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# 1 **Comparing global and local maps of the Caribbean pine forests of Andros, home of the** 2 **critically endangered Bahama Oriole**

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 25

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27 The R code generated during and implemented in the current study is available from the  
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## **Abstract**

Forest loss is occurring at alarming rates across the globe. The pine rockland forests of Andros, The Bahamas, likely represent the some of the largest stands of Bahamian subspecies of Caribbean pine in the world. Given the unique species that inhabit these pine forests, such as the endemic and endangered Bahama Oriole, monitoring habitats on Andros is crucial to inform conservation planning. We developed a 2019 land classification map to assess the status of nine terrestrial habitats on Andros. Our Random Forest classification model predicted habitat classes with high overall accuracy. Caribbean pine was the dominant land class making up roughly one-third of the total terrestrial area. Whereas much of the pine forest area was found as small patches, most were close to other patches of pine suggesting isolation of forest patches is low. We compared our known intact forest areas to recent forest loss identified by the Hansen et al. Global Forest Change product and assessed areas of habitat disturbance in high-resolution imagery. Our results suggest that this global map overpredicted forest loss on Andros. The small degree of true forest loss on Andros was driven mostly by anthropogenic activity. A cross-tabulation of the Hansen forest loss with fire data showed that understory fires were frequently

associated with falsely classified deforestation. Given the threats of climate change to this open forest type—intensifying fire regimes, strengthening hurricanes and sea level rise—monitoring changes in open forest extent is a critical task across the Caribbean region and the world.

**Keywords:** *Pinus caribea bahamensis*, *forest change*, *pine rockland*, *Icterus northropi*, *remote sensing*, *habitat classification*, *landscape metrics*, *climate change*

## Introduction

Globally, forests supply key ecological services, such as carbon sequestration, while also playing a vital role in supporting biodiversity (Parry et al., 2007; Singh, 2002; Wan, Wang, Qu, Liu, & Zhang, 2018). As such, forests are critical components to mitigating two prominent global threats: climate change and the global extinction crisis (Morris, 2010; Schleuning et al., 2011). Unfortunately, forests are under intense pressure from anthropogenic activity, and forest loss is occurring at alarming rates across the globe (Curtis, Slay, Harris, Tyukavina, & Hansen, 2018; Hansen et al., 2018). From 2001 – 2015, it is estimated that global tree cover declined by 314 million hectares, with almost half of the total loss occurring in the Americas (Curtis et al., 2018). The biggest drivers of forest loss included conversion to agriculture and commercial forestry followed by wildfire, with urbanization contributing a relatively small proportion of global tree cover decline (Curtis et al., 2018).

Increased deforestation and forest fragmentation may have profound impacts on local biodiversity and species composition, and it is still largely unclear how most forest species will respond to changes in habitat extent and distribution. A recent assessment explored the association



between forest loss and the conservation status of 20,000 species world-wide from three classes of terrestrial vertebrates (birds, mammals, and amphibians; Betts et al., 2017). Results from that study demonstrated that even small levels of deforestation and fragmentation were associated with increased extinction risk and low biodiversity (Betts et al., 2017). Thus, to inform conservation planning and attenuate the global extinction crisis, it is crucial that we are able to monitor changes in extent of a wide range of forest types, particularly in disproportionately biologically diverse regions like the islands of the Caribbean (Chen et al., 2015; Ghosh-Harihar et al., 2019; Helmer, Ramos, López, Quinones, & Diaz, 2002; Schleuning et al., 2011).

One such threatened Caribbean forest ecosystem is the pine rockland forest, found only in southern Florida, Cuba, Turks and Caicos, and The Bahamas (Myers et al., 2004; U.S. Fish and Wildlife Service, 1999). Pine rockland forest describes a geographically restricted and unique subtype of a more abundant, open pine ecosystem that occurs across the southeastern United States, as well as parts of Central and Latin America. Despite the nutrient-poor, limestone coral-rock (“rockland”) substrate uniquely characteristic of this ecosystem subtype, these open pine forests host a diverse array of plant and animal species. Unfortunately, urban development and agriculture have reduced the area of pine rockland in Florida to just two percent of its historical extent (Jones & Koptur, 2017; U.S. Fish and Wildlife Service, 1999). Within The Bahamas, pine rockland occurs on only four islands: Grand Bahama, New Providence, Abaco, and Andros (Myers et al., 2004). Despite extensive 20<sup>th</sup> century logging operations, much of the pine rockland in The Bahamas area has recovered, resulting in large, mostly even-aged stands of open-canopy pine (Myers et al., 2004).

Many of the largest remaining contiguous areas of pine rockland habitat likely are found on Andros – the largest island in The Bahamas (Myers et al., 2004). A sub-species of Caribbean

pine (*Pinus caribea* var. *bahamensis*, endemic to The Bahamas) dominates these open forests. The animal and plant biodiversity of these pinelands are notable, including several endemic species such as the critically endangered Bahama Oriole (*Icterus northropii*; Myers et al., 2004). This bird species, endemic to The Bahamas and once found on both Abaco and Andros, is now found solely on Andros, having been extirpated from Abaco during the latter half of the twentieth century (Stonko et al., 2018; Rowley et al., 2021). The association of the Bahama Oriole, among other species, with the pine forests on Andros highlights the critical role that a single, restricted habitat may play in conserving global biodiversity (Stonko et al., 2018; Yancy et al., 2020; Rowley et al., 2021).

As a whole, the Andros archipelago contributes greatly to global biodiversity, supporting a high number of species in a relatively small area and hosting six “Important Bird Areas” (Birdlife International). Of the 27 species and subspecies of birds endemic to The Bahamas, 17 occur on Andros (Currie et al., 2019). Reptile diversity is also high on Andros, where researchers have documented 10 of the 33 reptilian species and subspecies endemic to The Bahamas, including the endemic and endangered Andros rock iguana (*Cyclura cychlura cychlura*,; Currie et al., 2019). Other endemic vertebrates on Andros include the Bahamian funnel-eared bat (*Chilonatalus tumidifrons*), and the Bahamian mosquito fish (*Gambusia hubbsi*; Currie et al. 2019). In addition to vertebrates, many endemic species of invertebrates and plants also occur on Andros (Currie et al. 2019; Freid et al. 2014).

Given the presence of such globally unique species, monitoring the forested habitats of Andros is a high conservation priority, as land cover change could be among the factors threatening species like the Bahama Oriole. However, conducting environmental surveys on Andros is challenging ( Knapp & Owens, 2005; Freid, 2006; Koptur, William, & Olive, 2010; Lloyd &

Slater, 2010). Robust and extensive surveys require access to resources such as boats and planes, as road infrastructure on Andros is limited and biased towards the east coast. Furthermore, long-distance travel by foot is impeded by either jagged, rocky terrain (limestone and coral-rock) or swampy wetlands and mudflats (Freid, 2006; Knapp & Owens, 2005; Koptur et al., 2010; Lloyd & Slater, 2010). These challenges highlight the need for an efficient method to survey Andros' habitats and to be able to track any changes in forest distribution. In this study, we set out to map the terrestrial habitats of Andros via remote sensing to estimate present-day habitat distribution and disturbance, so that we can better characterize the potential drivers of forest loss on Andros.

The pine forests of Andros are fire dependent; they are adapted to a regime of frequent (1-7 years), low intensity understory fires (Harley, Grissino-Mayer, & Horn, 2013; Jones & Koptur, 2017; R. Myers et al., 2004; Noss, LaRoe, & Scott, 1995; Possley, Woodmansee, & Maschinski, 2008; U.S. Fish and Wildlife Service, 1999). It is currently unclear how much forest loss, if any, is driven by fire on Andros. However, understory fires in the region are predicted to increase in frequency and intensity as climate change increases regional temperature and decreases rainfall (Parry et al. 2007). Hotter and more arid dry seasons coupled with more extreme hurricane seasons may result in an intensified fire regime (Myers et al., 2004). As severe tropical storms and hurricanes deposit and scatter debris, fuel loads accumulate throughout the pine understory, exacerbating the intensiveness of the burns (Myers et al., 2004). With more frequent and intense understory fires, these open pine habitats may transition into grass and palm shrublands (Myers et al. 2004).

Another aspect of climate change threatening the Caribbean pine forests on Andros is sea-level rise and salt-water inundation of the freshwater table. As part of the Great Bahama Bank, much of Andros is low – only a few meters above sea-level in most places. While Caribbean pine

can survive at these low elevations, these habitats are vulnerable to even a small increase in sea-level. Sea-level rise drove the transition of pine forest to more salt-tolerant mangroves in the neighboring Florida Keys (Ross, O'Brien, & da Silveira Lobo Sternberg, 1994), and we have observed local instances of forest dieback due to hurricane-driven storm surges.

The most recent estimate of forest loss in The Bahamas from the Global Forest Change product (GFC; Hansen et al., 2013) shows forest loss occurring throughout remote areas of Andros. Although freely available global products like the GFC can track global trends in land cover change, these maps vary in accuracy across spatial scales and land cover classes and are particularly inaccurate in open forests with low or seasonal canopy cover (Bastin et al., 2017, 2019; Cunningham, Cunningham, & Fagan, 2019; Fagan, 2020; Helmer et al., 2002). It is crucial, therefore, that we determine to what extent actual forest loss is occurring on Andros, given the open canopy (20-80% cover) of the pine rockland forests.

Given the challenges associated with global maps and regional ground surveys, we first developed a local habitat classification map for Andros, distinguishing nine terrestrial habitats. Next, given the important role of the pine forest as habitat for the Bahama Oriole, we estimated two biologically meaningful habitat characteristics relevant to oriole distribution: patch size and isolation. Lastly, we investigated GFC-reported disturbance areas across Andros and assessed the potential role of understory fires and other drivers in causing real and apparent forest loss. Through this research, we present a straightforward methodology to better monitor and address the threats facing biodiversity in a region of global conservation interest, while also assessing how well global map products can be applied to characteristically open forests.

## Methods

### Study area

Andros is an archipelago consisting of three main islands: North Andros, Mangrove Cay, and South Andros (Figure 1). While geographically located in the Atlantic, Andros, and The Bahamas, are often colloquially included within the Caribbean biodiversity hot-spot region (Bellard et al. 2014; Myers et al. 2000).

Located between 24° and 27° latitude, Andros has a sub-tropical climate characterized by a wet season (May-October) and dry season (November-April), with a hurricane season lasting roughly from June through October. Lightning-sparked fires are a natural occurrence on Andros and an important factor in maintaining the pine forest ecosystem. The highest frequency of fire occurs toward the end of the dry season (Currie et al., 2019). As part of a large coral-rock limestone plateau known as the Great Bahama Bank, Andros is generally flat, with a maximum elevation of 18 meters above sea-level (Smith & Vankat, 1992). Towns and settlements on Andros are generally restricted to the east coast where elevation is highest (Figure 1).

*Figure 1. Geographic location of Andros and The Bahamas relative to mainland United States and Cuba (left). The three main islands of Andros are denoted as A. (North Andros), B. (Mangrove Cay), and C. (South Andros). Settlements (shown as black dots) on Andros are largely concentrated along the east coast (right). Maps were generated in QGIS with the ESRI Terrain base map.*

## Field data collection and habitat classes

We collected geo-referenced field data during the spring of 2017, 2018, and 2019. We characterized the habitat at each point as one of nine terrestrial land classes: pine rockland forest (hereafter Caribbean pine), broadleaf coppice, woody shrubland, grass shrubland, mangrove scrub, mudflat/barren/scrub (hereafter referred to as mudflat), sand, agriculture/secondary growth, and developed (Table 1). We used a total of 879 points in ArcMap™ v10.3 to manually create training polygons for each land class. We did not have on-the-ground reference points for sand or mudflat habitats because they are generally found throughout the remote western regions of Andros. We used high resolution imagery from the ESRI Google Earth satellite imagery basemap to guide manual generation of training polygons for the mudflat and sand class.

**Table 1.** Description of habitat / landcover classes defined in this study.

Habitat Class	Description
<i>Caribbean pine</i>	Open canopy forest ranging from 5 - 15 meters in height; comprised of Caribbean pine with a typical understory of broadleaf vegetation (e.g., poison wood, <i>Metopium toxiferum</i> ), key thatch palm ( <i>Leucothrynax morissi</i> ), and bracken fern ( <i>Pteridium aquilinum</i> )
<i>broadleaf coppice</i>	Dense, evergreen broadleaf forest usually with a closed canopy and generally underdeveloped understory
<i>woody shrubland</i>	Open shrublands prone to flooding; includes three related habitats dominated by either native palms (up to about five meters), low scattered pine (five to eight meters), or low, evergreen- broadleaf vegetation (one to two meters)
<i>grassy shrubland</i>	Open, wet grasslands dominated by sawgrass ( <i>Cladium jamaicense</i> )
<i>mangrove scrub</i>	Coastal mangrove dominated by red mangrove ( <i>Rhizophora mangle</i> ); often scattered, scrub-like and low (one to two meters); inland mangrove dominated by black mangrove ( <i>Avicennia germinans</i> ) and white mangroves (family Combretaceae)
<i>mudflat/barren/scrub</i>	Saline tidal mudflats often colonized by various species of algae and occurs in the low-lying western areas; sparse, scrub-like habitats on limestone substrate with scattered grass and broadleaf vegetation occurring in eastern, upland areas
<i>agriculture/secondary</i>	Cultivated fields largely concentrated on North Andros; also includes secondary growth on abandoned fields and citrus groves; often dominated by non-native species such as Brazilian pepper ( <i>Schinus terebinthifolius</i> ), umbrella tree ( <i>Schefflera actinophylla</i> ), and elephant grass ( <i>Cenchrus purpureus</i> )
<i>developed</i>	Roads, housing, and municipal structures associated with human activity; largely restricted to the east coast; vegetation includes a variety of native and non-native plant species (e.g., introduced coconut palm, <i>Coco nucifera</i> )
<i>sand</i>	Mostly barren, oolitic limestone; occurs as beaches along parts of the coast as well as near inland saline lakes

## Remote sensing data

We obtained atmospherically corrected surface reflectance (SR) multispectral data from the Landsat 8 satellite Operational Land Imager (OLI) sensors, Tier 1 (scene path 13, row 43) recorded during the 2019 dry season (January) from the United States Geological Survey (USGS) Earth Explorer database (LC08\_L1TP\_013043\_20190118\_20190201\_01\_T1). We set a maximum cloud-cover threshold of 10% and filtered search results to images that were largely void of clouds to simplify pre-processing. Landsat 8 “OLI only” SR image products consisted of nine bands including: eight spectral bands capturing electromagnetic reflectance wavelengths ranging between 0.43 and 2.29 micrometers ( $\mu\text{m}$ ) (bands 1-7), a cloud mask layer (“pixel\_qa” band), and a radiometric saturation layer (“radsat\_qa” band). We retained spectral Bands 2-7 as predictor variables. In addition to the six retained bands, we calculated Normalized Difference Vegetation Index (NDVI), which is useful in detecting green vegetation and commonly used in remote sensing classification approaches.

## Classification

Given its ability to handle high dimensional data with complex interactions, as well as its track record of accuracy in classification of remotely sensed data, we used the Random Forest machine learning classifier algorithm to predict land cover class across Andros (Nguyen, Doan, & Radeloff, 2018). Using the R package ‘randomForest’ (Liaw & Wiener, 2002), we implemented seven predictor variables (Landsat Bands 2 – 7 and NDVI) and the training data in a Random



Forest model, with parameters ‘ntree’ (number of decision trees) and ‘mtry’ (number of predictor variables at each node) set to five hundred and two, respectively.

#### Ad hoc reclassification

Several obvious misclassifications occurred due to the similarity of the spectral signatures of land cover classes, including classifying mudflat as developed land in western parts of the island where there is no development of any kind. In addition, some areas occupying the site of a historic citrus orchard were classified as broadleaf coppice, even though these areas are currently occupied by secondary growth characterized by non-native broadleaf trees and shrubs (e.g., Brazilian pepper, *Schinus terebinthifolia*). Misclassification also occurred where there was cloud cover or shadow, although these instances were minimal. We used raster calculator in ArcMap™ v10.3 to manually reclassify these known points of misclassification.

#### Accuracy assessment

Accuracy assessment was conducted in QGIS (version 3). From the classification map we extracted location and habitat class information for 2,306 randomly generated points throughout the study area. We manually assessed the accuracy of each class prediction at each point using high resolution satellite imagery (basemap: imagery @2020 Google). From these data we generated a confusion matrix and calculated users, producers, and overall accuracy, along with Cohen’s Kappa coefficient (Congalton & Green, 1999).

## Landscape metrics

We calculated basic patch and class level metrics for all classes in FRAGSTATS® (McCarigal et al., 2002), and analyzed North Andros, Mangrove Cay, and South Andros separately. As our immediate focus is the distribution of Bahama Oriole main breeding habitat, we only further analyzed the Caribbean pine class. To assess the patch characteristics that may be most relevant to the Bahama Oriole's distribution, we focused on patch area and Euclidean distance to nearest neighbor (a measure of patch isolation).

## Global forest loss layer and fire analysis

To determine the extent of forest loss on Andros, we first cross-tabulated the GFC forest loss layers for years 2017-2018 with our 2019 land class predictions. Since Caribbean pine may regenerate quickly (trees may reach up to six to eight meters in just three to five years) (Francis 1992) we only assessed 2017 and 2018 in this analysis to account for any potential regrowth since loss year. We estimated the number of pixels where true forest loss had occurred by quantifying the overlap of GFC forest loss with “developed” or “agriculture/secondary growth”. We then defined the GFC forest loss pixels that overlapped with standing forest classes in our land cover map (Caribbean pine and broadleaf coppice) as “false deforestation”. To understand which habitats are most associated with either true or false deforestation, we extracted habitat class information from our 2019 classification map for the 2017 and 2018 layers of the GFC.

To validate the accuracy of the GFC and local Andros map cross-tabulation, we visually assessed a random subset of 100 loss pixels extracted from GFC 2017 and 2018 disturbances using high-resolution satellite imagery (Map Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat / Copernicus). To understand forest loss over a longer period, we generated an additional

subset of 100 loss pixels from GFC 2008-2018 disturbed areas. We visually assessed the status of forest at each randomly selected loss pixel up to two years prior and two years post each GFC loss event (Map Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat / Copernicus).

Given the frequency of understory burns, we assessed the likelihood that these fire events may drive the false classification of deforestation on Andros. We generated burn date layers from the MODIS Burned Area product at 500 m<sup>2</sup> resolution. We then created a random subset of 3,248 GFC false deforestation pixels and extracted both GFC loss year and latest burn year for each pixel. We quantified the frequency of fire events that co-occurred (i.e., geographically, and either the same year or year before) with GFC false deforestation.

Lastly, to determine if fire is driving forest loss on Andros, we generated a subset of 100 randomly selected pixels from the burn date layer for 2017. We chose 2017 due to the relatively high prevalence of understory fires recorded for this year on Andros. We visually assessed these points where fire events occurred and determined the status of the pine forest up until four years post-burn.

## Results

### Accuracy

We successfully delineated nine terrestrial habitats and generated a digital land classification map of Andros (Figures 2, 3). We constructed an error matrix from the 2,291 randomly generated test points and estimated associated statistics including producer's accuracy, user's accuracy, overall accuracy (89%), and Cohen's Kappa (0.85) (Table 2). To supplement the small number of random points generated in the agriculture/secondary and developed classes (n = 7 and n = 6, respectively), we generated an additional error matrix which included 55 additional

points randomly generated for these two classes, lumping all other classes together, with high overall accuracy (99%) and Cohen's Kappa (0.89) (Online Resource 1).

*Figure 2. Land cover classification map of nine major terrestrial habitats on Andros.*

**Table 2.** Accuracy matrix for 2291 randomly generated reference points used to assess the accuracy of the RandomForest classification of 11 habitat classes in Andros, The Bahamas. Overall accuracy is italicized in bold.

Map Class	Code	Reference Data											Row Total	Producers Accuracy
		PNE	COP	WOD	GRS	MAN	MUD	AGR	DEV	SND	SHW	DPW		
Caribbean pine	PNE	<b>333</b>	9	17	3	7	4	2	0	0	0	0	375	0.89
broadleaf coppice	COP	2	<b>56</b>	0	0	0	0	0	0	0	0	0	58	0.97
woody shrubland	WOD	0	0	<b>69</b>	13	3	17	0	0	2	1	0	105	0.66
grassy shrubland	GRS	1	0	2	<b>94</b>	2	4	0	0	0	0	0	103	0.91
mangrove scrub	MAN	3	0	6	2	<b>108</b>	7	0	0	1	1	0	128	0.84
mudflat/barren/scrub	MDB	4	5	35	12	6	<b>176</b>	0	0	3	5	0	246	0.72
agriculture/secondary	AGR	0	0	0	0	0	0	<b>7</b>	0	0	0	0	7	1.00
developed	DEV	1	0	0	0	0	0	0	<b>4</b>	0	1	0	6	0.67
sand	SND	0	0	0	0	17	40	0	0	<b>140</b>	6	0	203	0.69
shallow water	SHW	0	0	0	0	0	1	0	0	0	<b>968</b>	0	969	1.00
deep water	DPW	1	0	0	0	0	0	0	0	0	0	<b>90</b>	91	0.99
Column Total		345	70	129	124	143	249	9	4	146	982	90		
User's Accuracy		0.97	0.80	0.53	0.76	0.76	0.71	0.78	1.00	0.96	0.99	1.00		<b><i>0.89</i></b>

## Class confusion

Of the terrestrial classes, our model performed best in predicting Caribbean pine (mean class accuracy = 0.92), followed by broadleaf coppice (mean class accuracy = 0.87). Confusion in the pine class was most associated with woody shrubland and coppice (Table 2). The coppice class was most often confused with pine habitat.

Our model performed moderately well in predicting grassy shrubland, sand, mangrove scrub, and mudflat (mean class accuracy = 0.84, 0.82, 0.80, 0.71, respectively). Grassy shrubland was most frequently confused with mudflat and woody shrubland. Model performance was weakest at predicting woody shrubland (mean class accuracy = 0.59), which was most frequently confused with mudflat, grassy shrubland, and pine.

Since anthropogenic habitats (agriculture/secondary growth and developed) are restricted to less than two percent of the total land area on Andros, these classes were under-represented in the initial accuracy assessment. Initial accuracy for these classes was low and imprecise. However, when we incorporated additional randomly generated reference points targeting these classes and analyzed confusion between agriculture/secondary growth, developed, and “all other” classes, accuracy for these two classes increased substantially (Online Resource 1).

## Distribution of land area

Our model predicted that terrestrial habitats on Andros occupied a total of 4,788 km<sup>2</sup> (Table 3). Two classes dominated the land area – Caribbean pine (1,388 km<sup>2</sup>) and mudflat (1,019 km<sup>2</sup>), with developed and agriculture/secondary growth restricted to just 24 km<sup>2</sup> and 32 km<sup>2</sup>, respectively. A general habitat gradient correlates with the elevation gradient on Andros. Highest elevation occurs on the eastern ridge, descending westwards into low-lying tidal flats. As such,

broadleaf coppice generally occurs along highest areas near the east coast, frequently followed by pine in more central parts of the island, giving way to more sparse, open, and wet shrublands (woody and grassy), with mangrove, mudflat, and sand being most prominent towards the west coast. We observed this gradient across most of Andros (Figure 3).

*Figure 3. Land cover classification map shown with corresponding Microsoft Virtual Earth (Bing Maps) satellite imagery for two areas of Andros (a) North Andros - highlighting a strip of land around San Andros, and (b) Mangrove Cay. These both illustrate a general east/west gradient in the distribution of terrestrial habitats, with forested and anthropogenic habitats largely restricted to the east and grading westward into woody and grassy shrublands and eventually mudflat, mangrove, and sand. See Figure 2 for legend.*

Table 3. Total area and percent of terrestrial habitat classes, in descending order from largest to smallest (total land area). North Andros includes the political districts of North Andros and Central Andros, including Big Wood Cay.

Class	North Andros		Mangrove Cay		South Andros		Total	
	km <sup>2</sup>	% Total	km <sup>2</sup>	% Total	km <sup>2</sup>	% Total	km <sup>2</sup>	% Total
Caribbean pine	1,073	31	139	33	176	18	1,388	29
mudflat/barren/scrub	708	21	62	15	249	26	1,019	21
sand	441	13	82	20	125	13	648	14
mangrove scrub	364	11	46	11	121	13	530	11
woody shrubland	367	11	33	8	91	9	491	10
grassy shrubland	304	9	25	6	72	7	401	8
broadleaf coppice	106	3	27	6	121	13	254	5
agriculture/secondary	27	1	2	0	4	0	32	1
developed	18	1	2	0	4	0	24	0
TOTAL	3,407		418		963		4,788	



Despite the characteristic low elevation of western parts of the island, there are areas that may reach 1 -2 meters above sea level (Freid, 2006). Our map predicted swaths of pine forest throughout these western “uplands”. Woody shrubland, referring to either sparsely distributed broadleaf, pine, or thatch, is also distributed throughout some of the western areas rising above sea level. Grassy shrublands generally occur where elevation is lower (0 – 0.5 meters above sea level).

Where elevation is at or below sea level (much of West Side National Park) and subject to extensive salt-water inundation, vegetation is largely limited to mangroves, which are often low and scattered. Some mangroves in the west, however, may form larger, more dense systems than what we observed during ground truth surveys in the east.

Mudflat was the second largest terrestrial class and includes very sparse, scrub-like habitats in the east, grading into barren, open mudflats in the west where salt-water inundation prevents the accumulation of sediment and organic matter, with the notable exception of various algal species (Black, 1933).

#### Distribution and extent of Caribbean Pine

We measured common landscape metrics using FRAGSTATS® (Online Resources 2 and 3). Preliminary efforts during the 2019 field season aimed at estimating territory size for orioles nesting in the pine forest suggested a minimum territory size of about 0.2 km<sup>2</sup>. On North Andros, about half of the total pine area (54% or 1,073 km<sup>2</sup>) is distributed as small patches under 0.2 km<sup>2</sup>, whereas pine area on Mangrove Cay is largely distributed as a few large patches (62% of pine is found as one large patch about 87 km<sup>2</sup>). Patch size distribution on South Andros is more evenly distributed, with 27% of pine patches under 0.2 km<sup>2</sup>, and 35% of pine area distributed as large

patches over 100 km<sup>2</sup>. Euclidean distance to nearest neighbor was low for most patches across all three islands, and 75% of all pine patches less are less than 100 meters to the nearest pine patch (Online Resource 3).

#### Global forest loss layer and fire analysis

The cross-tabulation of our local map with the GFC 2017 and 2018 loss layers suggested that, of the 24.5 km<sup>2</sup> of predicted forest disturbance area, only seven percent (1.7 km<sup>2</sup>) represented true forest loss (Table 4; Figure 4). The remaining 22.8 km<sup>2</sup> was classified as either Caribbean pine or broadleaf coppice by our local map, therefore defined as false deforestation. We found that GFC predicted loss was mostly associated with Caribbean pine (77%) (Table 5).

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Table 4. Results from the cross-tabulation of GFC forest loss with the local Andros map in km<sup>2</sup>. Local map agreement refers to the area of GFC that corresponds to either developed or agriculture/secondary growth classes. The difference between GFC estimated loss and local map agreement, therefore, represents "false deforestation". Local map agreement and total GFC estimated forest loss were used to calculate the percent of true forest loss.

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Year	GFC Estimated Forest Loss	Local Map Agreement	GFC False Deforestation	% True Forest Loss
2017	20.16	1.47	18.69	7
2018	4.37	0.26	4.11	6
Total	24.53	1.73	22.8	7

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*Figure 4. Comparison of Hansen's 2017-2018 Global Forest Loss layers with developed/cleared areas as defined by the local Andros map for the northern portion of North Andros.*

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Table 5. Distribution of GFC estimated forest loss across nine terrestrial habitats on Andros derived via cross-tabulation of the GFC forest loss layers (2017 and 2018) and the local Andros map.

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Land Cover Class	% GFC Disturbance by Class
Caribbean pine	77
agriculture/secondary	6
mudflat/barren/scrub	5
broadleaf coppice	4
developed	4
woody shrubland	2
mangrove scrub	1
grassy shrubland	< 1
sand	< 1

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Table 6. Results of a visual assessment of 100 randomly selected pixels from the GFC forest loss layers for 2017 and 2018 (50 pixels from each year) along with 100 pixels randomly selected from 2008 - 2018. Status was assessed at two years prior and two years post GFC predicted loss event. Italicized values represent subsets of the total number of forest loss points driven by either anthropogenic activity or understory fire. Data reported are for two years post loss event.

Loss / No Loss	2017	2018	2008-2018
No Forest Loss	43	42	68
Forest Loss	7	8	34
<i>anthropogenic driven loss</i>	7	8	32
<i>fire driven loss</i>	0	0	2
Percent "False Deforestation"	86%	84%	67%

To validate the accuracy of the previous analysis, we visually assessed a subset of 100 randomly selected GFC loss pixels using high-resolution satellite imagery. For 2017 and 2018 we found that roughly 85% of the GFC disturbances represented false deforestation (Table 6). When we performed this same analysis on a sperate dataset of 100 random GFC loss pixels selected over a longer period (2008-2018) we found that 67% (corresponding to roughly 70 km<sup>2</sup> over the ten-year period) of the GFC disturbances represented false deforestation.

To assess the role of fire in driving GFC false deforestation on Andros, we quantified the proportion of co-occurrences between a fire event and GFC predicted loss. Over a ten-year period (2008-2018), roughly 84% of the GFC loss pixels in this subset co-occurred with a fire event (Table 7). We found, however, that the association of fire and GFC predicted loss varied substantially across years (Table 7). Given the coarse spatial resolution of our burn layer, we

expect that the true percentage of predicted GFC loss and fire co-occurrence may be higher than indicated in this analysis.

Finally, to determine if understory fires are a driver of true forest loss on Andros, we generated a subset of 100 randomly selected pixels from the burn date layer. We found that fire rarely resulted in true forest loss (Table 8). While the high-resolution imagery showed clear evidence of understory burns, we found that fire resulted in true forest loss in only two percent of the assessed areas, suggesting fire-driven loss on Andros is extremely rare. Caribbean pine forest was fully recovered from understory burns 82% of the time. Conversion to developed or agriculture made up the remaining 16%, suggesting that anthropogenic activity is currently the most prominent driver of forest loss.

Table 7. Corresponding year for 3,248 points randomly generated from the GFC forest loss layer. We calculated the frequency of fire event co-occurring (same year as GFC loss or the years prior) with disturbance events during the period from 2008-2018. Co-occurrence of fire events with GFC false deforestation suggests that understory fires may play a role in driving the misclassification of forest loss on Andros.

Year	No. GFC "false deforestation"	No. GFC "false deforestation" + fire points	% Co-occurrence "false deforestation" + fire
2008	74	44	59
2009	196	168	86
2010	25	7	28
2011	226	203	90
2012	115	81	70
2013	473	390	82
2014	371	341	92
2015	446	404	91
2016	561	450	80
2017	605	501	83
2018	156	132	85
Total	3,248	2,721	84
<i>Mean</i>	<i>295</i>	<i>247</i>	<i>77</i>
<i>Range</i>	<i>580</i>	<i>494</i>	<i>62</i>
<i>SD</i>	<i>204</i>	<i>175</i>	<i>18</i>

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Table 8. The 2020 status of a subset of 100 random points that experienced a fire event in 2017. Fire recovered refers to the proportion of the time we determined a burned area recovered, with an observable increase in green vegetation at three years post-burn. Fire driven loss refers to the proportion of the time we determined a burned area had not recovered, with weak to low green vegetative signal observed at three years post-burn.

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Status 2020	% 2017 Fire points
Fire recovered	82
Fire driven loss	2
Agriculture/secondary growth	6
Developed	10

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416 **Discussion**

417       In this study we successfully generated a local land cover classification map that will  
 418       enable monitoring changes in the extent and distribution of Caribbean pine on Andros over time.  
 419       Given high mean class accuracy for the Caribbean pine class (92%), we were able to use this map  
 420       to assess the accuracy of the forest loss previously predicted by GFC as well as investigate the role  
 421       of fire in driving forest loss on Andros.

422       We found that Caribbean pine makes up the most extensive land cover class on Andros and  
 423       likely represents some of the largest areas of pine rockland habitat in the world (Myers et al.,  
 424       2004). The analysis of landscape metrics suggested that roughly 1/5<sup>th</sup> of the approximately 1,400  
 425       km<sup>2</sup> of Caribbean pine was present in small patches (less than 0.2 km<sup>2</sup>). However, we also  
 426       documented several potentially crucial large patches of pine on North Andros and Mangrove Cay  
 427       (Online Resource 5). The analysis also showed that most patches were within 100 meters of a  
 428       neighboring patch of pine, indicating moderate to low levels of patch isolation (Online Resource

3). It is important to note, however, with regards to ecological implications, that optimal patch size and degree of isolation will vary depending on the organism in question. For instance, a 2019 pilot study estimating territory size of Bahama Orioles breeding in the pine forest suggested a minimum area of 0.2 km<sup>2</sup>, and it is possible that orioles could occupy small patches of pine. We do not know, however, the extent to which edge-effects might impact the suitability of a particular patch to sustain even a single pair of orioles. Given our currently limited understanding of Bahama Oriole habitat use and territoriality, we estimate that roughly 1,200 of the 1,400 km<sup>2</sup> of Caribbean pine on Andros may be suitable habitat for the oriole (patches greater than 0.2 km<sup>2</sup>).

While the Bahama Oriole is also known to use developed habitats (Price et al., 2011), we did not focus on this class for the present analysis given that its distribution is small (1.7% of total suitable habitat), well known, and likely supports only a small percentage of the Bahama Oriole population. For example, on their 713 km<sup>2</sup> study site on North Andros, Rowley et al. (2020) estimated that there were between 1,200 and 2,800 orioles. Their study site included 480 km<sup>2</sup> of potentially suitable oriole habitat, most of which was pine (414 km<sup>2</sup>) with only 18 km<sup>2</sup> of developed habitat (Rowley et al., 2020).

Given that the total area of pine we mapped was 1,388 km<sup>2</sup>, we estimate that the Rowley et al., (2020) study site contained approximately one-half to one-third of the total area of suitable habitat (pine and developed) across Andros. Therefore, we conservatively estimate that there may be between roughly 2,000-8,000 individuals on all of Andros. Assuming the orioles are present in pine forest and developed habitats in similar densities, as suggested by Rowley et al. (2020), we estimate that only a very small percentage (1.7%) occur in developed habitats, while the majority of the population occurs in pine.



Comparison of our local map to the global forest cover map

The comparison of GFC with our data confirms that this global map overestimated forest loss on Andros. Our initial cross-tabulation of the full local map with GFC revealed a discrepancy of about 23 km<sup>2</sup>, suggesting the GFC over-predicted forest loss (“false deforestation”). The subsequent analysis of the subset of 100 GFC disturbances from 2017 and 2018 also found a high rate of GFC false deforestation (about 85%). The analysis of 100 2008-2018 disturbances showed a smaller, but substantial, discrepancy between GFC predicted for forest loss and true deforestation (about 67% false deforestation). The difference between these two analyses could also be due to the longer temporal span of the latter analysis (2008-2018) versus the 2017 and 2018 analyses. It is possible that deforestation was occurring at higher rates prior to 2017, and that may be reflected in the higher detection of true forest loss in the 2008-2018 analysis.

Regardless, both analyses show that the GFC overpredicted forest loss on Andros. These findings are consistent with previous studies that have demonstrated the challenges of mapping dry (less than 2,000 mm of rainfall per year) open forest cover (Bastin et al., 2017; Cunningham et al., 2019; Fagan, 2020). The pine rockland forests of Andros are characterized by an open canopy (20% - 80% cover) and a sub-tropical climate, averaging about 1,000 mm of rainfall per year. The results of the GFC and local map comparisons support previous research regarding the utility of global forest map products in relation to these open, sub-tropical forests. However, to our knowledge, our results are the first to show that, in addition to underestimating open tree cover, global maps like the GFC are likely to overestimate forest loss in open forests.

Our analysis of GFC forest loss and fire occurrence on Andros indicated that understory wildfires are a clear contributor to GFC misclassified forest loss within Caribbean pine habitats. Our analysis of 3,248 GFC/fire pixels indicated that fire events corresponded (same year or year

before) with nearly two-thirds of the misclassified GFC deforestation, demonstrating that regular understory fires are driving the GFC's overprediction of forest loss. Seasonal fires may alter the structure of the understory, resulting in a decline in leafy, broadleaf vegetation and an increase in herbaceous vegetation, thereby altering the spectral signature of this open habitat. Other potential drivers of the GFC false deforestation may include phenological changes in the pine understory. For instance, variation in seasonal precipitation may stress the understory vegetation. The spectral signature of vegetation changes as leaf structure and chlorophyll content breakdown in response to stress. Given the open canopy structure of the Caribbean pine forest, this change is easily detected and may explain some of the false deforestation not attributed to understory fire.

It is also possible that some false deforestation is attributed to the expansion of love vine (*Cassytha filiformis*) on Andros. Love vine is a native parasitic vine that can efficiently proliferate throughout the pine forest. It is likely that the spread of this expansive and dense understory vine, with its characteristic bright yellowish coloration, could alter the vegetative spectral signature of this open canopy habitat, resulting in the misclassification of forest loss.

Lastly, in addition to the biological and environmental factors potentially driving GFC misclassification, the coarse resolution of our MODIS derived burn data (500 km<sup>2</sup>) likely resulted in some understory fires going undetected and affected areas at burn area periphery may not have been captured by this analysis. Undetected fires not captured by this analysis may also be hidden drivers of GFC misclassifications.

Globally, 22% forest loss is attributed to wild fires (Curtis et al., 2018). However, the rockland pine ecosystems of Andros and The Bahamas (also Cuba and southern Florida) are fire-adapted, and the understory fires typical of this ecosystem rarely resulted in the loss of canopy cover in the present study. Our analysis suggests that fire driven forest loss remains minimal, with

only two percent of understory fires resulting in forest degradation lasting the duration of this study. However, the Caribbean region is expected to experience increasing minimum and maximum annual temperatures along with decreasing annual rainfall (Karmalkar et al., 2013; Nelson et al., 2018). Given these predicted changes, there is a real chance that fires typical of this habitat will become more frequent and more intense. Under a more intense fire regime, Caribbean pine on Andros may shift towards herbaceous grassland (Myers et al. 2004). As such, these factors associated with climate change may contribute to the risk of fire-driven degradation of Caribbean pine habitat under future climate scenarios.

#### Threats due to sea level rise and hurricanes

Sea-level rise is another component of climate change that may pose a future threat to Caribbean pine on Andros, particularly for the small patches of pine habitat throughout the low-lying western portions of the island (e.g., West Side National Park). As sea-levels rise, salt water may inundate the fresh ground-water aquifer (Holding & Allen, 2015). Moreover, the rate of groundwater recharge following salt water intrusion is partly dependent on precipitation, which as previously mentions, is expected to decrease in the Caribbean region (Holding & Allen, 2015; Karmalkar et al., 2013). So, the impacts of climate change on the freshwater lens is multifaceted: threatening salt water intrusion with relation to sea-level rise and a lower rate of freshwater recharge as annual rainfall decreases (Holding & Allen, 2015). Should the salinity of the freshwater aquifer on Andros increase, Caribbean pine habitat would almost certainly degrade and, eventually, transition into a more salt-tolerant ecosystem. Researchers have already documented the conversion of pine habitat into more salt-tolerant mangrove ecosystems throughout parts of the Florida Keys as sea-level there has risen roughly 22 cm over the last century (Ross et al., 1994;

Alexander, 1976). It is possible that many of the small, isolated patches of Caribbean pine found throughout Andros, especially in the west, may be lost as sea-levels rise and salt-water infiltrates the freshwater lens.

Not only are these pine forests vulnerable as sea-level rise compromises the freshwater lens, but, in recent years, hurricanes and tropical storms were strong enough for storm surge to decimate entire swaths of pine forest on the islands of Andros, Abaco, and Grand Bahama (e.g., Hurricane Matthew - Andros, 2016, and Hurricane Dorian – Abaco and Grand Bahama, 2019). Post-hurricane surveys conducted by The Bahamas National Trust (BNT) of the pine forests of Abaco and Grand Bahama revealed drastic declines in the populations of two endemic, forest-dependent bird species - the critically endangered Bahama Nuthatch (*Sitta pusilla insularis*) and the Bahama Warbler (*Setophaga dominica*) (Bahamas National Trust, pers. comm).

These same factors also threaten the local human population. Therefore, it is plausible that the population will respond to sea-level rise, as well as the rising threat of tropical storm surge, by migrating inland, ultimately resulting in increasing anthropogenic driven forest disturbance. Future research should focus on identifying where salt-water inundation is most likely to occur, so that we can have an accurate understanding of the future distribution of pine forests and other habitats on Andros.

Given the increasing threat of fire, sea-level rise, and human development, we now have a baseline map to enable monitoring of changes in the extent and distribution of the terrestrial habitats of Andros. Predicting how these habitats will respond to climate change and other factors will allow researchers to best approach these issues from a conservation perspective.

## **Conclusion**

This work, part of a broader conservation effort for the Bahama Oriole and the Andros archipelago, sheds light on several important issues. First, Caribbean pine – the habitat believed to be key to Bahama Oriole nesting success – is extensive across Andros, having important implication for the conservation status of this species. Second, actual forest loss in the pine forest is lower than that predicted by the GFC, demonstrating that global maps of forest change may overestimate disturbance in open, fire-adapted forests. The evidence presented here supports previous research highlighting the need for caution when implementing global maps at small local scales. It is urgent, however, that we stress that the threats of fire, sea-level rise, and human encroachment are almost certain to increase in the future, as the Caribbean region experiences a hotter, drier climate, with increasingly intense and unpredictable hurricanes. Given the prevalence of endemic species across the Andros archipelago, such as the Bahama Oriole, the work presented here can inform conservation to minimize biodiversity loss in this important island region.

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**Figure 1**

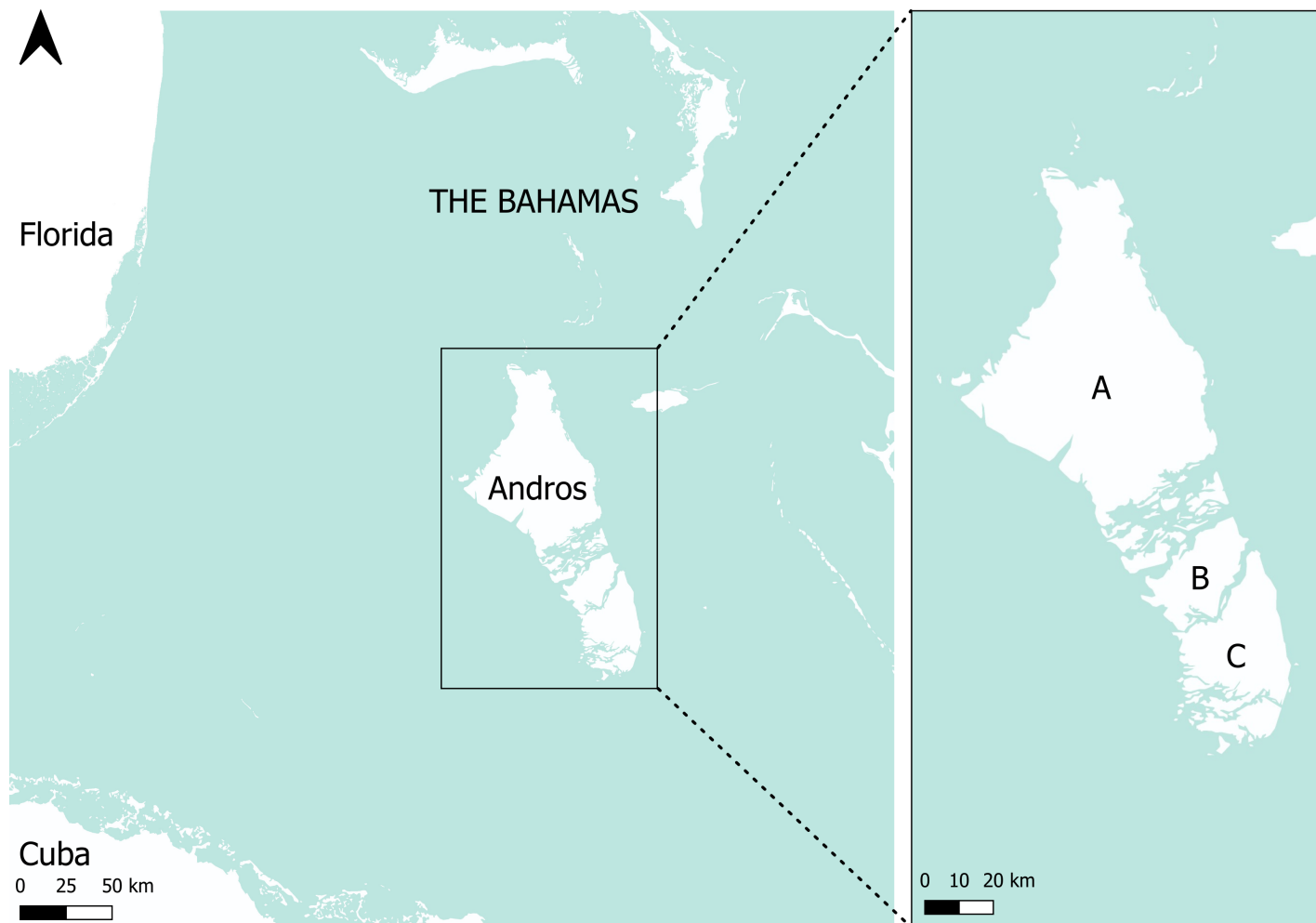


Figure 2

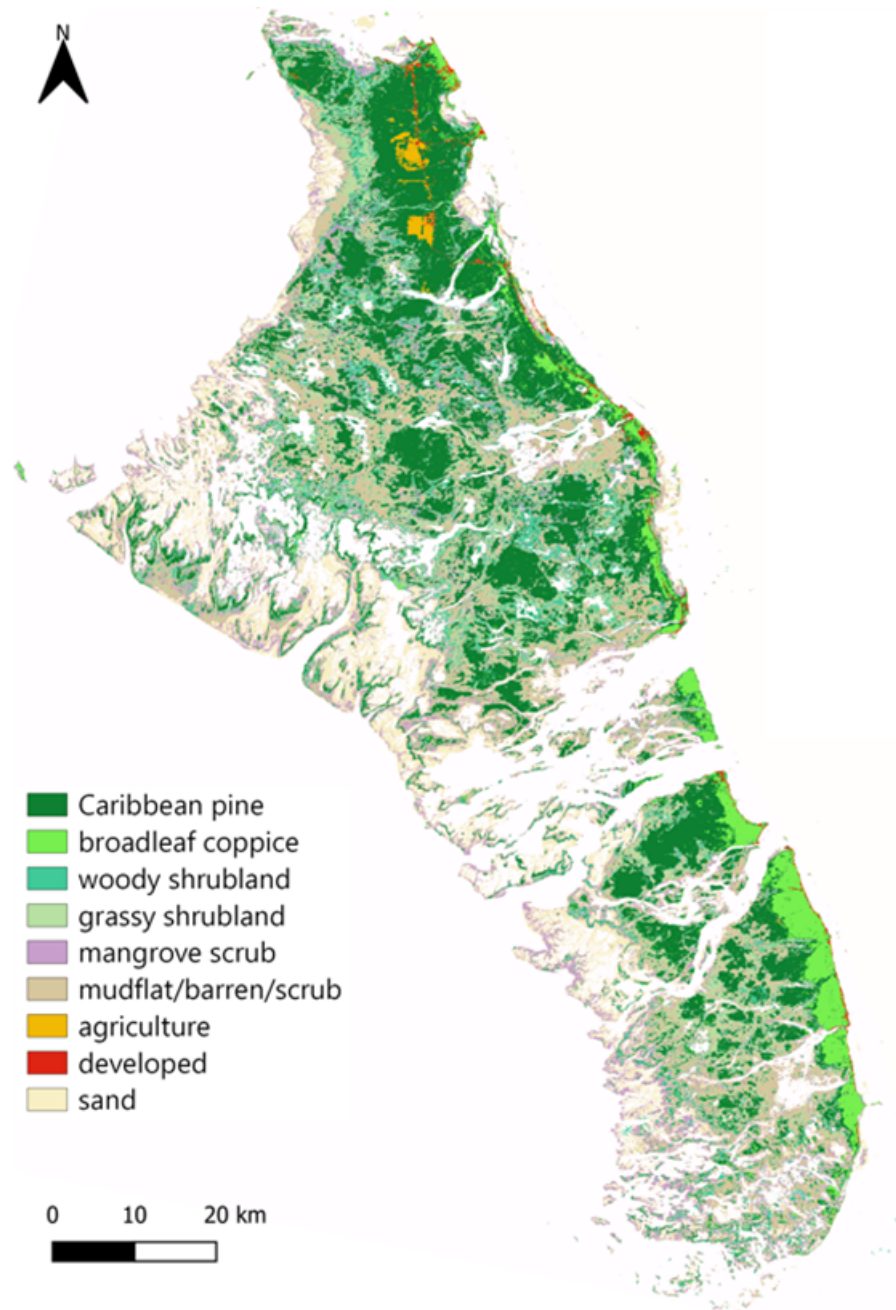


Figure 3

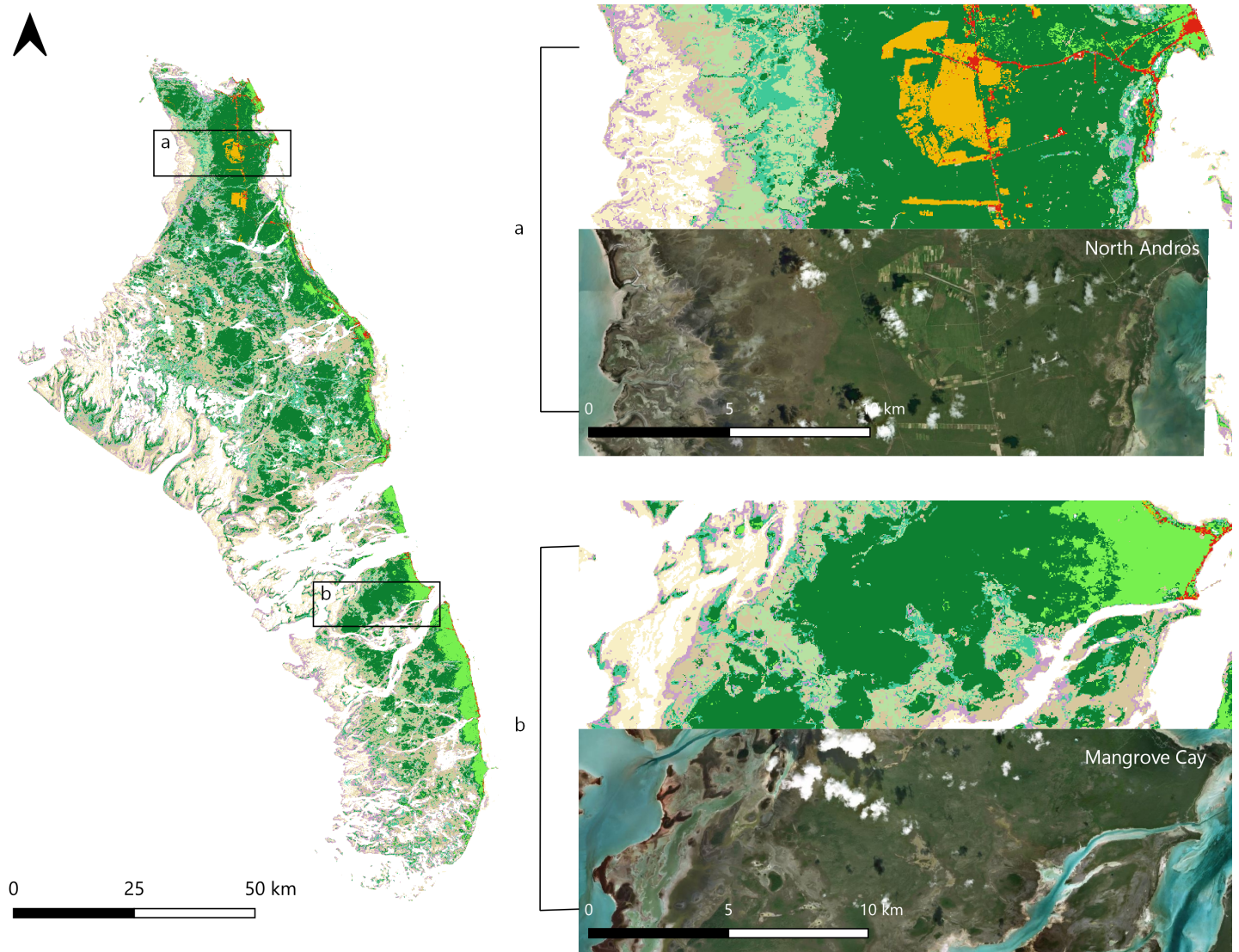


Figure 4





Figure 5

