Status of the invasion of Carpobrotus edulis in Uruguay based on community science records

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Abstract

Carpobrotus edulis, a highly invasive plant species repeatedly introduced along the Atlantic coast of South America, poses a significant threat to the ecological integrity of coastal dune ecosystems in Uruguay. This study used 15 years of iNaturalist records to assess the magnitude of *Carpobrotus*invasion, focusing on its distribution, abundance, and reproductive structures. Through the analysis of georeferenced and dated data, we determined that *Carpobrotus* has spread extensively, covering a 10-km-wide coastal area and occupying approximately 220 km along the Atlantic coast and the outer Rio de la Plata estuary. The presence of this species in both natural and urbanized areas highlights the urgent need for effective management strategies to mitigate its impact on native biodiversity. Utilizing community science platforms like iNaturalist has been instrumental in monitoring and documenting invasive species occurrences. However, further investigations are necessary, particularly in less sampled regions, to fully understand the extent of *Carpobrotus* invasion, especially along the eastern coast of Uruguay. To uphold conservation efforts and protect the country's coastal ecosystems, it is crucial for local authorities to reassess current practices related to exotic ornamental planting, which facilitates the spread of *Carpobrotus*. This study emphasizes the importance of robust monitoring programs in combating invasive species. By addressing the invasion of *C. edulis*, the ecological integrity of coastal dune ecosystems can be preserved, ensuring the survival of native flora and fauna along Uruguay's Atlantic coast.

Introduction

Carpobrotus edulis (Aizoaceae) is a perennial herb native to South Africa, that has been introduced to numerous temperate coastal dunes worldwide for ornamental and soil fixing purposes (Portela et al. 2023). This resilient, self-fertile plant showcases remarkable adaptability to a range of challenging conditions, including sandy soils, saline environments, intense solar radiation, and other environmental stressors (Campoy et al. 2018). It also displays extensive vegetative growth, enabling efficient colonization by its propagules (Souza-Alonso and González 2017; Roiloa 2019).

Carpobrotus edulis exhibits a highly invasive behavior, forming dense mats that significantly disrupt various components of dune ecosystems. Noteworthy consequences include impeding the regeneration of native species and inducing alterations in soil pH and organic matter levels (Portela et al. 2023). The presence of this species in invaded soils has been associated with diminished germination, survival, growth, and reproductive success of native plant species (Conser and Connor 2009). In addition to the widely reported effects on flora, this plant can impact other components of coastal dune communities (Campoy et al. 2018).

In Uruguay, the date and location of introduction of *C. edulis* remains unknown, and it is absent from early floristic reference lists for the country (e.g. Herter 1930, Legrand 1959). However, historical accounts suggest its presence in Punta del Este (Maldonado) around 75 years ago (E. Marchesi, pers. comm.). Partial surveys of coastal vegetation have mentioned its occurrence since the 2000s (Delfino and

Masciadri 2005; Castineira et al. 2013; Mai et al. 2022). In fact, local private and public stakeholders introduced *Carpobrotus edulis* for coastal resort ornamentation and dune stabilization (e.g. Puppo et al. 2020). Furthermore, due to its exceptional tolerance, its use in "green roof" installations is promoted (Rosatto et al. 2015), creating novel pathways for its expansion.

Despite the recognized risks, the extent of *Carpobrotus edulis* invasion in Uruguay remains unassessed. The lack of records in national herbarium collections hinders the study of its distribution and abundance. Only three records of the species have been collected in the Rocha Department, in the localities of Cabo Polonio and La Pedrera (F. Haretche, pers. comm.; E. Marchesi, pers. comm.; M. Valdivia, pers. comm.). Given the vulnerable state of the coastal dune system in Uruguay, threatened by urbanization, climate change, and exotic afforestation (Panario and Gutiérrez 2005), understanding the invasion's status is crucial for effective management. This study aims to report the extent of *C. edulis* invasion in Uruguay, including its geographic distribution and density patterns, using data gathered through community science efforts.

Methods

Data download

We used data sourced from iNaturalist, a comprehensive global platform for documenting species observations. This popular community science platform enables people to contribute valuable data by uploading photographs and audio recordings captured using their mobile devices, cameras or tablets. Records undergo a rigorous community-based identification process. An observation is regarded as “Research Grade” when it has location, date, media evidence, and two or more suggested identifications, more than two-thirds of which agree at a species level. iNaturalist has become a robust and influential platform for biodiversity monitoring on a global scale, gaining significant recognition and widespread adoption within the scientific community (Hochmair et al. 2020; Aristeidou et al. 2021). Notably, in the case of Uruguay, the coastal zone where *C. edulis* occurs has been extensively sampled by citizen efforts (Grattarola et al. 2020), offering valuable data for studying the invasion dynamics of this species. Research grade records of *Carpobrotus edulis* in Uruguay were downloaded on 2023-05-10 through the iNaturalist API (https://api.inaturalist.org/v1/docs/) using R (R Core Team 2023).

Spatial and temporal analysis

We quantified the number of *C. edulis* records per year, department and season. To assess the accumulation of records in space, we divided the coastal zone into grid cells of 10 x 10 km and downloaded all the records identified to the species level available on iNaturalist for this area. To quantify the level of sampling effort for the entire database and compare it to the *C. edulis* numbers, we used the curvilinearity of smoothed species accumulation curves at the grid cell level (following Grattarola et al. 2020). We assessed the spatial association between the total number of records and the number of records of *C. edulis* per grid cell and between the number of total human population and the number of records of *C. edulis* per grid cell using a corrected Pearson’s correlation for spatial autocorrelation

(following Grattarola et al. 2020). All maps were prepared using WGS 84 / UTM zone 21S projection. The code and data can be accessed at: https://github.com/bienflorencia/carpobrotus-uruguay.

Image categorization

We analyzed the photographic evidence of each record, considering photos taken at a minimum distance of approximately 1 meter. First, we classified the records based on the density of *C. edulis* plants. We distinguished between low density, characterized by isolated individuals; medium density, where the species formed spaced branches; high density, with dense mats and overlapping branches; and unable to detect, when the photo did not meet the distance criterion. Then, we examined the photos to identify reproductive structures such as buds, flowers, and fruits. To classify the records, we considered the categories established on iNaturalist: plants with visible but not open flower buds (flower budding), plants with visible flowers (flowering), plants with fruiting (fruiting), combinations of these stages (lowering/flower budding and flowering/fruiting) or records that did not provide any evidence of reproductive structures (no evidence of flowering/fruiting). Buds were recognized by their small and closed appearance, while flowers displayed vibrant yellow, white or pink petals. Fruits, resembling "figs," were identified by their ellipsoid shape and fleshy appearance. Finally, for each iNaturalist record, we examined the presence of urban structures such as streets, curbs, central flowerbeds, or parking lots on the sandy habitat. We categorized these observations using a binary criterion: "absent" for records that lacked any evidence and "present" for records that indicated the presence of the aforementioned infrastructure within a 5-meter distance radius.

Results

We observed a total of 204 records of *C. edulis* in Uruguay, made by 78 users from 2008-03-16 to 2023-05-10. The species occurs within 10 km of the coastline, occupying 22 grid cells, equivalent to *ca.* 220 km of invaded coast. The invaded area is associated with coastal dune ecosystems (Fig. 1a) and covers a portion of the Atlantic and the outer Rio de la Plata coasts. The records spanned four departments: Montevideo (12), Canelones (46), Maldonado (98), and Rocha (48) (Fig. 1b). Nineteen records (9.3% of the total) were reported within protected areas. These were Laguna Garzón and Cabo Polonio (Fig. 1b, protected areas shown in green). We did not observe records of *C. edulis* in Humedales del Santa Lucía, Isla de Flores, Laguna de Rocha, or Cerro Verde, the other coastal protected areas in Uruguay.

Records of *C. edulis* have increased strongly in the last three years (Fig. 1c). The species has been reported across all seasons, but mainly in the summer (52.9% of the total) when more people circulate through the shores and dunes.

Spatial distribution

The coastline of Uruguay has been unevenly sampled on iNaturalist (Fig. 2a). Highly surveyed areas correspond mostly to the surroundings of urbanized or protected areas (compare blue grid cells in Fig. 2a with Fig. 1b). Conversely, areas with low sampling effort are usually located within areas of low

urbanization. The spatial pattern of the national sampling effort (i.e., the total number of records) was significantly highly correlated with that of the number of *C. edulis* records ($r = 0.665$, $p < 0.001$). We observed that the western part of the *C. edulis* distribution (continuous along the coast) is located within areas of larger sampling efforts, while the gaps observed in Rocha correspond to less sampled areas (Fig 2a,b). However, this is not the case in Montevideo, an area with abundant sampling on iNaturalist but with a low number of records of *C. edulis*. This is consistent with finding very low levels of spatial correlation between the number of people living in the area and the number of *C. edulis* observations recorded ($r = 0.299$, $p < 0.05$). In this regard, we must consider that a significant portion of the dune system in the Montevideo Department has been removed or replaced (Gudynas 2000).

Density of the plants

Almost 70% of the records showed a medium (32.8%) or high (36.8 %) plant density (Table 1). Only 14.2% of the observations presented low density. The rest of the records could not be evaluated as they did not meet the minimum distance criteria.

Phenology

More than half of the *C. edulis* records did not show evidence of flowering or fruiting (57.4%). The rest of the records were divided into plants with flowering buds (1.5%), flowers (13.2%), or visible fruit (20.6%), and combinations of these phenological stages (5.4% of records were flowering and flower budding and 1.9% were flowering and fruiting). *Carpobrotus edulis* exhibited flowering primarily during the spring months, followed by fruiting in the summer. We also observed a smaller peak in flowering during the autumn, with fruits starting to appear in winter and increasing towards spring. This secondary peak in flowering during autumn suggests a potential extended reproductive period for *C. edulis*, which may contribute to its successful establishment and spread (Fig. 3).

Presence of human infrastructure

Infrastructure near the plants was observed in 22.5% of the records (Table 1). The majority of observations had no infrastructure (58.8%) and 18.6% could not be assessed because they did not meet the minimum distance criterion.

Table 1. Analysis of the photographic evidence of *Carpobrotus edulis* in Uruguay. (a) Density of plants. Low density, characterized by isolated individuals; medium density, where the species formed spaced branches; high density, with dense mats and overlapping branches; and not assessed, when the photo did not meet the distance criterion. (b) Presence of infrastructure such as streets, curbs, central flowerbeds, or parking lots on the sandy habitat. Absent for records that lacked any evidence and present for records that indicated the presence of the aforementioned infrastructure within a 5-meter distance radius.

(a)	Density	N	%
	high	75	36.8%
	medium	67	32.8%
	low	29	14.2%
	not assessed	33	16.2%
(b)	**Infrastructure**	**N**	%
	absent	120	58.8%
	present	46	22.5%
	not assessed	38	18.6%

Discussion

Carpobrotus edulis is widely distributed along the coastal dune belt of Uruguay, encompassing the Rio de la Plata estuary (Montevideo, Canelones, and parts of Maldonado Department) as well as the oceanic coast (parts of Maldonado and Rocha Departments). The process of real estate development and urbanization has led to the removal of significant patches of dune vegetation, while the afforestation with pines (*Pinus spp*) has caused further loss of these fragile ecosystems (Puppo et al. 2020). Our findings show that *Carpobrotus* is strongly invading the remaining coastal dune vegetation. A similar process is occurring with *Acacia longifolia* (Castineira et al. 2013). This alarming situation requires immediate attention and urgent actions, as it could lead to irreversible losses of important native biodiversity (Puppo et al. 2020). This invasion may affect native communities of the Uruguayan coast by replacing the coastal vegetation (Mai et al. 2022). For instance, Altuna et al. (1999) suggested that the invasion of *Carpobrotus* can lead to reduced availability of plants that serve as food resources for endemic coastal fauna.

The observed rise in *Carpobrotus* observations since 2019 is likely attributable to the increasing use of the iNaturalist app (Grattarola et al. 2020). The popularity of iNaturalist as a community science platform has greatly contributed to valuable species occurrence data collection, underscoring the importance of utilizing community science initiatives for monitoring and studying invasive species dynamics (Dimson et al. 2023). However, our analysis of iNaturalist records reveals that there are still areas with low or no occurrences, particularly in the eastern coast (i.e. Rocha Department). Further exploration is needed in these and other less sampled regions to assess the presence of *Carpobrotus*. If absent, preventive measures should be implemented to avoid its introduction.

Our observations clearly indicate a frequent association between the presence and density of *C. edulis* and human activity. This association was evident at the landscape scale, where the species is abundant

in urbanized areas (except for Montevideo), as well as at the individual site level, where it is frequently found in proximity to coastal constructions. Local governments commonly include *C. edulis* in their ornamental planting plans and may even provide artificial irrigation to ensure its growth (MZ, LRT and GL personal observations). These practices are counterproductive to Uruguay's national biodiversity strategy (MVOTMA 2016), and we strongly advocate for their urgent reassessment. Given the current awareness of the risks associated with biological invasions (Xu et al. 2014), Uruguay should critically review all activities carried out by national institutions that promote, directly or indirectly, the introduction and expansion of invasive species. Furthermore, despite the challenges posed by its removal and prevention of recolonization, as well as the significant soil alterations it causes, it is imperative to implement eradication and control of *C. edulis* in coastal dune ecosystems (Souza-Alonso and González 2017; Campoy et al. 2018; Roiloa et al. 2022). Along with this, the actions of the local authorities must be adjusted to stop using invasive species in public ornamentation and use instead, native herbaceous plants that provide the same services that are attributed to *C. edulis*.

The extensive engagement of people in coastal areas, where individuals spend considerable time, has facilitated robust data collection surpassing that found in scientific literature and collections. The information available in scientific collections tends to be biased, with little attention to alien species (Delisle et al. 2003). Moving forward, we recommend prioritizing sampling efforts in underrepresented regions, ensuring comprehensive coverage and filling data gaps. We also encourage iNaturalist users to capture reproductive structures in the photos, and to include both close-up and wider-range images to assess *C. edulis* local abundance and extension for a more comprehensive understanding of its invasion dynamics. While acknowledging the potential biases associated with community science data, iNaturalist remains a powerful tool for studying invasive species, and its continued use and engagement within the academic community are vital for advancing our knowledge in this field (Pyšek et al. 2020; Hausdorf 2023). Finally, we also want to emphasize the need to survey and monitor the threats to the coastal dunes, a very valuable and severely threatened ecosystem in Uruguay. Community science can help generate social awareness of the problem.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Data curation was performed by FG, LR-T, MZ, and GL, and analysis was performed by FG. The first draft of the manuscript was written by GL and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

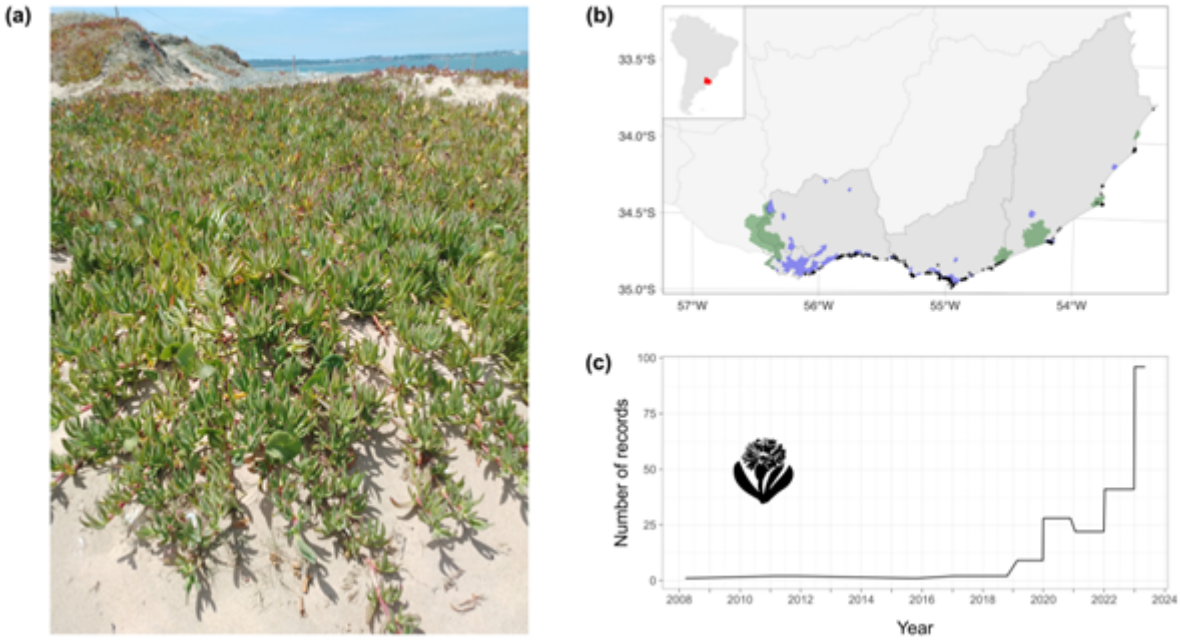

Figure 1

Records of *Carpobrotus edulis* in Uruguay downloaded from the iNaturalist platform. (a) Photo of the species forming a carpet over the coastal dunes in Maldonado Department (photo by laurillac). (b) Point occurrences (black dots) of the species in the sampled departments (from west to east, Montevideo, Canelones, Maldonado and Rocha; dark grey polygons). Protected coastal areas are shown in green and localities of more than 5 km^2 are shown in blue. (c) Number of records per year showing a steep increase over the last three years.

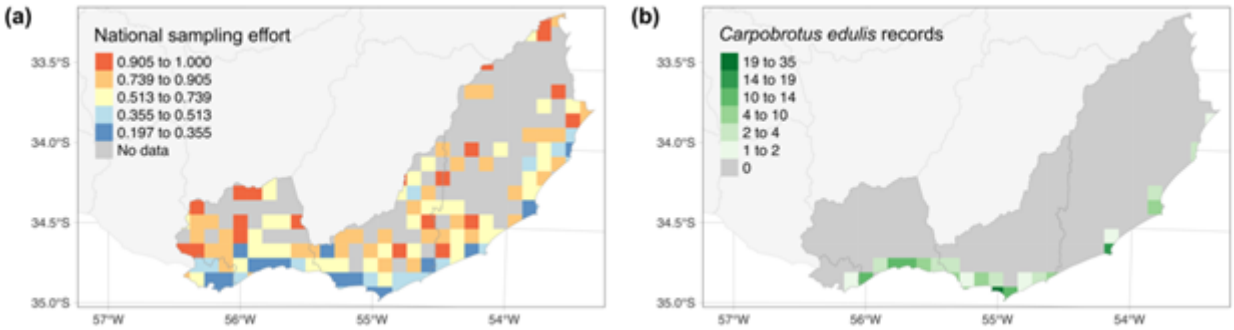

Figure 2

Spatial analysis of the records of *Carpobrotus edulis* in Uruguay downloaded from iNaturalist. (a) National sampling effort per grid cell, calculated as the degree of curvilinearity (mean slope) of the last 10% of the species accumulation curve for all records on iNaturalist. Poorly sampled grids are shown in orange while better sampled ones are shown in blue. (b) Accumulation of records of *Carpobrotus edulis* per grid cell in the departments of Montevideo, Canelones, Maldonado and Rocha is shown with a green scale (i.e., dark green grids represent higher accumulation). Grid cells are 10 x 10 km in size. Grid cells with no data are shown in dark grey.

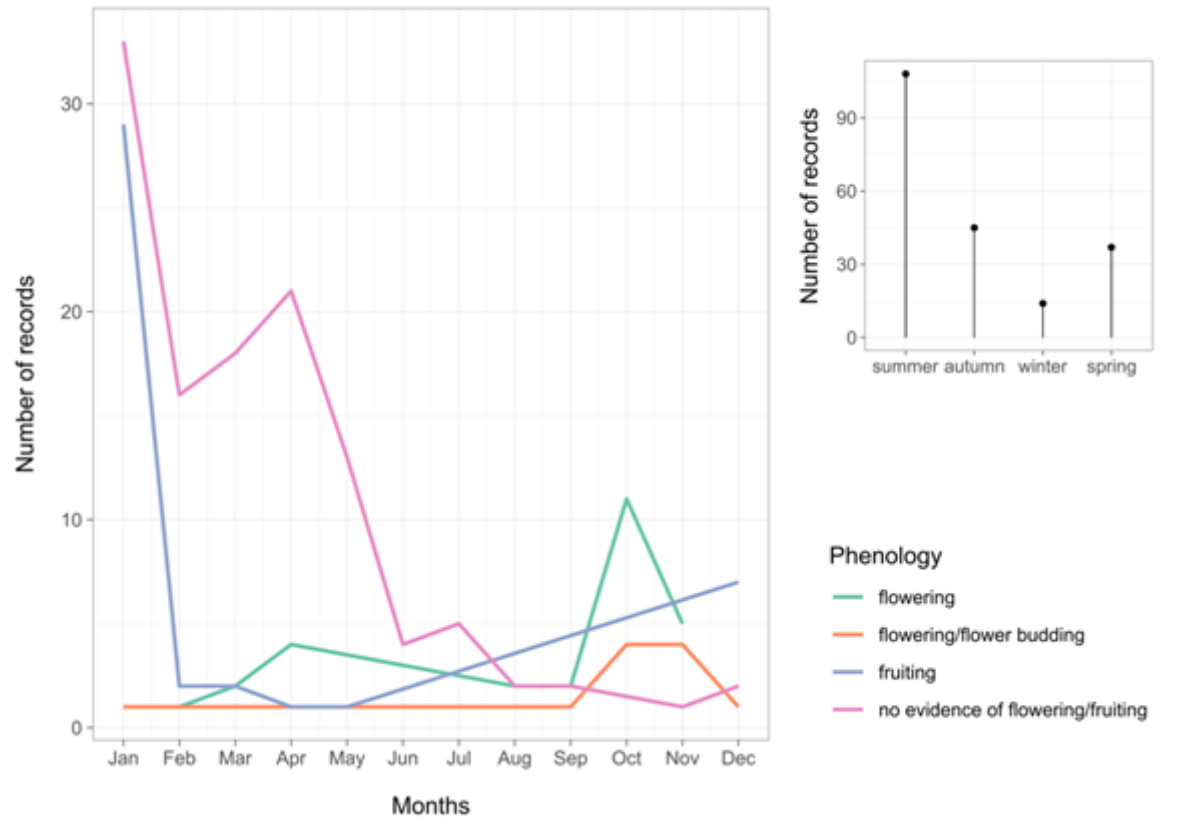

Figure 3

Phenological state of the records of *Carpobrotus edulis* in Uruguay is shown as the number of records per month. Plants with visible but not open flower buds (flower budding), plants with visible flowers (flowering), plants with fruiting (fruiting), combinations of these stages (lowering/flower budding and flowering/fruiting) or records that did not provide any evidence of reproductive structures (no evidence of flowering/fruiting). The number of records per season is shown in the top right. Summer (January, February, and March), autumn (April, May, and June), winter (July, August, and September), and spring (October, November, and December).