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# Land use patterns and influences of protected areas on mangroves of the eastern tropical Pacific

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ABSTRACT

Mangroves are one of the most productive ecosystems in the world, sustaining millions of coastal livelihoods. However, their area of occurrence has been greatly reduced over the last century. In this study, we identify potential drivers of land use and land cover change adjacent to mangroves on the Pacific shorelines of Colombia, Panama and Costa Rica. We also evaluate the effectiveness of protected areas at halting mangrove deforestation between 2000 and 2012. Across all countries, agriculture was the most dominant land use type adjacent to mangroves, inside and outside protected areas. Results show that a combined total of 564 ha were lost, representing an average loss rate of only 0.02% per year. 75% of the total mangrove loss occurred in locations outside protected areas, with only 138 ha cleared from inside protected areas. Results suggest current conservation policies for mangrove protection in the study countries are effective at reducing deforestation and set a positive example for regions where mangroves are in decline.

## 1. Introduction

It is estimated that by 2050, global crop production must double to meet the demands of a rising global population (Tilman et al., 2011). Despite suggestions to prevent the increase of cultivated area, the global pattern of increasing agricultural field sizes is often driven by government incentives, demand for biofuels, and technology (White and Roy, 2015). Worldwide rates of urban land expansion are higher than, or equal to, urban population growth rates (Seto et al., 2011). It is therefore expected that Land Use and Land Cover Change (LULCC) will increase as global population grows and developing countries become more affluent.

As LULCC intensifies, the effects of arable and urban land expansion may have significant and potentially irreversible consequences on ecosystem function and integrity (Foley et al., 2005). For instance, land conversion that removes primary forest has been shown to greatly reduce species diversity (Gibson et al., 2011). In the tropics, LULCC is associated with agricultural products for food, feed, and fuel (Gibbs et al., 2010; Blanco et al., 2012). Human reliance on natural environments is high in these regions and more than half of the new agricultural land created between 1980 and 2000 was via deforestation (Gibbs et al., 2010).

Mangrove forests are restricted to the interface between land and sea in tropical and subtropical latitudes. They are highly productive, provide a vast array of ecosystem services (Hogarth, 2007), and diversify and sustain livelihoods for millions of people (UNEP, 2014). Despite these widely appreciated values, mangrove cover is rapidly declining in different regions (Valiela et al., 2001; Alongi, 2008; Richards and Friess, 2015).

Estimates of global mangrove loss vary across regions and between methods used (Alongi, 2002; Giri et al., 2011; López Angarita et al., 2016). The development of optical remote sensing technology has allowed for a better estimation of mangrove coverage, and for the exploration of LULCC dynamics (Manson et al., 2001; Dahdouh-Guebas et al., 2004). Recently, development of new radar technology sensitive to forest spatial structure has allowed for accurate estimates of mangrove deforestation rates (Lucas et al., 2007; Simard et al., 2008; White and Roy, 2015; Hamilton, 2013; Thomas et al., 2017). However to date there is little information on the proximate drivers of LULCC in mangrove forests or replacement land uses (Tilman et al., 2011; Richards and Friess, 2015).

The Eastern Tropical Pacific (ETP) biogeographical region spans the

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**Fig. 1.** Geographical extent of the study (red line), on the Pacific coasts of Costa Rica, Panama, and Colombia (shaded green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

continental shelf and oceanic islands of Southern Baja California to northern Perú (Briggs, 1974), and supports a range of rich fisheries and exhibits many endemic species (Zapata and Robertson, 2006; Fiedler and Talley, 2006; Hogarth, 2007). In terms of mangrove protection in the region, 58% of mangroves that occur on the Pacific coast of Costa Rica are inside protected areas, compared to 51% in Panama and 28% in Colombia (López Angarita et al., 2016).

Mangrove cover in the ETP has followed global trends of decline, with its greatest loss occurring between the 1960s and 1990s (Valiela et al., 2001; López Angarita et al., 2016). Since then, countries in the ETP have strengthened their conservation policies for mangroves, via creation of protected areas and laws regulating mangrove use (Lacerda et al., 1993; ANAM-ARAP, 2013; López Angarita et al., 2016). To date there has been little or no assessment of the effectiveness of this protection.

In this study, we aim to identify the potential drivers of mangrove decline on the Pacific coasts of Costa Rica, Panama, and Colombia (Fig. 1) by mapping anthropogenic activities of LULCC in mangroves and performing analyses by country to compare trends within the region. Additionally, we determine the effectiveness of mangrove conservation policies by calculating rates of mangrove deforestation inside and outside protected areas, between 2000 and 2012.

## 2. Methods

### 2.1. Mangrove forest loss

To calculate the rate of mangrove deforestation we used the Global Forest Change dataset created by Hansen et al. (2013), which provides an index of annual deforestation between 2000 and 2015 per pixel (pixel size of 0.09 ha). These data are available up until 2015, but our study used the data between 2000 and 2012 only, to align with available land use data. We projected the Global Forest Change dataset for each country using UTM 18 N/17 N transformed from WGS84. Country-level mangrove areas were identified by overlaying the political limits of the studied countries with the global distribution of mangroves (Mangrove Forests of the World) in 2000 provided by Giri et al. (2011). Offshore islands were not included in our study. In a small section of the Colombian Pacific coast, we found a projection error causing misalignment of mangroves with the coastline in the Giri et al. (2011) global dataset, so we used Google satellite imagery and the mangrove distribution dataset for Colombia (IDEAM et al., 2007) to correct the error by manually fitting mangrove area polygons to the coastline. These steps resulted in a data layer of mangrove deforestation by country and year for the region of interest. This layer was used to calculate the percentage of mangroves deforested in the region for each country using number of pixels to estimate area. We obtained the rate of deforestation per year by dividing the percentage lost by the 12-years sampled (2000 not included and 2012 included). We used the same input layers (Global Forest Change and Mangrove Forests of the World) that Hamilton and Casey (2016) used, with a different methodological approximation, in their Global Database of Continuous Mangrove Forest Cover for the 21st Century, so we could compare our results with their deforestation rates.

### 2.2. Potential drivers of LULCC in mangrove areas

Ten different datasets of land cover with a resolution ≤ 30 $m^2$ were used to map the distribution of potential drivers of LULCC across the three countries (Table A1). We grouped potential drivers into three major classes: aquaculture, agriculture (includes cattle farms, oil palm plantations, and crops such as rice and fruits), and coastal development. Coastal development included towns and infrastructure such as ports and agricultural processing plants. Infrastructure was not analyzed as a separate class due to the few records associated with it. In this manuscript we used the term “potential drivers” to define land use types with