Land use change and its implications for biodiversity and jaguar conservation

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Protected areas are frequently established to prevent declines in biodiversity, but their effectiveness in preserving biodiversity can depend on how land outside their borders is managed. We evaluated how land use changes from 1989 to 2016 in the Reserva de la Biosfera Sierra del Abra Tanchipa (RBSAT) landscape might affect the role of the RBSAT for conservation of biodiversity, with an emphasis on conservation of jaguars, a keystone species. We estimated the rate of land use change within and surrounding the RBSAT, a 215 km² natural reserve in San Luis Potosí, Mexico, from 1989 to 2016 using supervised classifications of satellite imagery. We also analyzed the distribution of two GPS collared male jaguars. The RBSAT and surrounding landscape became increasingly fragmented and impacted by human use over the previous *ca*. 30 years. The largest increases were seen in infrastructure and intensive agriculture, while the largest decreases were seen in pasture, tropical deciduous forest, and secondary vegetation. Jaguars were located more frequently than expected in secondary vegetation, the most common cover class, which decreased from 34.8 % of the landscape to 32.1 % by 2016. Only 23 % of jaguar locations fell within the boundaries of the RBSAT, due to increases in preferred habitat attributes of jaguars and prey outside the Reserve. Increasing fragmentation compromises the RBSAT's role as a biodiversity reserve, especially for interior-dependent species. Fragmentation and edge habitats in combination with increasing agriculture enhance suitability of the landscape surrounding the RBSAT for prey of jaguar, and only 23 % of jaguar locations were within the RBSAT itself. This increases the likelihood of jaguar-related conflicts in surrounding communities. Regional landscape planning should include policies that incentivize practices that maintain remaining larger habitat patches and minimize the likelihood of human-wildlife conflicts.

Las áreas protegidas se establecen con frecuencia para evitar la disminución de la biodiversidad, pero su eficacia para preservar la biodiversidad puede depender de cómo se gestione la tierra fuera de sus fronteras. Se evaluó cómo los cambios en el uso del suelo de 1989 a 2016 en el paisaje de la Reserva de la Biosfera Sierra del Abra Tanchipa (RBSAT) podrían afectar el papel de la RBSAT para la conservación de la biodiversidad, con énfasis en la conservación de los jaguares, una especie clave. Se estimó la tasa de cambio de uso del suelo dentro y alrededor de la RBSAT, una reserva natural de 215 km2 en San Luis Potosí, México, de 1989 a 2016 utilizando clasificaciones supervisadas de imágenes satelitales. También se analizó la distribución de dos jaguares machos con collar GPS. La RBSAT y el paisaje circundante se fragmentaron cada vez más y se vieron afectados por el uso humano durante los ca. 30 años. Los mayores aumentos se observaron en infraestructura y agricultura intensiva, mientras que las mayores disminuciones se observaron en pastos, bosque tropical caducifolio y vegetación secundaria. Los jaguares se ubicaron con mayor frecuencia de lo esperado en la vegetación secundaria, la clase de cobertura más común, que disminuyó del 34,8 % del paisaje al 32,1 % en 2016. Solo el 23 % de las ubicaciones de jaguares se ubicaron dentro de los límites de la RBSAT, debido a aumentos en la preferencia. atributos de hábitat de jaguares y presas fuera de la Reserva. La creciente fragmentación compromete el papel del RBSAT como reserva de biodiversidad, especialmente para las especies dependientes del interior. La fragmentación y los hábitats de borde en combinación con el aumento de la agricultura mejoran la idoneidad del paisaje que rodea a la RBSAT para las presas del jaguar, y solo el 23 % de las ubicaciones de los jaguares estaban dentro de la propia RBSAT. Esto aumenta la probabilidad de conflictos relacionados con jaguares en las comunidades aledañas. La planificación del paisaje regional debe incluir políticas que incentiven prácticas que mantengan los parches de hábitat más grandes restantes y minimicen la probabilidad de conflictos entre humanos y vida silvestre.

Keywords: Land classification; land use change; natural reserve; México; *Panthera onca*.

Introduction

Many areas are experiencing major declines in biodiversity (Polasky *et al.* 2007), and the establishment of protected areas is a common method used to minimize losses. However, the effectiveness of protected areas in preserving biodiversity and supporting local economies depends in part on management of lands surrounding protected areas (Brandon *et al.* 2017). Large carnivores are especially difficult to maintain through protected areas due to large home ranges and the negative attitudes they evoke from some communities (Kellert *et al.* 1996; Inskip and Zimmermann 2009; Cortina-Villar *et al.* 2012).

These issues are concerns with the Reserva de la Biosfera Sierra del Abra Tanchipa (RBSAT), in the state of San Luis Potosi, northeastern México, which is in a landscape dominated by agricultural and livestock production. This small (215 km²) reserve was established in 1994 as a National Protected Area for the myriad of unique flora and fauna found in this environmental link among the peaks of the Sierra Madre Oriental (SMO). There are 25 species of birds and eight species of mammals considered endangered, threatened, or with restricted distributions in RBSAT (SEMARNAT 2010, 2019; Durán-Fernández *et al.* 2020), including many interior species (*i. e.*, species that require the interior of large contiguous patches of vegetation in a similar successional state ,Villard 1998, such as the elegant eagle (*Spizaetus ornatus*), red brocket deer (*Mazama temama*), and ocelot (*Leopardus pardalis*). However, the keystone species of the RBSAT and SMO is the jaguar (*Panthera onca*), and the RBSAT functions as a critical corridor in maintaining connectivity among jaguar populations in the SMO (Dueñas-López *et al.* 2015; Dueñas-López and Huerta-Rodríguez 2020). Ongoing studies of jaguar ecology (Rosas-Rosas *et al.* 2016; Silva-Caballero *et al.* 2022) further confirm the importance of the RBSAT landscape for this keystone large carnivore. Because of its role as a keystone carnivore, needs for large areas of minimally impacted habitat, and vulnerability to human-related mortality (Ripple *et al.* 2014), the jaguar is an effective management indicator species (MIS) for conservation of the RBSAT landscape, meaning that its status and trend provide insight into the overall health of the ecological system (Committee of Scientists 1999; Rosas-Rosas *et al.* 2020).

The highly productive valleys that border the Reserve are heavily impacted by human land use, including cattle ranching, cultivated crops, urban and rural developments, and mining operations (Dueñas-López *et al.* 2015; Durán-Fernández *et al.* 2020). The RBSAT is situated in the middle of two counties, Ciudad Valles and Tamuín, which have growing populations and robust local economies. Ciudad Valles had a 35 % increase in population from 1990 to 2015 (INEGI 2015) and is the number one producer of sugar cane in San Luis Potosí, with a production valued at $ 49 million USD in 2016 (SIAP 2017). The population of Tamuín increased 13 % from 1990 to 2015, and Tamuín leads the state in beef production with an eco-nomic impact of $ 269 million in 2016 (INEGI 2015; SIAP 2018). Cattle numbers more than doubled in Tamuín from 107,752 to 290,300, 2008 – 2016 (SIAP 2018), primarily related to feedlot production, but decreased in Ciudad Valles from 2,634 to 2,245.

Despite the ecological role of RBSAT as a biodiversity preserve, the types and rate of land use change remain unquantified around the RBSAT. Like many other areas in México, the landscape of the RBSAT is likely threatened by isolation, and land use surrounding the reserve has a major impact on its effectiveness in the conservation efforts of the SMO (Ortega-Huerta 2007; Chapa-Vargas and Monzalvo-Santos 2012; Rosas-Rosas *et al.* 2020). Likewise, jaguars and other sensitive wildlife move outside the boundaries of the RBSAT (Rosas-Rosas *et al.* 2016; Silva-Caballero *et al.* 2022), which highlights the need for coordinated management of the surrounding landscape to maintain viable habitat as well as decrease the likelihood of conflicts with local livestock producers and other residents of surrounding communities. Understanding the historic and current patterns of land use around RBSAT will inform strategies for future development and conservation efforts to preserve the ecological function of the Reserve and promote coexistence with its keystone species. Therefore, our goal was to document the type and rate of land use change within the RBSAT and its surrounding landscape over the last 27 years and assess how land use changes might influence efforts to conserve jaguars, one of the keystone species of the RBSAT, and thus maintain the role of the RBSAT landscape for conservation of biodiversity.

Materials and methods

Study Area. Our study area included the RBSAT and a 10 km buffer of the surrounding landscape, representing 1,080 km² of tropical deciduous forest, secondary vegetation, agricultural and livestock production areas, rural communities, and gravel mines (Figure 1). The RBSAT is located between 22° 04′ 38″, 22° 23′ 56″ N and -98° 53′ 07″, -99° 00′ 44″ and contains 214 km² of contiguous dry tropical deciduous forest, ranging in elevation from 120 to 820 masl (Arriaga *et al.* 2000; CONANP 2014). The climate is classified as sub-humid with summer rains from June to September, an average annual rainfall of 965 mm, and an annual average temperature of 25.7° C (CONANP 2014). The Reserve provides habitat for 420 species of plants, 259 species of birds, 56 species of mammals, 50 species of reptiles, and 17 species of amphibians (Durán-Fernández *et al.* 2020).

Land Use Change Data. We selected satellite images used to estimate land use change based on strict criteria, including temporal availability (during the dry season) and the percentage of cloud coverage (< 10 %). These criteria emphasize the contrast between dense forest, secondary vegetation, pastures, and agriculture (most notably sugar cane, which is a crop that stays green throughout the year), facilitating the differentiation among land uses (Fichera *et al.* 2012; Mei *et al.* 2016).
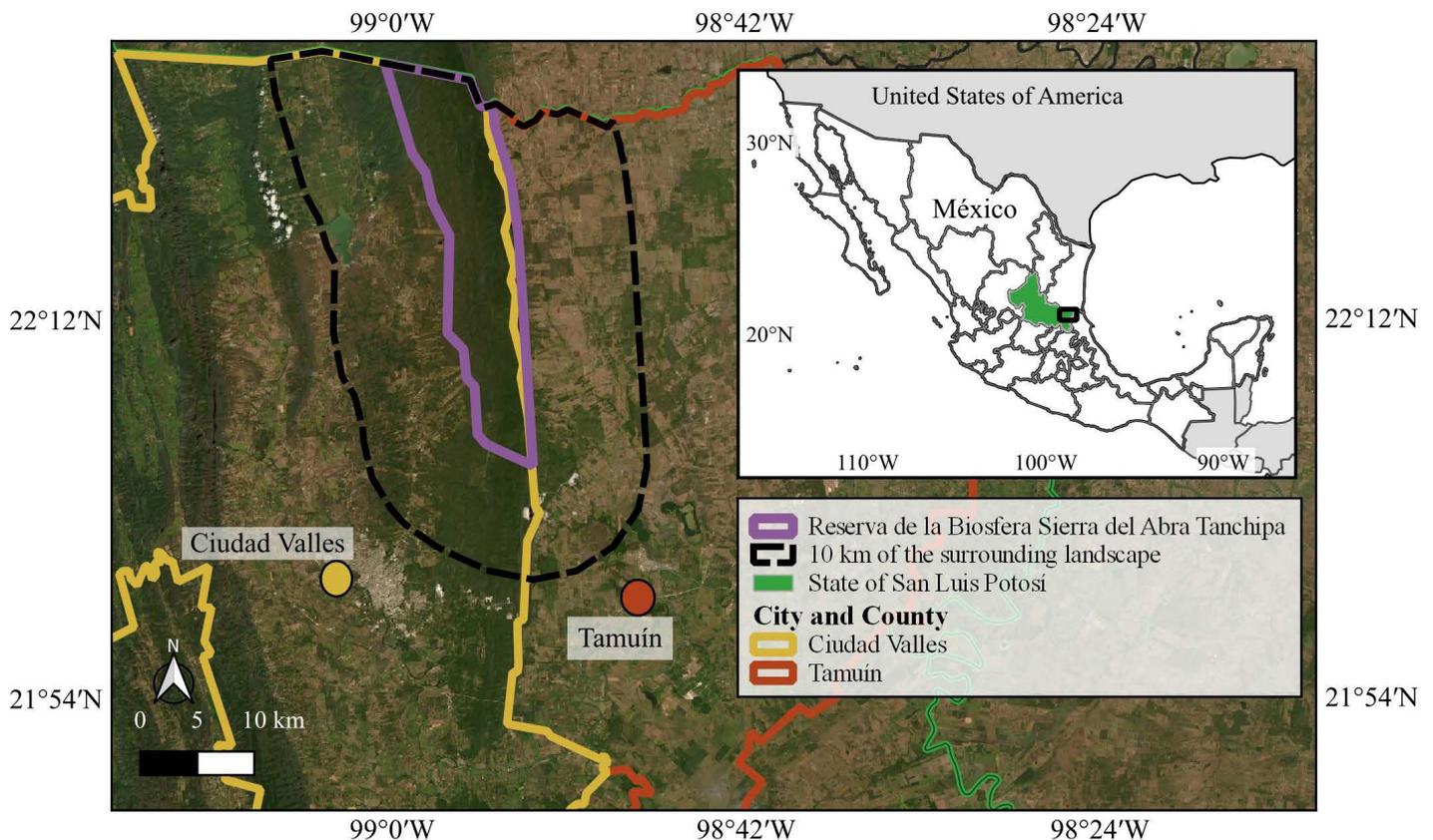
Figure 1. The study area, including the Reserva de la Biosfera Sierra del Abra Tanchipa and ten km of its surrounding landscape, and the complex matrix of land use from a satellite image captured on March 25, 2016.

We analyzed two 30-m spatial resolution satellite images, downloaded from the online platform EarthExplorer (USGS 2018). The most appropriate available images from the end of the dry season with no cloud coverage were from the Landsat 4 Thematic Mapper (TM; 7 March 1989) and Landsat 8 Operational Land Imager (OLI; 25 March 2016), which spanned a period of 27 years. We were interested in maximizing the time span as much as possible, and these images fit all criteria. We followed the methodological processing (*i. e.*, preprocessing of the satellite images, supervised classification, and accuracy assessment; see below) of data common to analyses of land use change (*e. g.*, Reyes-Hernández *et al.* 2006; Sahagún-Sánchez *et al.* 2011; Horvat 2013; Fernández-Landa *et al.* 2016; Mei *et al.* 2016). We used the software programs QGIS (QGIS Development Team 2018) and SAGA GIS (Conrad *et al.* 2015) for all analyses.

Preprocessing. Geographic, radiance, and atmospheric interference are the three components of preprocessing corrections for satellite images commonly applied before classification (Horvat 2013). Geographic corrections were not necessary for our images, as the Landsat images we used had been geo-referenced by the USGS (2015) to the Universal Transverse Mercator (UTM) projection. We corrected for radiance using the Semi-Automatic Classification Plugin for QGIS (SCP; Congedo 2018). Last, we corrected for atmospheric interference using a Dark Object Subtraction (DOS1) correction within the SCP plugin (Hadjimitsis *et al.* 2010). We then clipped the corrected images to the study area.

Supervised Classification. We included six classes in our supervised classification: agriculture, infrastructure, pasture, secondary vegetation, tropical deciduous forest, and water. We selected these classes based on two cartographic maps from the National Institute of Statistics Geography and Information Technology (INEGI 2018), Series I from 1985 and Series VI from 2016 (Table 1), which included 13 land use types (LUTs) within our study area.

We developed a training file based on the above classes using three data inputs (Foody 2002; Reyes-Hernández *et al.* 2006; Grinand *et al.* 2013). The first level of data was INEGI Series I and VI land use and vegetation maps. The second level were the satellite images projected in natural color (Landsat 8, bands 7 – 5 – 3; Landsat 4, bands 3 – 2 – 1) and false color composite images that highlight vegetation (Landsat 8, bands 6 – 5 – 4 and 4 – 3 – 2; Landsat 4, bands 5 – 4 – 3 and 4 – 3 – 2). These provided greater detail than the land use and vegetation maps. The third input was personal knowledge of the region provided by the authors. We used the classification algorithm K-nearest Neighbors Classification in SAGA GIS (Qian *et al.* 2014; Conrad *et al.* 2015) for our supervised classification, with the training file serving as the basis for the classification. We ran 15 iterations of the classification; after every iteration, we reviewed the classification results, and strengthened the training files in misclassified areas.

Accuracy Assessment. We used the final classifications from 1989 and 2016 and two verification files for accuracy

assessment. The verification files included high-resolution (1-m; Planet Team 2017) satellite imagery from March 2016 and field surveys used to classify areas with a high level of certainty to serve as controls. We then ran the Confusion Matrix (Grid/Polygon) module in SAGA GIS (Conrad *et al.* 2015) for each image, which compared the classification and the verification files to assess their level of agreement. This generated the overall accuracy and kappa index values.

Land Use Trends. We ran the Confusion Matrix (Grid/Grid) module in SAGA GIS (Conrad *et al.* 2015) with the two classified images to calculate the land use change from 1989 to 2016. We calculated rate of change following Miranda-Aragón *et al.* (2013) and Sahagún-Sánchez *et al.* (2011) using RC = ,(A_2 / A_1) ^ (1 / n) – 1,, where RC = rate of change, A_1 = area in the first year (ha), A_2 = area in the final year (ha), and n = number of years in the analysis period. Positive percentages represent increases in area and negative percentages represent losses in area, and the larger the number, the greater the magnitude of change.

Jaguar and Land Use Change. We used jaguar movement data from an ongoing project in the SMO (Rosas-Rosas *et al.* 2016; Silva-Caballero *et al.* 2022) to analyze the relationship between land use change and occurrence of jaguars. Data was collected from two male jaguars in 2016 and 2017 fitted with GPS collars (VECTRONIC Aerospace GmbH; Rosas-Rosas *et al.* 2016). We used 100 randomly selected GPS records within the study area from each jaguar and assigned a land use class to each record using the plugin Add Grid Values to Points in SAGA GIS (Conrad *et al.* 2015). We then calculated the percentage of records within each class.

To address the potential effects of land use change on jaguars, we compared the location points with a transition change map that described how each pixel shifted in its land use from 1989 to 2016. We used the Chi-square goodness of fit test and Bonferroni simultaneous confidence intervals to test whether jaguar records were random or if they were associated with certain land use classes (Neu *et al.* 1974; Byers *et al.* 1984). We excluded water as a potential land use type in the analysis due to its small percentage of surface area.

Results

Accuracies of the classifications were 91 % for both 1989 and 2016. Kappa values were 83 % for 1989 and 84 % for 2016; kappa values of 81 % – 100 % indicate an almost perfect level of agreement (Landis and Koch 1977). From 1989 to 2016 the RBSAT landscape shifted from a more contiguous landscape towards greater heterogeneity and fragmentation (Figure 2). The largest increases were seen in infrastructure (+6.0 %) and intensive agriculture (+5.5 %), while the largest decreases were seen in pasture (–5.7 %), tropical deciduous forest (–3.0 %), and secondary vegetation (–2.7 %); the latter was the most common cover class, comprising 34.8 % of the landscape in 1989 and 32.1 % in 2016 (Table 2). The greatest rates of annual change were

Table 1. Original categories of land use types (LUTs) from INEGI Series I and VI, and the six classes established for use in this study.

Land Use Class/Included LUTs	I	VI
Agriculture		
Semi-permanent irrigated agriculture		X
Seasonal agriculture		X
Annual and semi-permanent seasonal agriculture		X
Semi-permanent seasonal agriculture		X
Seasonal agricultura	X	
Infrastructure		
Urban zone		X
Water		
Bodies of water	X	X
Pasture		
Permanent cultivated pasture	X	X
Managed pasture (native species)	X	X
Tropical Deciduous Forest		
Tropical deciduous forest	X	X
Secondary Vegetation		
Marsh		X
Tropical deciduous forest – secondary arboreal vegetation	X	X
Tropical deciduous forest – secondary shrub vegetation	X	X
Excluded		
Lacking vegetation		X

seen in infrastructure and agriculture (+4.5 % and +2.3 %, respectively), while pasture (–0.9 %) showed the greatest rate of annual loss.

Notable results in the change matrix included 20,463 ha (19.1 %) of tropical deciduous forest that remained unchanged, the majority of which was located in the RBSAT, in which 21,464 ha was protected (Table 3). Similarly, 17,364 ha of secondary vegetation were conserved (16.2 %). Since 1989, pasture conversions included 5,661 ha to intensive agriculture, 5,692 ha to secondary vegetation, and 4,208 ha to infrastructure. Infrastructure, tropical deciduous forest, secondary vegetation, and pasture all transitioned to water, but only accounted for 0.2 % of the total area.

Expected distribution of jaguars based on the spatial availability of each land use class differed significantly from actual locations of jaguars (χ^2_4 = 121.7, P < 0.001). Bonferroni CIs indicated that jaguars were found proportionately more than expected in secondary vegetation (66 % ,57 to 81 %, of locations v. 32 % expected) and were located in tropical deciduous forest (26 % ,13 to 35 %, of locations v. 27 % expected) according to its availability. Few locations were in infrastructure (3 % ,1 to 7 %, of locations v. 9 % expected), agriculture (4 % ,2 to 5 %, of locations v. 12 % expected), and pasture (2 % ,1 to 7 %, of locations v. 20 % expected). While the majority of tropical deciduous forest and other land use types were conserved from 1989 to 2016 within the RBSAT, only 23 % of jaguar locations fell within the boundaries of the RBSAT. In contrast, jaguars were comparably located in areas of stable (*i. e.*, unchanged) secondary vegetation (22 to 38 % of locations) as well as in secondary vegetation that had previously been tropical deciduous forest in 1989
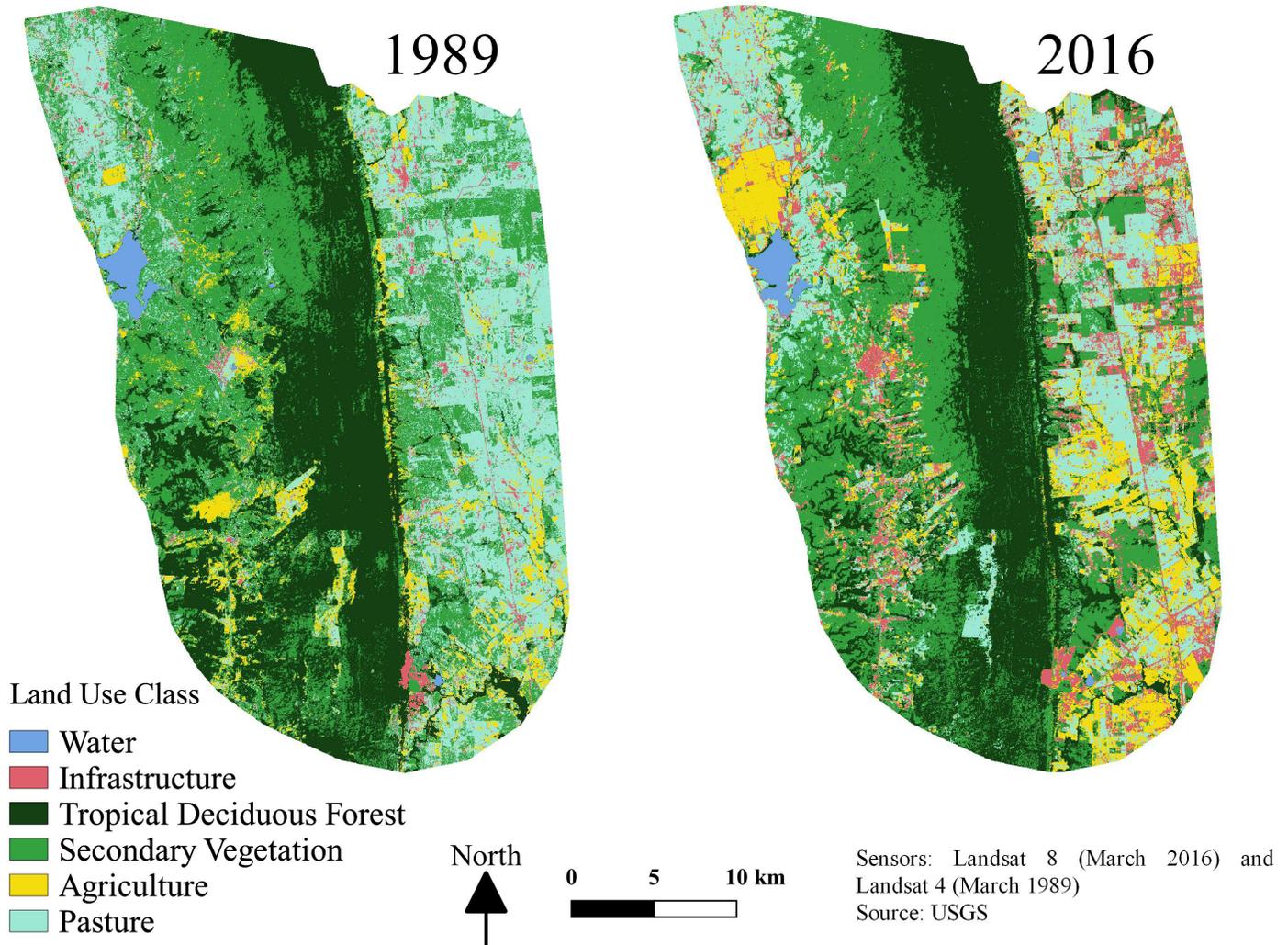
Figure 2. Land use classes of the RBSAT and ten km of the surrounding landscape from 1989 and 2016 analyzed using satellite imagery.

(25 %) and in secondary vegetation that had been pasture in 1989 (38 %).

Discussion

The RBSAT and surrounding landscape changed considerably over the previous *ca*. 30 years, becoming increasingly fragmented and impacted by human use, particularly intensive agriculture and urbanization (Tables 2 and 3; Figure 2). Based on the accuracies of our supervised land use classification, these changes were real rather than artifacts of selected land use data inputs. Classifications showed high accuracy (91 % for 1989 and 2016), and kappa values (83 % for 1989 and 84 % for 2016) indicated an almost perfect level of agreement (*i. e*., $\geq$ 81 %; Landis and Koch 1977). Our values were also similar or superior to previous classifications performed in México at the state level. For example, Chapa-Vargas and Monzalvo-Santos (2012) obtained a 72 % overall accuracy and 69 % Kappa in San Luis Potosí; Porter-Bolland *et al*. (2007) obtained an 87 % overall accuracy in Campeche; and Currit (2005) obtained an 86 % overall accuracy and 85 % Kappa in Chihuahua. At the national level, Velázquez *et al*. (2010) obtained a 71 % overall accuracy of a classification of México. Thus, our

mapping accurately classified the changing land use of the RBSAT landscape.

The increases in infrastructure and intensive agriculture and the decrease in pasture reflected a regional trend of shifting from less intensive cattle ranching towards intensive agriculture, specifically production of sugar cane and citrus (SIAP 2017). The increase in infrastructure reflected the development of commercial and residential infrastructure as a consequence of significant population growth in both Ciudad Valles (increase of 35 %) and Tamuín (increase of 14 %) from 1990 to 2015 (INEGI 2015). These trends follow a national and state-level trend of increasing fragmentation driven by anthropogenic modifications (Mas *et al.* 2009; Velázquez *et al.* 2010). For example, Miranda-Aragón *et al*. (2013) identified high rates of change in San Luis Potosí towards seasonal agriculture (+1.1 %) and irrigated agriculture (+4.8 %) between 1993 and 2007, similar to the annual rate of change (+2.3 %) to all forms of intensive agriculture combined that we observed from 1989 to 2016. Concurrently, less intensive agricultural uses declined, as reflected in the decrease in cover of pastures during our evaluation period. Despite the decrease in pasture, however, cattle production and associated activities are still common and

Table 2. Totals and change in area in hectares (ha) and percent (%) measured by the classification of satellite imagery from 1989 and 2016.

	1989		2016		Change 1989 to 2016		
	Ha	%	ha	%	Ha	%	% change/ year
Water	1,180	1.1	1,215	1.1	+35	0.0	0.1
Infrastructure	2,858	2.6	9,330	8.6	+6,472	6.0	4.5
TDF	31,931	29.6	28.640	26.5	−3,291	−3.0	−0.4
Secondary veg	37,599	34.8	34,631	32.1	−2,968	−2.7	−0.3
Agriculture	6,843	6.3	12,778	11.8	+5,935	5.5	2.3
Pasture	27,610	25.6	21,428	19.8	−6,182	−5.7	−0.9

economically significant in the RBSAT landscape, especially in Tamuín (Silva-Caballero *et al.* 2022).

These and other (*e. g.*, the loss of tropical deciduous forest and secondary vegetation) land use trends in the RBSAT landscape could compromise the ecological role of the reserve. Increasing fragmentation of the immediate surrounding landscape decreases habitat quantity and quality for interior-dependent species such as the elegant eagle and ocelot, thus decreasing the effectiveness of the overall RBSAT landscape as a biodiversity reserve. Loss, or decreases in the size of, large patches that support interior species can affect biodiversity by negatively impacting populations of interior species (Villard 1998), as well as increasing vulnerability to humans and other human-associated threats (*e. g.*, domestic cats and dogs; Doherty *et al.* 2016). Conversely, edge-dependent species, which include many of the key prey species of jaguars (Escamilla *et al.* 2000; Ávila-Nájera *et al.* 2011; Silva-Caballero *et al.* 2022), are benefitted by these changes in land use and increasing fragmentation of the RBSAT landscape, likely resulting in increased abundance, particularly outside of the RBSAT boundary. Consequently, most kill sites of livestock (and natural prey) by jaguars were outside the RBSAT boundary (Silva-Caballero 2019; Silva-Caballero *et al.* 2022).

These changes increase the likelihood of conflicts between jaguars and humans (Rosas-Rosas *et al.* 2015; Guerrero-Rodríguez *et al.* 2020), as only 23 % of jaguar locations were within the boundary of the RBSAT and jaguars were primarily associated with secondary vegetation, which is decreasing within the RBSAT itself. Better habitat quality for jaguars and their prey outside of the RBSAT boundary facilitates potential conflicts with humans. For example, livestock comprised 66 % of the biomass in jaguar diets in the RBSAT landscape, with all depredation occurring outside the RBSAT boundary (Silva-Caballero 2019; Silva-Caballero *et al.* 2022).

Secondary vegetation can result from abandonment of pastures or agricultural fields, and thinning or other alterations of tropical deciduous forest (Table 3; Wandelli and Fearnside 2015). Significantly, jaguars were frequently located in secondary vegetation that had transitioned from pasture and tropical deciduous forest in the RBSAT landscape (primarily outside the RBSAT border; Figure 3) in addition to their use of secondary vegetation that remained unchanged from 1989 to 2016. The apparent preference and use of secondary vegetation outside of the RBSAT boundary by jaguars in association with the preponderance of livestock in jaguar diets (Silva-Caballero *et al.* 2022) emphasizes the need to include local stakeholders in the greater RBSAT landscape in conservation efforts, including secondary vegetation.

Moreover, the expansion of intensive agriculture, increases in habitat edge due to fragmentation, and continued importance of livestock production and associated improvements (especially water) may attract prey species to, or increase their populations in, these land uses (Rosas-Rosas *et al.* 2020; Silva-Caballero *et al.* 2022). For example, Escamilla e*t al.* (2000) and Ávila-Nájera *et al.* (2011) found that collared peccary (*Pecari tajacu*), white-tailed deer (*Odocoileus virginianus*), and white-nosed coati (*Nasua narica*), important prey species for jaguars in the RBSAT (Hernández-SaintMartín *et al.* 2015; Silva-Caballero 2019; Silva-Caballero *et al.* 2022, preferentially used mosaics of tropical deciduous forest, agriculture, and livestock pasture. Consequently, so did jaguars and pumas (*Puma con-*
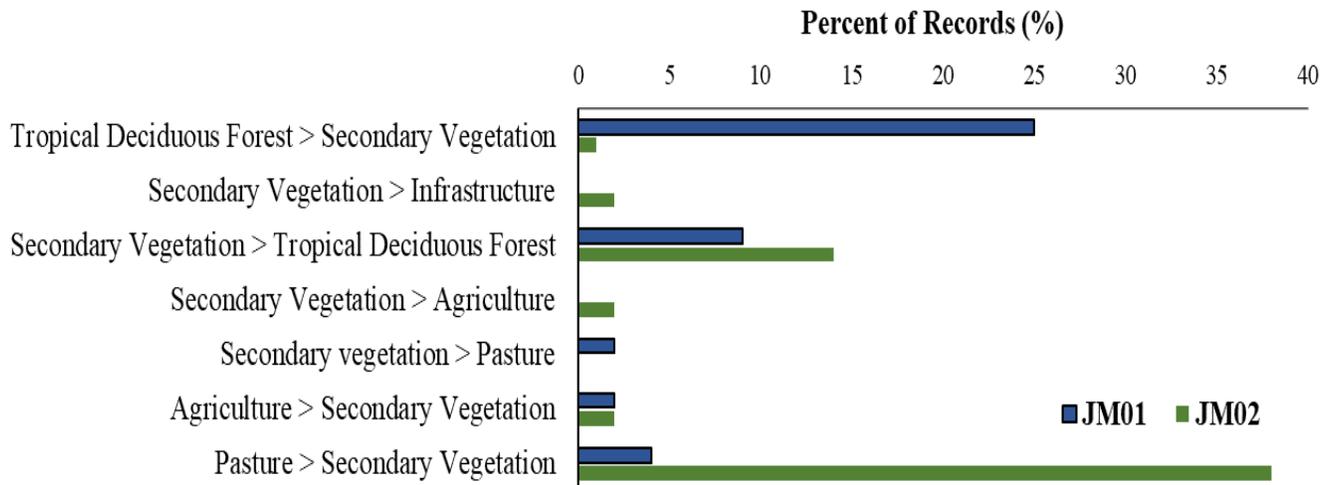
Figure 3. The percent of records associated with transitions in secondary vegetation from 1989 to 2016 from two jaguars (grey and white bars) within the RBSAT landscape. The symbol > indicates a transition between land use classes from 1989 to 2016.

Table 3. Confusion matrix of land use changes in area (%) from 1989 to 2016. Unchanged land use are in *****. Retrogressive land use change is *italicized*.

	Land use classes from 2016 imagery						
Land use	**Water**	**Infrastructure**	**Tropical forest**	**Secondary veg**	**Agriculture**	**Pasture**	**Total (1989)**
Water	0.90 % *	0.04 %	0.02 %	0.07 %	0.03 %	0.05 %	1.10 %
Infrastructure	0.01 %	0.8 3% *	0.09 %	0.32 %	0.48 %	0.94 %	2.67 %
TDF	0.05 %	0.43 %	19.14 % *	8.31 %	0.84 %	0.78 %	29.54 %
Secondary Veg	0.09 %	2.81 %	5.21 %	16.24 % *	3.55 %	6.84 %	34.73 %
Agriculture	0.02 %	0.65 %	0.94 %	1.70 %	1.69 % *	1.38 %	6.38 %
Pasture	0.07 %	3.94 %	1.13 %	5.32 %	5.29 %	9.82 % *	25.57 %
Total (2016)	1.14 %	8.69 %	26.52 %	31.96 %	11.88 %	19.82 %	

color; Escamilla *et al.* 2000; Hernández-SaintMartín *et al.* 2015). Further, the RBSAT lacks permanent water sources (Hernández-SaintMartín *et al.* 2013; Silva-Caballero *et al.* 2022). Consequently, wildlife, including jaguars and their prey, seek water outside of the boundaries of the Reserve during the dry season (Hernández-SaintMartín *et al.* 2013), which increases the vulnerability of livestock and natural prey to predation (Silva-Caballero *et al.* 2022). Water developments are most common in livestock enterprises, intensive agriculture (irrigation), and human developed (*e. g.*, residential, etc.) areas, where presence of jaguars frequently results in serious conflicts (Guerrero-Rodríguez *et al.* 2020; Silva-Caballero *et al.* 2022).

The rapid increases in infrastructure, intensive agriculture, and habitat fragmentation have and will continue to dramatically change the RBSAT landscape, and thus affect the wildlife that utilize the landscape. Managers and stakeholders need to seek approaches that account for the response of resident wildlife including interior-dependent species and jaguars, mitigate conflicts, and protect the economic viability of adjacent communities (Olvera-Hernández *et al.* 2020; Silva-Caballero *et al.* 2022). Minimization of loss of tropical deciduous forest and other large habitat patches in the RBSAT itself is likely the only practical means of minimizing loss of biodiversity in the RBSAT landscape, especially for interior-dependent species given the already significant fragmentation in the surrounding landscape. Characteristics associated with human-jaguar conflict areas (especially with livestock) include proximity to a protected area and seasonal availability of water (Rosas-Rosas *et al.* 2010; Peña-Mondragón and Castillo 2013; Alfaro *et al.* 2016; Silva-Caballero *et al.* 2022). Both of these are present in the RBSAT landscape, as are associated livestock depredation conflicts (Silva-Caballero *et al.* 2022), and are likely to become more prevalent given the changes in land use away from natural vegetation towards intensive agricultural and infrastructure development. The combination of a decrease in preferred jaguar habitat within the RBSAT and likely increases in preferred prey outside of the RBSAT as a consequence of increasing fragmentation, intensive agriculture, and permanent water infrastructure, will likely lead to in increased conflicts between humans and jaguars (Rosas-Rosas *et al.* 2010; Guerrero-Rodríguez *et al.* 2020;

Peña-Mondragón and Castillo 2013; Alfaro *et al.* 2016; Silva-Caballero *et al.* 2022).

Conservation of the RBSAT landscape is thus dependent upon a mutually beneficial relationship between the objectives of the Reserve and the economic viability of adjacent communities, necessitating management strategies that reflect the interests of both entities. The trends in land use in the RBSAT landscape towards increasingly fragmented intensive agricultural and infrastructure development are likely to decrease the ecological values of the Reserve (*i. e.*, biodiversity, habitat linkage, jaguar conservation because of increased conflicts and illegal killing) and increase conflicts between adjacent landowners and wildlife, including large carnivores (because even perceived conflicts with large carnivores can facilitate intolerance; Rosas-Rosas *et al.* 2015). This outcome, unless changed, results in a loss for both the RBSAT and surrounding communities. Stakeholder driven adaptable land use planning and management based upon the necessity and expectation of shared use that is advantageous for both communities and the Reserve is necessary to minimize both the future loss of ecological values and potential human-wildlife conflicts (Rosas-Rosas *et al.* 2015, 2020). However, adaptive management requires structured monitoring and a willingness to change methods and alter tactics depending on the feedback and results (Williams 2011). Consequently, working with members of the community on site-specific conservation strategies is critical to maintain or enhance the ecological role of the RBSAT and its surrounding landscape.

Acknowledgements

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