Land-cover change in Cuba and implications for the area of distribution of a specialist's host-plant

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ABSTRACT

Changes in land cover directly affect biodiversity. Here, we assessed land-cover change in Cuba in the past 35 years and analyzed how this change may affect the distribution of *Omphalea* plants and *Urania boisduvalii* moths. We analyzed the vegetation cover of the Cuban archipelago for 1985 and 2020. We used Google Earth Engine to classify two satellite image compositions into seven cover types: forest and shrubs, mangrove, soil without vegetation cover, wetlands, pine forest, agriculture, and water bodies. We considered four different areas for quantifications of land-cover change: (1) Cuban archipelago, (2) protected areas, (3) areas of potential distribution of *Omphalea*, and (4) areas of potential distribution of the plant within the protected areas. We found that "forest and shrubs", which is cover type in which *Omphalea* populations have been reported, has increased significantly in Cuba in the past 35 years, and that most of the gained forest and shrub areas were agricultural land in the past. This same pattern was observed in the areas of potential distribution of *Omphalea*; whereas almost all cover types were mostly stable inside the protected areas. The transformation of agricultural areas into forest and shrubs could represent an interesting opportunity for biodiversity conservation in Cuba. Other detailed studies about biodiversity composition in areas of forest and shrubs gain would greatly benefit our understanding of the value of such areas for conservation.

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INTRODUCTION

Habitat degradation is one of the most important anthropogenic causes of biodiversity loss, driven mostly by changes in land use (*Leemans & de Groot, 2003*; *Baude, Meyer & Schindewolf, 2019*; *Santos et al., 2020*; *Stanturf, 2021*). Habitat loss often involves deteriorating habitat quality and habitat fragmentation which have ecological, genetic, and evolutionary consequences (*Sih, Jonsson & Luikart, 2000*; *Hanski, 2011*). This is a problem for most species, but it may be especially important for those with a restricted distribution or those that depend on a specific climate or habitat for survival (*Devictor, Julliard & Jiguet, 2008*). How habitat modifications are affecting species has been the focus of

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attention in several studies (*Brooks et al., 2002*). Those studies have been mainly focused on plants, birds, and mammals (*Zechmeister et al., 2003*; *de Lima et al., 2013*; *Powers & Jetz, 2019*). However, other groups like insects are underrepresented (*Basset & Lamarre, 2019*), despite documented examples of extinctions due to habitat loss (*Dunn, 2005*).

Land cover and land use changes have a large effect in the current distribution of insects' species (*Bommarco et al., 2014*). Some species are highly sensitive to these changes, experiencing population decline in areas where the non-natural cover types increase (*Fox et al., 2014*). For example, some studies have reported that bee population has been declining due to habitat cover change (*Nemésio et al., 2016*). The effects of land use change on species richness/diversity on Lepidoptera, on the other hand, do not have a consensus among previous studies as other factors, like habitat heterogeneity, are also important (*Nuñez-Penichet et al., 2021*). In this group, some studies reported that the butterfly communities are more diverse in undisturbed (or the least disturbed) forest than in disturbed habitats, and others reported the opposite trend (*Koh, 2007*).

The neotropical genus *Urania* (Uraniidae) includes four species of diurnal moths, *U. sloanus* (endemic to Jamaica, presumed extinct; *Lees & Smith, 1991*), *U. fulgens* (from Mexico to northern Colombia), *U. leilus* (from southern Colombia to Bolivia), and *U. boisduvalii* (endemic to Cuba; *Nazari et al., 2016*). These moths feed, during their larvae stages, exclusively on *Omphalea* (*Euphorbiaceae*) plants (*Lees & Smith, 1991*; *Smith, 1991*, *1992*; *Nuñez-Penichet & Barro, 2020*). These plants have toxins that protect them from insects, but *Urania* larvae can tolerate them (*Smith, 1992*). However, when *Omphalea* plants are being eaten for several generations of these moths, they increase the levels of toxicity as a defense mechanism against *Urania* herbivory (*Lees & Smith, 1991*), forcing them to move to a different host-plant population (*Smith, 1983*). Therefore, *Urania* needs to have several patches of *Omphalea* available to guarantee its survival.

In Cuba, there are three species of *Omphalea* plants (*Lees & Smith, 1991*) mainly distributed in coastal and other karstic zones with primary or secondary forest and shrubs vegetation. *Omphalea trichotoma* (distributed in western and eastern Cuba) and *O. hypoleuca* (reported only from Viñales, Pinar del Río) are endemic (*Greuter & Rankin, 2016*), while *O. diandra* is widely distributed in the neotropics (*Lees & Smith, 1991*). In this archipelago, these plants are present in areas that have been under pressure from the development of infrastructure for tourism and oil extraction activities (*Camacho, Baena & Leyva, 2010*) enhancing the importance of studying their populations and how they may be affected.

Given the direct dependence on host plant availability, *Urania* moths appear to be highly sensitive to changes in land use (*Lees & Smith, 1991*). For instance, *U. sloanus* is now considered extinct due to habitat degradation (*Lees & Smith, 1991*). However, no study has explored how distributional areas of these moths and plants are being affected over time due to land-cover change. This is especially important in the case of the endemic moth *Urania boisduvalii*, due to the risk the host plants are being exposed to. Here, we aimed (1) to evaluate the change in land use in Cuba in the past 35 years, and (2) to analyze how these land use changes may affect the distribution of *Omphalea* plants and *Urania boisduvalii* moths. Portions of this text were previously published as part of a preprint (*Nuñez-Penichet, Maita-Chamba & Soberón, 2023*; https://www.biorxiv.org/node/3004963.full).

METHODS

To evaluate land use change in Cuba (Appendix 1 S1), we analyzed the vegetation cover in this archipelago of the years 1985 (beginning of Landsat 5) and 2020 using Landsat images and Google Earth Engine (GEE; *Gorelick et al., 2017*) for the supervised classification processing. GEE, is a cloud geospatial processing platform on Google computational infrastructure, used in different studies with spatial and temporal scales (*Gorelick et al., 2017*). This platform has been used in studies exploring vegetation succession (*Adagbasa & Mukwada, 2022*), species distribution (*Crego, Stabach & Connette, 2022*; *Crego et al., 2023*), and to characterize large landscapes (*Rippel et al., 2023*). GEE has been also used to map deforestation and forest degradation (*Shimizu et al., 2022*; *Wimberly et al., 2022*), predict effects of climate change (*Workie & Debella, 2018*; *Shiff, Lensky & Bonfil, 2021*), assess the impacts of wildfires (*dos Santos et al., 2023*; *Parra et al., 2023*), and detect changes in land use and land cover (*Phan, Kuch & Lehnert, 2020*; *Tassi et al., 2021*; *González-González, Clerici & Quesada, 2022*; *Biswas et al., 2023*).

Our study area (Cuban archipelago) was covered by sixteen scenes (paths: 10 to 17 and rows: 44 to 46) of the Landsat 5 ETM sensor (1985) and the Landsat 8 OLI/TIRS sensor (2020), with images at 30-m resolution. To minimize temporal, spatial, and spectral varying scattering and absorbing effects of atmospheric gasses and aerosols, we used the collection 2 of Land Surface Reflectance (*Vermote et al., 2016*). Cloud-free images of Cuba were produced by using those with cloud cover ≤50% and a temporal filter, including the years 1984–1988 for the period 1985 and the years 2020–2021 for 2020. Cloud and cloud shadows were masked using pixel quality attributes generated from the C Function of Mask (CFMASK) algorithm (QA_PIXEL Bitmask) for both sensors (*Zhu & Woodcock, 2012*; *Foga et al., 2017*).

The resulting images (1985 and 2020) were classified into seven cover types to represent areas in which *Omphalea* populations have been reported (forest and shrubs, considered as suitable) and areas in which *Omphalea* species have not been reported (mangrove, soil without vegetation cover, wetlands, pine forest, agriculture, and water bodies, considered as unsuitable areas for *Omphalea* plants; *Nuñez-Penichet et al., 2016*). The distribution of *Omphalea* in Cuba was estimated by *Nuñez-Penichet et al. (2019)* from post-processing bioclimatic models with suitable cover types and reported as raster files. The cover types were classified by regions of interest (ROI) for each of the categories on the Google Earth Engine. The number of ROIs selected for each category varied to represent the full range of appearances within each category (300 for forest and shrubs, 100 for mangrove, 50 for soil without vegetation cover, 100 for wetlands, 100 for pine forest, 100 for agriculture, and 100 for water bodies). All ROIs were selected manually based on visual interpretation of the respective Landsat images from GEE and were divided randomly into training (70%) and testing (30%).

We selected Random Forest as the classification algorithm as it has been widely used on land use and land cover change investigations (*Alencar et al., 2020*; *Souza et al., 2020*;

Osman et al., 2023; Shimabukuro et al., 2023). Also, this algorithm is good at handling outliers and noisy datasets, has high processing speed (Jin et al., 2018), has good performance with complex datasets (Belgiu & Drăguţ, 2016), and has higher accuracy than other algorithms (Sheykhmousa et al., 2020; Talukdar et al., 2020). The classified images were post-processed in QGIS.org (2022) to correct misclassified pixels using a raster calculator and elevational considerations (Appendix 2 S1). We assessed the accuracy of classifications on the GEE platform, using the resulting images from the post-processing analyses and 100 new validation ROIs created randomly for each of the considered cover types but water bodies in which we used only 50. We used measures extracted from confusion matrix, such as: (1) overall accuracy (OA), which is calculated dividing the total number of correctly classified values by the total number of values (Story & Congalton, 1986; Congalton, 1991), and (2) kappa coefficient (Fitzgerald & Lees, 1994; Fielding & Bell, 1997) for measuring the agreement between classification and truth values.

The resulting classified images of Cuba were masked to: (1) terrestrial protected areas (CNAP, 2013); (2) potential distribution areas of *Omphalea* (from Nuñez-Penichet et al., 2019), hereafter OD; and (3) potential distribution areas of the plant within protected areas (Nuñez-Penichet et al., 2016). This last one was included as 23.57% of OD is inside a protected area in Cuba. We quantified the percentage of each of the seven cover types and their changes between periods for all Cuba and in each of the masked areas (areas of interest).

To assess the significance of observed changes, we used a bootstrap approach (Weber & Langille, 2007) whereby the classification categories were assigned randomly (1,000 times) to both years. With this, we created a distribution of random changes, and compared the observed percentage difference with the distribution of random values. Observed values above the 99 percentiles, or below the first, were considered significantly non-random.

All these analyses were done in R Core Team (2020) using the package terra (Hijmans, 2022). All the code needed to reproduce these analyses is openly available at https://github.com/claununez/Land-coverChangeCuba. All the data needed is openly available at https://figshare.com/articles/dataset/Data_for_the_manuscript_Land-cover_change_in_Cuba_may_favor_biodiversity_An_example_using_Omphalea_plants_and_Urania_boisduvalii/21779129.

RESULTS

We obtained an overall accuracy (OA) of 92.7% and 87.6% for 1985 and 2020 classifications, with a Kappa coefficient of 0.91 and 0.85, respectively. The values of OA for each land cover type ranged from 80% (pine forest) to 100% (agriculture) in 1985, and from 71% (wetlands) to 99% (forest and shrubs) in 2020 (Table S1). All the observed values were significant ($p < 0.01$) using the two-tailed bootstrap test described in the methods.

We found that, in the past 35 years, forest and shrub areas have increased across the entire Cuban territory (from 17.02% in 1985 to 38.12% in 2020; Table 1). Agricultural lands and soils without vegetation cover, on the other hand, showed a reduction from 59.62% to 41.26% and from 3.56% to 1.16%, respectively (Table 1 and Fig. 1). The other

Table 1 Percentage of area classified as one of the seven classification types considered for the years 1985 and 2020. *Omphalea* includes all the species of *Omphalea* genus distributed in Cuba combined and the areas of potential distribution of *Omphalea* is referring to these species' potential distribution in Cuba. The protected areas in Cuba are referring to the terrestrial protected areas only.

Classification type	Cuba		Protected areas in Cuba		Areas of potential distribution of *Omphalea*		Areas of potential distribution of *Omphalea* inside protected areas	
	1985	2020	1985	2020	1985	2020	1985	2020
Forest and shrubs	17.02	38.12	29.08	37.02	47.48	70.09	59.31	72.16
Mangrove	4.64	5.80	15.31	19.83	2.15	2.13	4.63	4.42
Soil without vegetation cover	3.56	1.16	2.85	0.98	1.64	0.44	1.31	0.42
Wetland	4.08	3.68	11.39	9.85	1.40	1.25	2.03	2.07
Pine forest	1.86	1.47	3.94	2.58	6.06	3.87	11.64	7.13
Agriculture	59.62	41.26	13.09	8.16	37.92	19.11	15.57	8.95
Water bodies	9.23	8.50	24.34	21.58	3.35	3.11	5.53	4.85

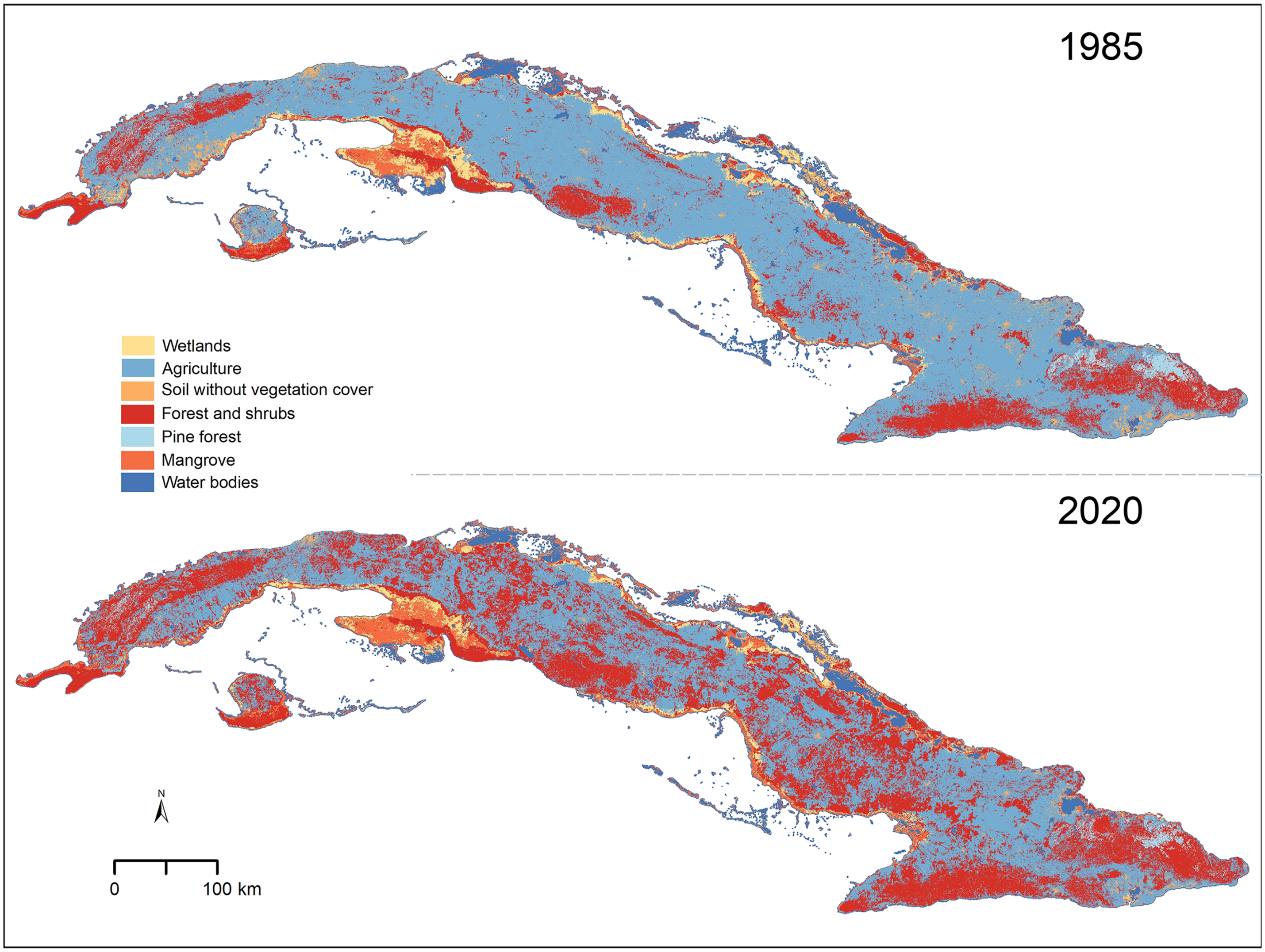

Figure 1 Vegetation types in Cuba for the years 1985 and 2020. Cuban silhouette from *ESRI (2016)*. Full-size DOI: 10.7717/peerj.17563/fig-1

Table 2 Percentage of change between the classification types considered, during the period 1985–2020. *Omphalea* includes all the species of the genus *Omphalea* distributed in Cuba combined and the areas of potential distribution of *Omphalea* is referring to these species' potential distribution in Cuba.

Type of change	Cuba	Protected areas in Cuba	Areas of potential distribution of *Omphalea*	Areas of potential distribution of *Omphalea* inside protected areas
Stable forest and shrubs	15.01	26.40	43.72	55.25
Mangrove to forest and shrubs	0.49	1.50	0.67	1.76
Soil without vegetation cover to forest and shrubs	0.36	0.08	0.30	0.06
Wetlands to forest and shrubs	0.53	0.86	0.43	0.42
Pine forest to forest and shrubs	0.94	2.02	3.18	6.06
Agriculture to forest and shrubs	20.69	5.91	21.75	8.57
Water bodies to forest and shrubs	0.11	0.25	0.03	0.04
Stable mangrove	3.67	12.23	1.27	2.46
Forest and shrubs to mangrove	0.21	0.85	0.22	0.63
Soil without vegetation cover to mangrove	0.19	0.71	0.11	0.28
Wetlands to mangrove	0.93	3.88	0.20	0.47
Pine forest to mangrove	0.00	0.00	0.00	0.00
Agriculture to mangrove	0.17	0.32	0.08	0.09
Water bodies to mangrove	0.61	1.84	0.26	0.48
Stable soil without vegetation cover	0.73	0.66	0.28	0.28
Forest and shrubs to soil without vegetation cover	0.01	0.02	0.01	0.02
Mangrove to soil without vegetation cover	0.00	0.01	0.00	0.00
Wetlands to soil without vegetation cover	0.06	0.21	0.03	0.06
Pine forest to soil without vegetation cover	0.00	0.00	0.00	0.00
Agriculture to soil without vegetation cover	0.36	0.07	0.11	0.04
Water bodies to soil without vegetation cover	0.00	0.02	0.00	0.01
Stable wetlands	2.36	6.12	0.65	0.95
Forest and shrubs to wetlands	0.13	0.37	0.08	0.15
Mangrove to wetlands	0.30	1.02	0.10	0.21
Soil without vegetation cover to wetlands	0.24	0.68	0.14	0.25
Pine forest to wetlands	0.00	0.00	0.00	0.00
Agriculture to wetlands	0.31	0.50	0.10	0.13
Water bodies to wetlands	0.35	1.16	0.18	0.36
Stable pine forest	0.74	1.80	2.50	5.23
Forest and shrubs to pine forest	0.31	0.54	0.82	1.39
Mangrove to pine forest	0.00	0.00	0.00	0.00
Soil without vegetation cover to pine forest	0.01	0.00	0.00	0.00
Wetlands to pine forest	0.00	0.00	0.00	0.00
Agriculture to pine forest	0.38	0.24	0.53	0.51
Water bodies to pine forest	0.03	0.00	0.01	0.00
Stable agriculture	37.50	6.04	15.23	6.22
Forest and shrubs to agriculture	1.30	0.88	2.60	1.86
Mangrove to agriculture	0.08	0.21	0.05	0.09
Soil without vegetation cover to agriculture	1.95	0.43	0.75	0.28

Table 2 (continued)

Type of change	Cuba	Protected areas in Cuba	Areas of potential distribution of *Omphalea*	Areas of potential distribution of *Omphalea* inside protected areas
Wetlands to agriculture	0.18	0.23	0.08	0.10
Pine forest to agriculture	0.14	0.12	0.35	0.34
Water bodies to agriculture	0.11	0.25	0.05	0.07
Stable water bodies	8.00	20.83	2.82	4.56
Forest and shrubs to water bodies	0.04	0.01	0.03	0.00
Mangrove to water bodies	0.10	0.33	0.05	0.11
Soil without vegetation cover to water bodies	0.08	0.29	0.06	0.14
Wetlands to water bodies	0.03	0.10	0.01	0.03
Pine forest to water bodies	0.04	0.00	0.03	0.00
Agriculture to water bodies	0.21	0.02	0.12	0.00

four types of cover considered (mangrove, wetland, pine forest, and water bodies) were present in similar proportions in the two scenarios studied (Table 1). Most areas that changed from one cover type to another were located inland, especially in areas of low elevation (Fig. 1 and Appendix 1 S1).

In the areas of potential distribution of *Omphalea* plants, we found a similar pattern to the one described above for Cuba except for the pine forest, which decreased from 1985 to 2020 (Table 1). Most of these changes in the different cover types were concentrated in central Cuba, whereas stable areas were mostly in Guanahacabibes (westernmost part of Cuba), the southern part of Isla de la Juventud, and highlands (Appendix 1 S1 and Fig. S1). Inside the protected areas in Cuba and in the OD that were inside the protected areas, we detected small changes in the percentage of area of each cover type between the two analyzed periods (1985 and 2020) (Table 1, Figs. S2 and S3). The biggest changes were in the forest and shrubs (increased) and in the agricultural lands (decreased) (Table 1, Figs. S2 and S3).

We found that only 15.01% of the Cuban area classified as forest and shrubs in 2020, was classified as the same category in 1985 (Table 2). The low stability of this cover type was also found when quantifying in the other areas of interest, with 26.40% of the protected areas in Cuba, 43.72% of the OD, and 55.25% of the OD inside protected areas found to be forest and shrubs in both time periods analyzed (Table 2). Not many of the forest and shrubs areas changed to other cover types, and most of the forest and shrub areas gained in Cuba in 2020 were agricultural lands in the past (Table 2). The proportion of change from agricultural land to forest and shrubs was also high in the OD and the other areas of interest (Table 2). The agricultural lands that changed to forest and shrubs by 2020 were distributed in small patches across the Cuban archipelago and were less predominant in the eastern region (Fig. 2). The areas that changed to forest and shrubs in OD were also small patches, but their spatial distribution helped increase the connectivity among larger stable forest and shrubs areas (Fig. 2 and Table 2).

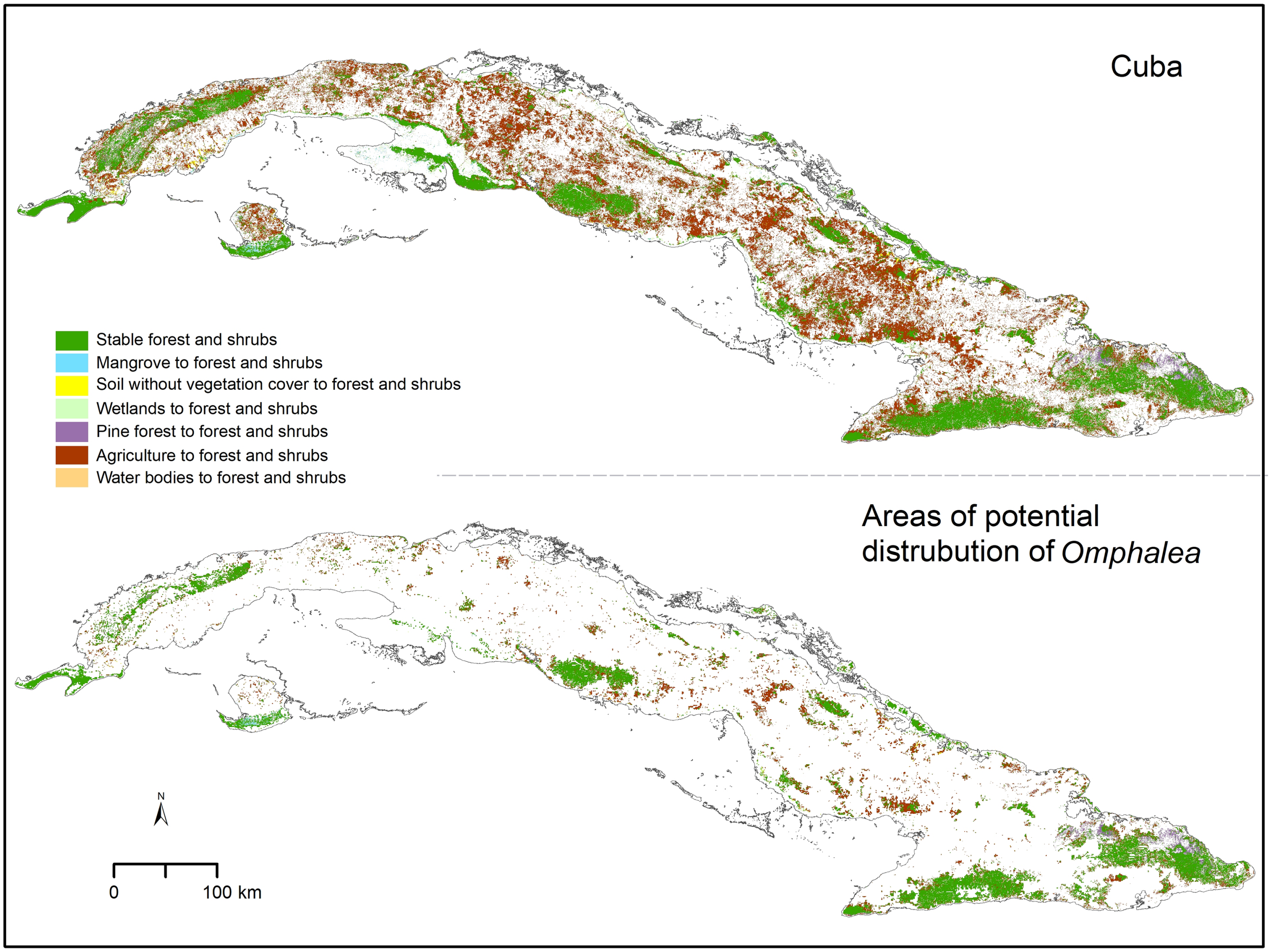

Figure 2 **Forest and shrubs change.** *Omphalea* includes all the species of *Omphalea* genus distributed in Cuba combined and the areas of potential distribution of *Omphalea* is referring to these species' potential distribution in Cuba. Cuban silhouette from *ESRI (2016)*.

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DISCUSSION

Environmental monitoring sciences have undergone a rapid evolution due to global environmental changes and the technological development of Earth Observation (EO; *Appel et al., 2018*). Several platforms, such as Google Earth Engine (GEE), Sentinel Hub, Open Data Cube, SEPAL, openEO, JEODPP, and pipsCloud, have been developed to address challenges associated with storing, accessing, processing, and analyzing large geospatial datasets generated by EO satellites (*Gomes, Queiroz & Ferreira, 2020*). China, USA, India, and Brazil lead as the countries with higher contributions to the use of GEE for the visualization and processing of geospatial data, while other countries like Cuba, have few or no data showing the use of this platform to address biological questions. Among the EO satellites, Landsat has been the most used, mainly applied to study changes in cropland-vegetation as well as characterization of land use and land cover (*Velastegui-Montoya et al., 2023*). Landsat images have been previously used in Cuba to study change of cover types (*e.g.*, *Hernández & Cruz, 2016*). Our results show, not only how land cover in Cuba has changed in 35 years, but also how these changes may affect the distribution of *Omphalea* plants and *Urania boisduvalii* moths, using the GEE platform.

The general global trend in forest cover is towards loss (*Keenan et al., 2015*), and cover loss is associated with changes in plant-herbivore networks. However, we found that in Cuba, forest and shrubs (*i.e.*, suitable vegetation cover for *Omphalea*) have increased considerably in the past 35 years, mostly replacing agricultural lands (Fig. 1 and Table 1). Although there have been some reforestation efforts in specific localities of Cuba (*Gebelein, 2012*; *Izquierdo et al., 2015*) that may have influenced the changes in soil without vegetation cover observed, our results may be due to the fact that in Cuba, before 1990, extensive areas were dedicated to growing sugarcane, especially in the center of the island (Appendix 1 S1), but after 1990, the intensity of sugarcane production decreased (*Suárez et al., 2012*; *Machado, 2018*). This explanation was also presented by *Clark, Aide & Riner (2012)* after finding a 10% increase in closed-canopy forest area, mainly in the Cuban Dry Forests ecoregion, from 2001 to 2010, and by *Álvarez-Berríos et al. (2013)* while analyzing changes in Cuba woody areas and agricultural lands. Our results also concur with *Sagastume et al. (2018)* who reported that over half of agricultural land in Cuba is currently unused and with *Stuhlmacher et al. (2020)* who found that between the years 1985 and 2010, ~18% of Cuban croplands changed to barren/grass/shrublands, built-up lands, and forest. Although the trend we report for Cuba is opposite to the general global pattern, it is an example of how land use change is a complex phenomenon resulting from multiple causes, and difficult to predict (*Lambin et al., 2001*).

Forest and shrub cover increase within areas of potential distribution of *Omphalea* (Table 1 and Fig. S1) may in fact represent an advantage for populations of these plants as these areas are known to be climatically suitable (*Nuñez-Penichet et al., 2016*). Given the obligated relationship between *Urania boisduvalii* and *Omphalea* plants, which also drives the moth's dispersal patterns in the country (*Nuñez-Penichet, Soberón & Osorio-Olvera, 2023*), these gained areas could indirectly benefit the moth. The increment of forest and shrubs could increase connectivity among fragmented patches with plant populations facilitating *Urania* moth's movements (Figs. 2 and S1). In fact, several of the stable and gained shrub and forest patches are located in the potential migratory paths of *U. boisduvalii* identified in a previous study (*Nuñez-Penichet et al., 2019*).

On the other hand, the increment of forest and shrubs in the Cuban territory does not necessarily imply an increase of *Omphalea* plants or an increment in favorable conditions for *Urania* moths. Species distributions depend on the presence of suitable abiotic conditions, accessibility, and biotic interactions (*Soberón & Peterson, 2005*). In Cuba, a significant portion of unused agricultural lands have been reported to be covered with shrub invasive species (*e.g.*, *Dichrostachys cinerea*, *Sagastume et al., 2016*, *2018*; *Valero-Jorge et al., 2024* and *Vachellia farnesiana*, *Fernandez et al., 2018*), which causes a displacement of native plant communities (*Ruiz, Remond & Fernandez, 2010*). In the last decades, several studies have focused on testing the potential of *D. cinerea* high-quality biomass to produce a sustainable biofuel (*Sagastume et al., 2018*; *Reyes et al., 2022*) as an alternative source of energy, and therefore little effort is targeted on controlling this invasive plant. For this reason, performing fieldwork in the gained forest and shrubs areas will be necessary to assess whether they can actually benefit the conservation of *Omphalea* plants and *Urania* moths.

When we focused on the protected areas in Cuba and areas of potential distribution for *Omphalea* inside protected areas, we detected that, in the two time-periods analyzed, stability was high for all cover types explored. The exceptions were the increase of forest and shrubs, and the decrease of agriculture areas and soils without vegetation cover (Figs. S2 and S3). This concurs with what has been previously reported for 10 National Parks in Cuba (*Hernández & Cruz, 2016*). In fact, these results may reflect the role of the protective areas in preserving the landscape in Cuba. However, interpretations about the conservation status of natural vegetation should be done cautiously. In our study, and based on our goal, we included all types of forests and shrubs in a single category, and therefore, we are not accounting for changes at a finer detail (*e.g.*, changes from tropical rain forest to secondary vegetation dominated by alien species). Because of this, forest and shrub gains do not necessarily represent positive rates of change for primary or native vegetation.

Here we are presenting results that suggest the distribution of *Omphalea* plants and, therefore, for *Urania* moths in Cuba may be increasing, since we find that the areas with suitable conditions for these species have been increasing considerably. Moreover, our results suggest that land-use changes in Cuba may favor not only *Urania* and *Omphalea* but other species that live in forests and shrubs. However, the presence of invasive species in those gained forest and shrubs areas should be monitored in the field as they may represent a serious threat to native biodiversity.

Changes in land use in Cuba during the last 35 years may represent a significant opportunity for biodiversity conservation and sustainable management of its natural vegetation. However, further studies that allow understanding the community composition and structure in such forests and shrubs are needed to assess the value of these lands for biodiversity conservation in the country.

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Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Claudia Nuñez-Penichet conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Juan Maita conceived and designed the experiments, performed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Jorge Soberon conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

All the code needed to reproduce these analyses is available at GitHub and Zenodo:

- https://github.com/claununez/Land-coverChangeCuba.

- Claudia Nuñez-Penichet. (2024). claununez/Land-coverChangeCuba: Land-cover change in Cuba (v1.0.0). Zenodo. https://doi.org/10.5281/zenodo.11252550.

All the data needed is available at figshare: Nuñez-Penichet, Claudia; Soberon, Jorge (2022). Data for the manuscript: Land-cover change in Cuba and how it is affecting the areas of distribution of Omphalea (Angiosperma: Euphorbiaceae) and *Urania boisduvalii* (Lepidoptera: Uraniidae). figshare. Dataset. https://doi.org/10.6084/m9.figshare.21779129.v2.

Supplemental Information

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REFERENCES

Álvarez-Berríos NL, Redo DJ, Aide TM, Clark ML, Grau R. 2013. Land change in the Greater Antilles between 2001 and 2010. *Land* **2(2)**:81–107 DOI 10.3390/land2020081.

Adagbasa EG, Mukwada G. 2022. Mapping vegetation species succession in a mountainous grassland ecosystem using Landsat, ASTER MI, and Sentinel-2 data. *PLOS ONE* **17(1)**:e0256672 DOI 10.1371/journal.pone.0256672.

Alencar AZ, Shimbo J, Lenti F, Balzani Marques C, Zimbres B, Rosa M, Arruda V, Castro I, Fernandes Márcico Ribeiro J, Varela V, Alencar I, Piontekowski V, Ribeiro VMC, Bustamante M, Eyji Sano E, Barroso M. 2020. Mapping three decades of changes in the Brazilian savanna native vegetation using Landsat data processed in the Google Earth Engine platform. *Remote Sensing* **12(6)**:924 DOI 10.3390/rs12060924.

Appel M, Lahn F, Buytaert W, Pebesma E. 2018. Open and scalable analytics of large Earth observation datasets: from scenes to multidimensional arrays using SciDB and GDAL. *ISPRS Journal of Photogrammetry and Remote Sensing* **138(1)**:47–56 DOI 10.1016/j.isprsjprs.2018.01.014.

Basset Y, Lamarre GPA. 2019. Toward a world that values insects. *Science* **364(6447)**:1230–1231 DOI 10.1126/science.aaw7071.

Baude M, Meyer BC, Schindewolf M. 2019. Land use change in an agricultural landscape causing degradation of soil based ecosystem services. *Science of the Total Environment* **659**:1526–1536 DOI 10.1016/j.scitotenv.2018.12.455.

Belgiu M, Drăguţ L. 2016. Random forest in remote sensing: a review of applications and future directions. *ISPRS Journal of Photogrammetry and Remote Sensing* **114(Part A)**:24–31 DOI 10.1016/j.isprsjprs.2016.01.011.

Biswas J, Jobaer MA, Haque SF, Islam Shozib MS, Limon ZA. 2023. Mapping and monitoring land use land cover dynamics employing Google Earth Engine and machine learning algorithms on Chattogram, Bangladesh. *Heliyon* **9(11)**:e21245 DOI 10.1016/j.heliyon.2023.e21245.

Bommarco R, Lindborg R, Marini L, Öckinger E. 2014. Extinction debt for plants and flower-visiting insects in landscapes with contrasting land use history. *Diversity and Distributions* **20(5)**:591–599 DOI 10.1111/ddi.12187.

Brooks TM, Mittermeier RA, Mittermeier CG, Da Fonseca GAB, Rylands AB, Konstant WR, Flick P, Pilgrim J, Oldfield S, Magin G, Hilton-Taylor C. 2002. Habitat loss and extinction in the hotspots of biodiversity. *Conservation Biology* **16(4)**:909–923 DOI 10.1046/j.1523-1739.2002.00530.x.

Camacho JA, Baena GSG, Leyva GP. 2010. *Strengthening the management of comprehensive development and sustainable development of the Guanahacabibes Peninsula, Biosphere Reserve, Cuba*. Havana, Cuba: Scientific-Technical Editorial (in Spanish).

Clark ML, Aide TM, Riner G. 2012. Land change for all municipalities in Latin America and the Caribbean assessed from 250-m MODIS imagery (2001–2010). *Remote Sensing of Environment* **126(2)**:84–103 DOI 10.1016/j.rse.2012.08.013.

CNAP. 2013. *Plan of the national system of protected areas 2014–2020*. Havana, Cuba: Ministry of Science Technology and Environment (in Spanish).

Congalton RG. 1991. A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment* **37(1)**:35–46 DOI 10.1016/0034-4257(91)90048-B.

Crego RD, Fennessy J, Brown MB, Connette G, Stacy-Dawes J, Masiaine S, Stabach JA. 2023. Combining species distribution models and moderate resolution satellite information to guide conservation programs for reticulated giraffe. *Animal Conservation* **27(2)**:160–170 DOI 10.1111/acv.12894.

Crego RD, Stabach JA, Connette G. 2022. Implementation of species distribution models in Google Earth Engine. *Diversity and Distributions* **28(5)**:904–916 DOI 10.1111/ddi.13491.

de Lima RF, Dallimer M, Atkinson PW, Barlow J. 2013. Biodiversity and land-use change: understanding the complex responses of an endemic-rich bird assemblage. *Diversity and Distributions* **19(4)**:411–422 DOI 10.1111/ddi.12015.

Devictor V, Julliard R, Jiguet F. 2008. Distribution of specialist and generalist species along spatial gradients of habitat disturbance and fragmentation. *Oikos* **117(4)**:507–514 DOI 10.1111/j.0030-1299.2008.16215.x.

dos Santos SMB, Duverger SG, Bento-Gonçalves A, Franca-Rocha W, Vieira A, Teixeira G. 2023. Remote sensing applications for mapping large wildfires based on machine learning and time series in northwestern Portugal. *Fire: Forum for International Research in Education* **6(2)**:43 DOI 10.3390/fire6020043.

Dunn RR. 2005. Modern insect extinctions, the neglected majority. *Conservation Biology* **19(4)**:1030–1036 DOI 10.1111/j.1523-1739.2005.00078.x.

ESRI. 2016. *ArcMap 10.5.1*. Redlands, USA: Esri Inc.

Fernandez M, Williams J, Figueroa G, Graddy-Lovelace G, Machado M, Vazquez L, Perez N, Casimiro L, Romero G, Funes-Aguilar F. 2018. New opportunities, new challenges: harnessing Cuba's advances in agroecology and sustainable agriculture in the context of changing relations with the United States. *Elementa: Science of the Anthropocene* **6(8)**:76 DOI 10.1525/elementa.337.

Fielding AH, Bell JF. 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* **24(1)**:38–49 DOI 10.1017/S0376892997000088.

Fitzgerald RW, Lees BG. 1994. Assessing the classification accuracy of multisource remote sensing data. *Remote Sensing of Environment* **47(3)**:362–368 DOI 10.1016/0034-4257(94)90103-1.

Foga S, Scaramuzza PL, Guo S, Zhu Z, Dilley RD, Beckmann T, Schmidt GL, Dwyer JL, Joseph Hughes M, Laue B. 2017. Cloud detection algorithm comparison and validation for operational Landsat data products. *Remote Sensing of Environment* **194(10)**:379–390 DOI 10.1016/j.rse.2017.03.026.

Fox R, Oliver TH, Harrower C, Parsons MS, Thomas CD, Roy DB. 2014. Long-term changes to the frequency of occurrence of British moths are consistent with opposing and synergistic effects of climate and land-use changes. *Journal of Applied Ecology* **51(4)**:949–957 DOI 10.1111/1365-2664.12256.

Gebelein J. 2012. History of remote sensing and GIS as it relates to assessment of land use and land cover changes over time. In: Gebelein J, ed. *A Geographic Perspective of Cuban Landscapes*. Dordrecht: Springer Netherlands, 55–75.

Gomes VCF, Queiroz GR, Ferreira KR. 2020. An overview of platforms for big earth observation data management and analysis. *Remote Sensing* **12(8)**:1253 DOI 10.3390/rs12081253.

González-González A, Clerici N, Quesada B. 2022. A 30 m-resolution land use-land cover product for the Colombian Andes and Amazon using cloud-computing. *International Journal of Applied Earth Observation and Geoinformation* **107(1)**:102688 DOI 10.1016/j.jag.2022.102688.

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* **202(3)**:18–27 DOI 10.1016/j.rse.2017.06.031.

Greuter W, Rankin R. 2016. *Espermatófitos de Cuba: inventario preliminar. Parte II: inventario*. La Habana, Cuba: Botanischer Garten & Botanisches Museum Berlin-Dahlem.

Hanski I. 2011. Habitat loss, the dynamics of biodiversity, and a perspective on conservation. *AMBIO* **40(3)**:248–255 DOI 10.1007/s13280-011-0147-3.

Hernández MR, Cruz DF. 2016. Natural vegetation cover in National Parks of Cuba: multitemporal analysis and future variation of bioclimatic conditions. *Revista del Jardín Botánico Nacional* **37**:93–102.

Hijmans RJ. 2022. Terra: spatial data analysis. R package version 1.5–21. *Available at https://CRAN.R-project.org/package=terra*.

Izquierdo EG, Blanco JA, GeadaLópez G, Sospedra RS, González MG, Moreno BM, González AJG, Fonseca JS. 2015. Actions for the restoration of the biodiversity of forest ecosystems in Cuba. In: *Biodiversity in Ecosystems–Linking Structure and Function*. London: IntechOpen.

Jin Y, Liu X, Chen Y, Liang X. 2018. Land-cover mapping using random forest classification and incorporating NDVI time-series and texture: a case study of central Shandong. *International Journal of Remote Sensing* **39(23)**:8703–8723 DOI 10.1080/01431161.2018.1490976.

Keenan RJ, Reams GA, Achard F, de Freitas JV, Grainger A, Lindquist E. 2015. Dynamics of global forest area: results from the FAO global forest resources assessment 2015. *Forest Ecology and Management* **352(S)**:9–20 DOI 10.1016/j.foreco.2015.06.014.

Koh LP. 2007. Impacts of land use change on South-east Asian forest butterflies: a review. *Journal of Applied Ecology* **44(4)**:703–713 DOI 10.1111/j.1365-2664.2007.01324.x.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* **11(4)**:261–269 DOI 10.1016/S0959-3780(01)00007-3.

Leemans R, de Groot RS. 2003. *Millennium ecosystem assessment: ecosystems and human well-being: a framework for assessment.* Washington/Covelo/London: Island Press.

Lees DC, Smith NG. 1991. Foodplant associations of the Uraniinae (Uraniidae) and their systematic, evolutionary, and ecological significance. *Journal of the Lepidopterists' Society* **45**:296–347.

Machado MR. 2018. What's going on with land-use in Cuba?: disparate data sets and the Cuban agricultural transition. *Journal of Land Use Science* **13(4)**:439–446 DOI 10.1080/1747423X.2018.1533044.

Nazari V, Schmidt BC, Prosser S, Hebert PDN. 2016. Century-old DNA barcodes reveal phylogenetic placement of the extinct Jamaican Sunset Moth, *Urania sloanus* Cramer (Lepidoptera: Uraniidae). *PLOS ONE* **11(10)**:e0164405 DOI 10.1371/journal.pone.0164405.

Nemésio A, Silva DP, Nabout JC, Varela S. 2016. Effects of climate change and habitat loss on a forest-dependent bee species in a tropical fragmented landscape. *Insect Conservation and Diversity* **9(2)**:149–160 DOI 10.1111/icad.12154.

Nuñez-Penichet C, Barro A. 2020. Caterpillars of *Urania boisduvalii* (Uraniidae) feed on *Omphalea trichotoma* (Euphorbiaceae) fruits in Western Cuba. *The Journal of the Lepidopterists' Society* **74(2)**:124–126 DOI 10.18473/lepi.74i2.a7.

Nuñez-Penichet C, Cobos ME, Amaro JG, Barro A. 2016. Potential distribution of the genus Omphalea (Euphorbiaceae) in Cuba: approximation to its real distribution. *Garden Magazine National Botanist* **37**:165–175 (in Spanish).

Nuñez-Penichet C, Cobos ME, Barro A, Soberón J. 2019. Potential migratory routes of *Urania boisduvalii* (Lepidoptera: Uraniidae) among host plant populations. *Diversity and Distributions* **25(3)**:478–488 DOI 10.1111/ddi.12881.

Nuñez-Penichet C, Cobos ME, Checa MF, Quinde JD, Aguirre Z, Aguirre N. 2021. High diversity of diurnal Lepidoptera associated with landscape heterogeneity in semi-urban areas of Loja City, southern Ecuador. *Urban Ecosystems* **24(6)**:1155–1164 DOI 10.1007/s11252-021-01110-w.

Nuñez-Penichet C, Maita-Chamba J, Soberón J. 2023. Land-cover change in Cuba may favor biodiversity: an example using *Omphalea* (Angiosperma: Euphorbiaceae) and *Urania boisduvalii* (Lepidoptera: Uraniidae). *bioRxiv preprint* DOI 10.1101/2023.02.17.529023.

Nuñez-Penichet C, Soberón J, Osorio-Olvera L. 2023. The dispersal patterns of a migratory insect are driven by biotic interactions. *Journal of Biogeography* **50(8)**:1331–1484 DOI 10.1111/jbi.14669.

Osman MAA, Abdel-Rahman EM, Onono JO, Olaka LA, Elhag MM, Adan M, Tonnang HEZ. 2023. Mapping, intensities and future prediction of land use/land cover dynamics using google earth engine and CA- artificial neural network model. *PLOS ONE* **18(7)**:e0288694 DOI 10.1371/journal.pone.0288694.

Parra LMP, Santos FC, Negri RG, Colnago M, Bressane A, Dias MA, Casaca W. 2023. Assessing the impacts of catastrophic 2020 wildfires in the Brazilian pantanal using MODIS data and Google Earth Engine: a case study in the world's largest sanctuary for Jaguars. *Earth Science Informatics* **16**:3257–3267 DOI 10.1007/s12145-023-01080-x.

Phan TN, Kuch V, Lehnert LW. 2020. Land cover classification using Google Earth Engine and random forest classifier—the role of image composition. *Remote Sensing* **12(15)**:2411 DOI 10.3390/rs12152411.

Powers RP, Jetz W. 2019. Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nature Climate Change* **9(4)**:323–329 DOI 10.1038/s41558-019-0406-z.

QGIS.org. 2022. Geographic information system. *Available at https://qgis.org/es/site/* (accessed 13 February 2023).

R Core Team. 2020. R: a language and environment for statistical computing. *Available at http://www.R-project.org/*.

Reyes YA, Pérez M, Barrera EL, Martínez Y, Cheng KK. 2022. Thermochemical conversion processes of Dichrostachys cinerea as a biofuel: a review of the Cuban case. *Renewable and Sustainable Energy Reviews* **160**:112322 DOI 10.1016/j.rser.2022.112322.

Rippel TM, Minsavage-Davis CD, Shirey V, Wimp GM. 2023. Simple machine learning with aerial imagery reveals severe loss of a salt marsh foundation species. *Estuaries and Coasts* **46(4)**:1110–1122 DOI 10.1007/s12237-023-01192-z.

Ruiz JDS, Remond RN, Fernandez D. 2010. An analysis of the spatial colonization of scrubland intrusive species in the Itabo and Guanabo Watershed, Cuba. *Remote Sensing* **2(3)**:740–757 DOI 10.3390/rs2030740.

Sagastume AG, Cabello JJE, Hens L, Vandecasteele C. 2016. The biomass-based electricity generation potential of the province of Cienfuegos, Cuba. *Waste and Biomass Valorization* **8(6)**:2075–2085 DOI 10.1007/s12649-016-9687-x.

Sagastume AG, Cabello JJE, Huisingh D, Vandecasteele C, Hens L. 2018. The current potential of low-carbon economy and biomass-based electricity in Cuba. The case of sugarcane, energy cane and marabu (*Dichrostachys cinerea*) as biomass sources. *Journal of Cleaner Production* **172(1)**:2108–2122 DOI 10.1016/j.jclepro.2017.11.209.

Santos DC, Souza-Filho PWM, Cardoso GF, dos Santos JF. 2020. Land cover change, landscape degradation, and restoration along a railway line in the Amazon biome, Brazil. *Land Degradation & Development* **31(15)**:2033–2046 DOI 10.1002/ldr.3514.

Sheykhmousa M, Mahdianpari M, Ghanbari H, Mohammadimanesh F, Ghamisi P, Homayouni S. 2020. Support vector machine versus random forest for remote sensing image classification: a meta-analysis and systematic review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **13**:6308–6325 DOI 10.1109/JSTARS.2020.3026724.

Shiff S, Lensky IM, Bonfil DJ. 2021. Using satellite data to optimize wheat yield and quality under climate change. *Remote Sensing* **13(11)**:2049 DOI 10.3390/rs13112049.

Shimabukuro YE, Arai E, da Silva GM, Hoffmann TB, Duarte V, Martini PR, Dutra AC, Mataveli G, Cassol HLG, Adami M. 2023. Mapping land use and land cover classes in São Paulo state, southeast of Brazil, using Landsat-8 OLI multispectral data and the derived spectral indices and fraction images. *Forests* **14(8)**:1669 DOI 10.3390/f14081669.

Shimizu K, Ota T, Onda N, Mizoue N. 2022. Combining post-disturbance land cover and tree canopy cover from Landsat time series data for mapping deforestation, forest degradation, and recovery across Cambodia. *International Journal of Digital Earth* **15(1)**:832–852 DOI 10.1080/17538947.2022.2061618.

Sih A, Jonsson BG, Luikart G. 2000. Habitat loss: ecological, evolutionary and genetic consequences. *Trends in Ecology & Evolution* **15(4)**:132–134 DOI 10.1016/S0169-5347(99)01799-1.

Smith NG. 1983. Host plant toxicity and migration in the dayflying moth *Urania*. *The Florida Entomologist* **66(1)**:76–85 DOI 10.2307/3494552.

Smith NG. 1991. *Urania fulgens* (Colipato verde, Green Urania). In: Janzen DH, ed. *Historia Natural de Costa Rica*. Chicago, USA: The University of Chicago Press, 822.

Smith NG. 1992. Reproductive behavior and ecology of *Urania* (Lepidoptera: Uraniidae) moths and of their larval food plants, *Omphalea* spp. (Euphorbiaceae). In: Quintero D, Aiello A, eds. *Insects of Panama and Mesoamerica. Selected Studies*. Oxford: Oxford University Press, 576–593.

Soberón J, Peterson AT. 2005. Interpretation of models of fundamental ecological niches and species' distributional areas. *Biodiversity Informatics* **2**:1–10 DOI 10.17161/bi.v2i0.4.

Souza CM, Z. Shimbo J, Rosa MR, Parente LL, A. Alencar A, Rudorff BFT, Hasenack H, Matsumoto M, Ferreira GL, Souza-Filho PWM, de Oliveira SW, Rocha WF, Fonseca AV, Marques CB, Diniz CG, Costa D, Monteiro D, Rosa ER, Vélez-Martin E, Weber EJ, Lenti FEB, Paternost FF, Pareyn FGC, Siqueira JV, Viera JL, Neto LCF, Saraiva MM, Sales MH, Salgado MPG, Vasconcelos R, Galano S, Mesquita VV, Azevedo T. 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. *Remote Sensing* **12(17)**:2735 DOI 10.3390/rs12172735.

Stanturf JA. 2021. Landscape degradation and restoration. In: *Soils and Landscape Restoration*. Amsterdam, The Netherlands: Elsevier, 125–159.

Story M, Congalton RG. 1986. Accuracy assessment: a user's perspective. *Photogrammetric Engineering and Remote Sensing* **52**:397–399.

Stuhlmacher M, Turner IIBL, Frazier AE, Kim Y, Leffel J. 2020. Institutional shifts and landscape change: the impact of the Período Especial on Cuba's land system architecture. *Journal of Land Use Science* **15(5)**:690–706 DOI 10.1080/1747423X.2020.1829119.

Suárez JA, Beatóna PA, Faxas RE, Pérez OM. 2012. Energy, environment and development in Cuba. *Renewable and Sustainable Energy Reviews* **16(5)**:2724–2731 DOI 10.1016/j.rser.2012.02.023.

Talukdar S, Singha P, Mahato S, Shahfahad, Pal S, Liou Y-A, Rahman A. 2020. Land-use land-cover classification by machine learning classifiers for satellite observations—a review. *Remote Sensing* **12(7)**:1135 DOI 10.3390/rs12071135.

Tassi A, Gigante D, Modica G, Di Martino L, Vizzari M. 2021. Pixel- vs. object-based Landsat 8 data classification in Google Earth Engine using Random Forest: the case study of Maiella National Park. *Remote Sensing* **13(12)**:2299 DOI 10.3390/rs13122299.

Valero-Jorge A, González-De Zayas R, Matos-Pupo F, Becerra-González AL, Álvarez-Taboada F. 2024. Mapping and monitoring of the invasive species Dichrostachys cinerea (Marabú) in central Cuba using Landsat imagery and machine learning (1994–2022). *Remote Sensing* **16(5)**:798 DOI 10.3390/rs16050798.

Velastegui-Montoya A, Montalván-Burbano N, Carrión-Mero P, Rivera-Torres H, Sadeck L, Adami M. 2023. Google earth engine: a global analysis and future trends. *Remote Sensing* **15(14)**:3675 DOI 10.3390/rs15143675.

Vermote E, Justice C, Claverie M, Franch B. 2016. Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sensing of Environment* **185(8)**:46–56 DOI 10.1016/j.rse.2016.04.008.

Weber KT, Langille J. 2007. Improving classification accuracy assessments with statistical Bootstrap resampling techniques. *GIScience & Remote Sensing* **44(3)**:237–250 DOI 10.2747/1548-1603.44.3.237.

Wimberly MC, Dwomoh FK, Numata I, Mensah F, Amoako J, Nekorchuk DM, McMahon A. 2022. Historical trends of degradation, loss, and recovery in the tropical forest reserves of Ghana. *International Journal of Digital Earth* **15(1)**:30–51 DOI 10.1080/17538947.2021.2012533.

Workie TG, Debella HJ. 2018. Climate change and its effects on vegetation phenology across ecoregions of Ethiopia. *Global Ecology and Conservation* **13(11)**:e00366 DOI 10.1016/j.gecco.2017.e00366.

Zechmeister HG, Schmitzberger I, Steurer B, Peterseil J, Wrbka T. 2003. The influence of land-use practices and economics on plant species richness in meadows. *Biological Conservation* **114(2)**:165–177 DOI 10.1016/S0006-3207(03)00020-X.

Zhu Z, Woodcock CE. 2012. Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment* **118(24)**:83–94 DOI 10.1016/j.rse.2011.10.028.