers in developing countries. Environmental Research Letters 7: 12.

IDB (INTERAMERICAN DEVELOPMENT BANK), 2002. Land Administration and Regularization Project (PN-0148) - Loan Proposal. p. 37. Inter-American Development Bank.

IDB (INTERAMERICAN DEVELOPMENT BANK), 2014. Comparative Evaluation: Land Regularization and Administration Projects. Office of Evaluation and Oversight, OVE, Washington, D. C.

IDIAP (INSTITUTO DE INVESTIGACIÓN AGROPECUARIA DE PANAMÁ). 2010. Segundo informe nacional del estado de los recursos fitogenéticos para la alimentación y la agricultura en Panamá. p. 87. IDIAP & FAO, Panamá.

IEG (INDEPENDENT EVALUATION GROUP). 2016. Lessons from Land Administration Projects: A Review of Project Performance Assessments. IEG Category 1 Learning Product. World Bank, Washington, D.C.

IMBENS, G. W., and J. M. WOOLDRIDGE. 2009. Recent Developments in the Econometrics of Program Evaluation. Journal of Economic Literature 47: 5-86.

INEC (INSTITUTO NACIONAL DE ESTADÍSTICO Y CENSO). 1990. el IX Censo de Población y V de Vivienda: 1990. Contraloría General de la República de Panamá, Cuidad de Panamá, Panamá.

INEC (INSTITUTO NACIONAL DE ESTADÍSTICO Y CENSO). 2000. el X Censo de Población y VI de Vivienda de 14 mayo 2000. Contraloría General de la República de Panamá, Cuidad de Panamá, Panamá.

INEC (INSTITUTO NACIONAL DE ESTADÍSTICO Y CENSO). 2010. el XI Censo de Población y VII de Vivienda 2010. Contraloría General de la República de Panamá, Cuidad de Panamá, Panamá.

INEC (INSTITUTO NACIONAL DE ESTADÍSTICO Y CENSO) and MIDA (MINISTERIO DE DESARROLLO AGROPECUARIO). 2001. el VI Censo Nacional Agropecuario. Contraloría General de la República de Panamá, Cuidad de Panamá, Panamá.

INEC (INSTITUTO NACIONAL DE ESTADÍSTICO Y CENSO) and MIDA (MINISTERIO DE DESARROLLO AGROPECUARIO). 2011. el VII Censo Nacional Agropecuario. Contraloría General de la República de Panamá, Cuidad de Panamá, Panamá.

IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany.

ITTO (International Tropical Timber Organization). 2009. Tropical forest tenure assessment: Trends, challenges and opportunities. ITTO Technical Series, p. 46. International Tropical Timber Organization, Rights and Resources Initiative, Yokohama, Japan & Washington, D.C.

JARAMILLO, C. F., and T. C. KELLY. 1999. Deforestation and Property Rights. In K. Keipi (Ed.). Forest Resource Policy in Latin America, pp. 111-133. Inter-American Development Bank, Washington, D.C.

JONES, J. R. 1990. *Colonization and environment: land settlement projects in Central America*. United Nations University Press, Tokyo, Japan.

JOPPA, L. and A. PFAFF. 2009. High and Far: Biases in the location of protected areas. PLoS ONE 4(12).

JORDAN, O. 2018. The privatization of environmental discourse: Clean Development and indigenous territoriality in Western Panama. Abya Yala 2: 141-168.

KAIMOWITZ, D. 1996. Livestock and deforestation in Central America in the 1980s and 1990s: a policy perspective. Center for International Forestry Research, Jakarta, Indonesia.

KATILA, P., C. J. P. COLFER, W. DE JONG , G. GALLOWAY, P. PACHECO, and G. WINKEL. (Eds.) 2020. *Sustainable Development Goals: Their Impacts on Forests and People*. Cambridge University Press.

KEIPI, K. 1995. Inter-American Development Bank assistance for forest conservation and management in Latin America and the Caribbean. The Forestry Chronicle 71: 508-513.

KEIPI, K. 1999. Forest Resource Policy in Latin America. Inter-American Development Bank, Washington, D. C.

KÖHL, M., R. LASCO, M. CIFUENTES, Ö. JONSSON, K. T. KORHONEN, P. MUNDHENK, J. DE JESUS NAVAR, and G. STINSON. 2015. Changes in forest production, biomass and carbon:

Results from the 2015 UN FAO Global Forest Resource Assessment. Forest Ecology and Management 352: 21-34.

LAWLOR, K., E. SILLS, S. ATMADJA, L. LIN, and K. SONGWATHANA. 2020. SDG 1: No poverty - impacts on social protection, tenure security and building resilience on forests. In P. Katila, C. J. P. Colfer, W. de Jong , G. Galloway, P. Pacheco and G. Winkel (Eds.). *Sustainable Development Goals: Their Impacts on Forests and People*, pp. 17-47. Cambridge University Press.

LAZOS-CHAVERO, E., J. ZINDA, A. BENNETT-CURRY, P. BALVANERA, G. BLOOMFIELD, C. LINDELL, and C. NEGRA. 2016. Stakeholders and tropical reforestation: challenges, trade-offs, and strategies in dynamic environments. Biotropica 48: 900-914.

LEEPER, T. J. 2016. margins: An r port of stata's 'margins' command. Available at the Comprehensive R Archive Network (CRAN).

LISCOW, Z. D. 2013. Do property rights promote investment but cause deforestation? Quasi-experimental evidence from Nicaragua. Journal of Environmental Economics and Management 65: 241-261.

MATEO-VEGA, J., A. K. SPALDING, G. M. HICKEY, and C. POTVIN. 2018. Deforestation, Territorial Conflicts, and Pluralism in the Forests of Eastern Panama: A Place for Reducing Emissions from Deforestation and Forest Degradation? Case Studies in the Environment.

METZEL, R. 2010. From “Finca” to Forest: Forest Cover Change and Land Management in Los Santos, Panama. PhD Dissertation. Princeton University.

METZEL, R., and F. MONTAGNINI. 2014. Factors associated with protecting and planting trees in a Panamanian agricultural landscape. Bois et Forêts des Tropíques 342.

MEYFROIDT, P., and E. F. LAMBIN. 2011. Global Forest Transition: Prospects for an End to Deforestation. Annual Review of Environment and Resources 36: 343-371.

MIAMBIENTE. 2019. Alianza por el Millón: REDD+ de Panamá. MiAMBIENTE y UNDP, Cuidad de Panamá, Panamá.

MILLER, S. W. 2014. Minding the Gap: Pan-Americanism's Highway, American Environmentalism, and Remembering the Failure to Close the Darian Gap. Environmental History 19: 189-216.

MIN-VENDITTI, A. A., G. W. MOORE, and F. FLEISHMAN. 2017. What policies improve forest cover? A systematic review of research from Mesoamerica. Global Environmental Change 47: 21-27.

MURRAY, B. C. 2000. Carbon values, reforestation, and 'perverse' incentives under the Kyoto protocol: An empirical analysis. Mitigation and Adaptation Strategies for Global Change 5: 271-295.

NAUDTS, K., Y. CHEN, M. J. MCGRATH, J. RYDER, A. VALADE, J. OTTO, and S. LUYSSAERT. 2016. Europe´s forest management did not mitigate climate warming. Science: 597-.

NELSON, G. C., V. HARRIS, and S. W. STONE. 2001. Deforestation, Land Use, and Property Rights: Empirical Evidence from Darien, Panama. Land Economics 77: 187-205.

NIESTEN, E., P. C. FRUMHOFF, M. MANION, and J. HARDNER. 2002. Designing a carbon market that protects forests in developing countries. Philosophical Transactions of the Royal Society A 1037.

NYDF ASSESSMENT PARTNERS. 2019. Protecting and Restoring Forests: A Story of Large Commitments yet Limited Progress. New York Declaration on Forests Five-Year Assessment Report. Climate Focus (coordinator and editor).

OESTREICHER, J. S., K. BENESSAIAH, M. C. RUIZ-JAEN, S. SLOAN, K. TURNER, J. PELLETIER, B. GUAY, K. E. CLARK, D. G. ROCHE, M. MEINERS, and C. POTVIN. 2009. Avoiding deforestation in Panamanian protected areas: An analysis of protection effectiveness and implications for reducing emissions from deforestation and forest degradation. Global Environmental Change-Human and Policy Dimensions 19: 279-291.

OLDEKOP, J. A., G. HOLMES, W. E. HARRIS, and K. L. EVANS. 2015. A global assessment of the social and conservation outcomes of protected areas. Conservation Biology 30: 133-141.

OSTROM, E., and M. COX. 2010. Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. Environmental Conservation 37: 451-463.

PACHECO, P., M. AGUILAR-STOEN, J. BORNER, A. ETTER, L. PUTZEL, and M. D. C. VERA DIAZ. 2011. Landscape Transformation in Tropical Latin America: Assessing Trends and Policy Implications for REDD+ Forests 2.

PERZ, S. G., and D. L. SKOLE. 2003. Secondary forest expansion in the Brazilian Amazon and the refinement of forest transition theory. Society & Natural Resources 16: 277-294.

PETERSON ST-LAURENT, G., N. GELINAS, and C. POTVIN. 2013. REDD+ and the agriculture frontier: Understanding colonists' utilization of the land. Land Use Policy 31: 516-525.

PORTER-BOLLAND, L., ELLIS, E. A., GUARIGUATA, M. R., RUIZ-MALLEN, I., NEGRETE-YANKELEVICH, S., REYES-GARCIA, V. 2012. Community managed forests and forest protected areas: An assessment of their conservation effectiveness across the tropics. Forest Ecology and Management 268: 6-17.

POTEETE, A. R., and E. OSTROM. 2004. Heterogeneity, group size and collective action: The role of institutions in forest management. Development and Change 35: 435-461.

RASMUSSEN, L. V., S. JUNG, A. D. BRITES, C. WATKINS, and A. AGRAWAL. 2017. Understanding smallholders' intended deforestation behavior in the Brazilian Cerrado following environmental registry. Environmental Research Letters 12.

RECIO, M. E. 2011. REDD+: aspectos legales relativos a su aplicación en Panamá. Consultoria para ONU-REDD Panama.

RECIO, M. E. 2014. Panama resource tenure and sustainable landscapes assessment. USAID Tenure and Global Climate Change Program (TGCC). USAID, Washington, D.C.

REDO, D. J., H. R. GRAU, T. M. AIDEA, and M. L. CLARK. 2012. Asymmetric forest transition driven by the interaction of socioeconomic development and environmental heterogeneity in Central America. PNAS 109: 8839-8844.

RIBOT, J. C., A. AGRAWAL, and A. M. LARSON. 2006. Recentralizing while decentralizing: How national governments re-appropriate forest resources. World Development 34: 1864-1886.

ROBINSON, B. E., M. B. HOLLAND, and L. NAUGHTON-TREVES. 2014. Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation. Global Environmental Change 29: 281-293.

ROBINSON, B. E., M. B. HOLLAND, and L. NAUGHTON-TREVES. 2017. Community land titles alone will not protect forests. Proceedings of the national academy of sciences 114: E5764-E5764.

ROEBELING, P. C., and E. M. T. HENDRIX. 2010. Land speculation and interest rate subsidies as a cause of deforestation: The role of cattle ranching in Costa Rica. Land Use Policy 27: 489-496.

ROLDAN ORTIGA, R. 2004. Models for recognizing indigenous land rights in Latin America. Paper No. 99. The World Bank Environment Department.

ROSENBAUM, P., 2002. Observational Studies, 2nd ed. Springer, New York.

ROSENBAUM, P., D. RUBIN. 1983. The central role of the propensity score in observational studies for causal effects. Biometrika 70, 41–55.

RUDEL, T. K., P. MEYFROIDT, R. L. CHAZDON, F. BONGERS, S. SLOAN, H. R. GRAU, T. VAN HOLT, and L. SCHNEIDER. 2019. Whither the forest transition? Climate change, policy responses, and redistributed forests in the twenty-first century. Ambio 49: 74-84.

RUDEL, T. K., S. SLOAN, R. L. CHAZDON, and R. GRAU. 2016. The drivers of tree cover expansion: Global, temperate, and tropical zone analyses. Land Use Policy 58: 502-513.

SANDBROOK, C., F. NELSON, W. M. ADAMS, and A. AGRAWAL. 2010. Carbon, forests and the REDD paradox. Oryx 44: 330-334.

SAVENER, A. 2013. A host gaze composed of mediated resistance in Panama: Power inversion in Kuna Yala. In O. Moufakkir and Y. Reisinger (Eds.). The Host Gaze in Global Tourism, pp. 67-80. CABI, Boston, MA.

SAYER, J., T. SUNDERLAND, J. GHAZOUL, J.-L. PFUND, D. SHEIL, E. MEIJAARD, M. VENTER, A. K. BOEDHIHARTONO, M. DAY, C. GARCIA, C. VEN OOSTEN, and L. BUCK. 2013. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. Proceedings of the national academy of sciences 110: 8349-8356.

SCHNEIDER, R. R. 1994. Government and the economy on the Amazon frontier. Latin America and the Caribbean Technical Department regional studies program no. 34. World Bank, Washington, D. C.

SEYMOUR, F., and J. BUSCH. 2016. Why Forests? Why Now? : The Science, Economics, and Politics of Tropical Forests and Climate Change. Center for Global Development, Washington, DC.

SJAASTAD, E., and D. W. BROMLEY. 1997. Indigenous land rights in sub-Saharan Africa: appropriation, security, and investment demand. World Development 25: 549-562.

SLOAN, S. 2008. Reforestation amidst deforestation: Simultaneity and succession. Global Environmental Change-Human and Policy Dimensions 18: 425-441.

SLOAN, S. 2015. The development-driven forest transition and its utility for REDD+. Ecological Economics 116: 1-11.

SMITH, D. A., M. B. HOLLAND, A. MICHON, A. IBANEZ, and F. HERRERA. 2017. The hidden layer of indigenous land tenure: informal forest ownership and its implications for forest use and conservation in Panama's largest collective territory. International Forestry Review 19: 478-494.

SONG, X.-P., M. HANSEN, S. V. STEHMAN, P. V. POTAPOV, A. TYUKAVINA, E. VERMOTE, and J. R. TOWNSHEND. 2018. Global land change 1982-2016. Nature: 639-643.

SPALDING, A. K. 2017. Exploring the evolution of land tenure and land use change in Panama: Linking land policy with development outcomes. Land Use Policy 61: 543-552.

STRI GIS LABORATORY. 2011. Panama's Road Network version 2011. Smithsonian Tropical Research Institute, Panama City, Panama.

SUNDERLIN, W. D., J. HATCHER, and M. LIDDLE. 2008. From Exclusion to Ownership? Challenges and Opportunities in Advancing Forest Tenure Reform. Rights and Resources Initiative, Washington, D.C.

SWAMY, L., E. DRAZEN, W. R. JOHNSON, and J. J. BUKOSKI. 2018. The future of tropical forests under the United Nations Sustainable Development Goals. Journal of Sustainable Forestry 37: 221-256.
SUNDERLIN, W. D. 2011. The Global forest tenure transition: background, substance, and prospects. In T. Sikor and J. Stahl (Eds.). Forests and People: Property, Governance and Human Rights. Routledge.

SUNDERLIN, W. D., C. DE SASSI, E. O. SILLS, A. E. DUCHELLE, A. M. LARSON, I. A. P. RESOSUDARMO, A. AWONO, D. L. KWEKA, and T. B. HUYNH. 2018. Creating an appropriate tenure foundation for REDD plus: The record to date and prospects for the future. World Development 106: 376-392.

TAKAHASHI, R., and K. OTSUKA. 2016. Determinants of Forest Degradation under Private and Common Property Regimes: The Case of Ethiopia. Land Economics 92: 450-467.

TIMKO, J., P. LE BILLON, H. ZERRIFFI, J. HONEY-ROSES, I. DE LA ROCHE, C. GASTON, T. C. H. SUNDERLAND, and R. KOZAK. 2018. A policy nexus approach to forests and the SDGs:tradeoffs and synergies. Current Opinion in Environmental Sustainability 34: 7-12.

TRESIERRA, J. C. 1999. Rights of Indigenous Peoples over Tropical Forest Resources. In K. Keipi (Ed.). Forest Resource Policy in Latin America. Inter-American Development Bank, Washington, D. C.

UN-REDD. 2016. Programas Nacionales Informe final, Panamá. UN-REDD, Panamá.

UN-REDD. 2017. Ninth Consolidated Annual Progress Report on Activities Implemented under the UN-REDD Programme Fund for the Period 1 January–31 December 2017. United Nations.

URIARTE, M., and R. L. CHAZDON. 2016. Incorporating natural regeneration in forest landscape restoration in tropical regions: synthesis and key research gaps. Biotropica 48: 915-924.

VELÁSQUEZ RUNK, J. 2012. Indigenous Land and Environmental Conflicts in Panama: Neoliberal Multiculturalism, Changing Legislation, and Human Rights. Journal of Latin American Geography 11: 21-47.

VELÁSQUEZ RUNK, J. 2017. *Crafting Wounaan landscapes*. University of Arizona Press, Tuscon, Arizona.

VERGARA-ASENJO, G., J. MATEO-VEGA, A. ALVARADO, and C. POTVIN. 2017. A participatory approach to elucidate the consequences of land invasions on REDD+ initiatives: A case study with Indigenous communities in Panama. Plos One 12: e0189463.

VERGARA-ASENJO, G., and C. POTVIN. 2014. Forest protection and tenure status: The key role of indigenous peoples and protected areas in Panama. Global Environmental Change 28: 205-215.

WALI, A. 1993. The transformation of a frontier: state and regional relationships in Panama 1972-1990. Human Organization 52: 115-129.

WALKER, K. L. 2021. Panama Vegetation Time Series Maps. Figshare data repository. DOI: 10.6084/m9.figshare.14120603. Available at: https://figshare.com/articles/dataset/Panama_Vegetation_Time_Series_Maps/14120603

WALKER, K. L. 2020. Capturing ephemeral forest dynamics with hybrid time-series and composite mapping in the Republic of Panama. International Journal of Applied Earth Observation and Geoinformation 87: 1-13.

WATSON, J. E. M., T. EVANS, O. VENTER, B. WILLIAMS, A. TULLOCH, C. STEWART, I. D. THOMPSON, J. C. RAY, K. MURRAY, A. SALAZAR, et al. 2018. The exceptional value of intact forest ecosystems. Nature Ecology & Evolution 2: 599-610.

WORLD BANK. 2004. Sustaining Forests. The World Bank, Washington, D.C.

WRIGHT, S. J., and M. J. SAMANIEGO. 2008. Historical, Demographic, and Economic Correlates of Land-Use Change in the Republic of Panama. Ecology and Society 13.

WUNDER, S. 2001. Poverty alleviation and tropical forests - What scope for synergies? World Development 29: 1817-1833.

WUNDER, S. 2013. When payments for environmental services will work for conservation. Conservation Letters.

WWF (World Wildlife Fund). 2018. Living Planet Report - 2018: Aiming Higher. In M. Grooten and R. E. A. Almond (Eds.). WWF, Gland, Switzerland.

ZEILEIS A. 2004. Econometric Computing with HC and HAC Covariance Matrix Estimators. Journal of Statistical Software, **11**(10), 1–17.

ZEILEIS A., S. KÖLL, N. Graham. 2020. Various Versatile Variances: An Object-Oriented Implementation of Clustered Covariances in R. Journal of Statistical Software, **95**(1), 1–36.