

Research article

Ecological and human-induced factors driving the invasion of *Neurada procumbens* in a protected coastal dune ecosystem: insights from chorological analysis within an environmental management framework



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ARTICLE INFO

Keywords:

Biological invasions monitoring
Chorological cartography
Eco-anthropic factors
Geographic information systems
Zonal statistics
Arid aeolian sedimentary system
Neurada procumbens

ABSTRACT

The management of invasive alien species represents a major challenge for the administration of protected natural areas. Understanding the factors that influence the spread of such taxa is essential for designing effective control and eradication strategies. This study investigates the interplay between abiotic, biotic, and anthropogenic factors and the increasing distribution and abundance of *Neurada procumbens*, an invasive psammophilous plant species, within a protected arid aeolian sedimentary system subject to intensive tourist activity. Based on the comparative results of two chorological inventories conducted 16 years apart, we analysed the colonization dynamics of the taxon and contrasted these with the environmental factors considered to influence the colonization success of *N. procumbens*. Chorological cartography was applied to 417 UTM grid cells, and abundance increases were categorized to support statistical analysis. Eco-anthropic variables were derived from GIS-based zonal statistics, including aeolian sediment transport, vegetation density, and trail density. Correlation analyses revealed that aeolian sedimentary dynamics are the primary limiting factor for the expansion of the species in the Maspalomas dune field (Canary Islands, Spain). Vegetation density also showed a biotic resistance effect, while trail density indicates a propagule dispersal factor, particularly in newly colonized areas near urban access points. Given its dominance in stabilized dune areas and its expansion over 16 years, the inclusion of *N. procumbens* in the Spanish Catalogue of Invasive Alien Species is recommended. These insights are currently informing management actions for the monitoring and control of this invasive alien species in the Maspalomas Dunes Special Nature Reserve.

1. Introduction

The transport of people, living organisms, and goods across distant regions is widely recognized as the primary driver of the introduction and spread of non-native species (Capinha et al., 2015; Morente-López et al., 2023). This process has led to the naturalization and proliferation of species in regions beyond their native distribution areas (Lambdon et al., 2012) particularly in ecosystems that offer favourable conditions for the establishment of their populations. In such contexts, invasive behaviour may emerge, often resulting in the displacement or extinction of native species (Bellard et al., 2016). This phenomenon, which transforms the floristic composition and structure of plant communities

(Bernard-Verdier and Hulme, 2015; Gross et al., 2013), has pronounced impacts on oceanic island territories (Kueffer et al., 2010), characterized by high levels of endemism and ecological fragility (Wood et al., 2017). In view of such circumstances, the UN Convention on Biological Diversity (UNEP, 2014) identifies invasive alien species (IAS) as one of the leading causes of biodiversity loss. In the European Union, this recognition has led to the implementation of regulations requiring member states to adopt measures for the detection, control, and eradication of IAS. Effectively undertaking of these tasks remains a significant challenge for natural area managers (Caffrey et al., 2014; Dick et al., 2014; Essl et al., 2015), particularly in ecosystems where biotic elements require protection and conservation.

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A wide range of methodologies for the monitoring of IAS have been documented in the literature, spanning from predictive approaches (Iacona et al., 2016) to techniques based on morphological detection (Carlier et al., 2020). Most studies employ synchronic approaches aimed at quantifying at one point in time the coverage of invasive species (Bradley, 2014; Nininahazwe et al., 2023), although these methods often face limitations when detecting small herbaceous plants with low coverage. Moreover, such analyses may yield error margins that restrict the formulation of effective management strategies. Diachronic approaches, involving long-term monitoring over several years, have also been employed to trace the origins and expansion patterns of IAS (Whitney and Gabler, 2008; Comin et al., 2011; Vecchio et al., 2015; Jantzi et al., 2021). Studies employing such approaches require extensive data series to analyse colonization factors based on distribution increases but often focus solely on spatial chorology without accounting for natural dynamics.

In their literature review, Sylvie and Brisson (2018) emphasize that effective IAS management must consider not only species distribution but also factors such as abiotic resistance (Catford et al., 2009), biotic constraints (Melbourne et al., 2007) and propagule dispersal capacity (Lockwood et al., 2005). Spatial statistics have proven invaluable for the modelling of ecological factors that influence species distribution and abundance (Gelfand, 2022). In this regard, anthropogenic factors should also be included among the variables shaping the distribution patterns of invasive species in areas undergoing naturalization (Xiao-Wen et al., 2006).

Based on the above, this study adopts a diachronic approach to examine the relationships between abiotic, biotic, and anthropogenic factors and the increasing distribution and abundance of *Neurada procumbens*, an invasive alien psammophilous plant species. The study area is a protected arid aeolian sedimentary system surrounded by one of Spain's largest tourist complexes, the development of which began in the 1960s (Domínguez-Mujica et al., 2011). By comparing the evolution of the species' distribution and abundance in a natural system under intense human pressure, the aim is to identify the key drivers of its spread. This information is crucial for the prioritization of areas for the implementation of control and eradication measures and for the proposal of interventions based on the factors that either limit or facilitate

its expansion in a dynamic environment such as a transgressive dune system with high visitor influx.

1.1. Study species: *Neurada procumbens*

Neurada procumbens (Fig. 1A) is an annual herbaceous plant (Turki, 2008), native to the subtropical desert belt extending from North Africa to western India (Marwat and Siddiqui, 2013). It is a ruderal psammophilous species that produces spiny discoid fruits (Fig. 1B) adapted for ectozoochorous dispersal through a mechanism that allows the fruits to adhere to the surface of animals or human footwear (Meikle, 1966; Albrecht et al., 2002) (Fig. 1C). The taxon is distributed exclusively in desert environments, restricted to sandy substrates with low organic matter content (Bhandari, 1990). The phenological cycle of this taxon is triggered by rainfall events; therefore, in dry years it persists as a seed bank. Studies conducted in its native distribution area show that the plant's germination success is sensitive to competition with other species (Kadmon, 1997) and is conditioned by the stability of the sandy substrates on which it grows (Hegazy et al., 2014).

Outside its native range, *N. procumbens* was first recorded in 2000 in the Simpson Desert, Northern Territory, Australia (Albrecht et al., 2002), from where it has spread to other sandy environments in Central Australia. Its expansion has been linked to access track networks, prompting its management and control to be declared an issue of concern (Department of Land Resource Management, n.d.). In Australia, Albrecht et al. (2002) documented that high-density coverage of *N. procumbens* in the central desert competes with the germination and growth of native species and noted the inconvenience caused by its highly adhesive fruits. Beyond these effects, the species has exhibited a strong capacity for expansion since its initial detection in the Simpson-Strzelecki Dunefields bioregion. A record from the Kalahari Desert is also available (GBIF, 2025); however, no scientific literature references associated with this location have been found. In Spain, the species has been identified in the Tabernas Desert (Andalusia) (GBIF, 2025) and in the Maspalomas Dunes Special Nature Reserve, located at the southern tip of Gran Canaria. It was first cited in this area by Sunding (1972), associated with the *Euphorbia paralias-Cyperetum capitati* plant community of the inner dunes. It is considered that the species was

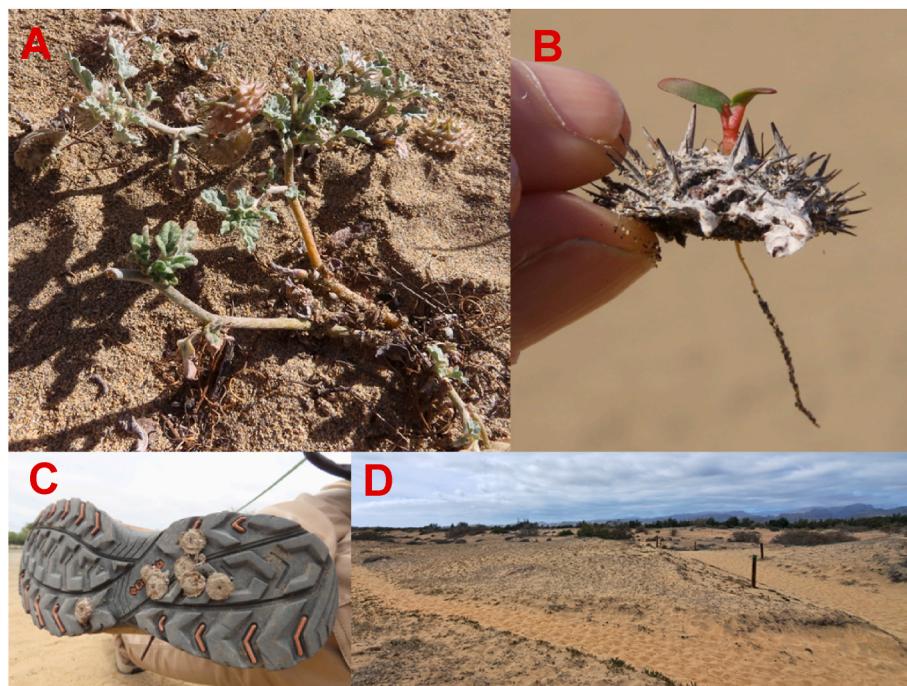


Fig. 1. A: Example of *Neurada procumbens*. B: Fruit detail. C: Shoe sole with attached fruits. D: Area with abundant presence of the taxon.

introduced to this site attached to the hooves of dromedaries brought to the island in the late 19th century for agricultural purposes (Sunding, 1972). Currently, *N. procumbens* is widespread across the stabilized dunes of Maspalomas, as confirmed by vegetation inventories conducted by Hernández Cordero (2012), and is the dominant herbaceous species in certain areas (Fig. 1D).

The Maspalomas Dunes Special Nature Reserve ($27^{\circ}44'34''N$; $15^{\circ}34'50''W$) comprises an arid transgressive dune field, subdivided into distinct units based on its aeolian sedimentary dynamics (Hernández-Cordero et al., 2015a). The area is part of the Natura 2000 network due to the presence of various EU habitat (Hernández-Cordero et al., 2015b). However, the ecosystem is subject to considerable anthropogenic pressure, having been surrounded by urban developments, infrastructure, and tourist facilities (Hernández Calvento, 2006; García-Romero et al., 2016; Hernández-Cordero et al., 2019). One of the main disturbances to the dynamics of the natural system stems from interference caused by this urban expansion, which has altered local aeolian sediment transport. More specifically, the prevailing trade wind patterns that drive dune migration in a NE-SW direction have been disrupted (Máyer Suárez et al., 2012), resulting in reduced sediment mobility in the wind shadow zones located leeward of built-up areas (Hernández Calvento, 2006; Hernández-Calvento et al., 2014). Furthermore, the touristic appeal of the dune field has led to socio-environmental conflicts arising from recreational use of the area (García-Romero et al., 2016; Peña-Alonso et al., 2019; Sanromualdo-Collado et al., 2021a). Given the adaptation of *N. procumbens* for zootochorous dispersal and the continuous flow of visitors in the reserve, including areas where recreational activities are prohibited, we hypothesized that anthropochorous transport may be facilitating the spread of *N. procumbens* (Hernández-Cordero, 2012).

Within the natural reserve, a habitat classified as therophytic grassland has been identified, characterized by psammophilous herbaceous species such as *Cyperus capitatus*, *Ononis tournefortii*, *Mairetis microsperma*, and *Lobularia libica* (Salas-Pascual et al., 2018). The plant also extends into gallery forests dominated by tarahales (*Tamarix canariensis*), a Macaronesian-exclusive habitat subtype that remains poorly studied due to the severe reduction of its natural range caused by human occupation. Within this context, the *Tamarix* community in the Maspalomas dune field stands out as one of the most representative examples under natural conditions. To date, no research has addressed potential interspecific competition in this reserve, and the persistence of this community has only been documented in the Macaronesian archipelagos in Maspalomas. *N. procumbens* predominantly colonizes areas with stable sand cover and fixed or stabilizing dunes, on nutrient-poor soils and outside interdunal depressions influenced by phreatic upwellings. Its competitive capacity against juvenile *Tamarix canariensis* remains uncertain. However, chorological surveys have revealed a noticeable absence or reduced abundance of the herbaceous species typically associated with its floristic assemblage, which contribute to the composition and structure of this habitat. Although the invasiveness and interspecific competition remain unstudied, evidence suggests that its spread leads to the displacement of these species when *N. procumbens* becomes dominant (Albrecht et al., 2002). Consequently, therophytic grasslands transition from multispecific to monospecific communities, a process that not only modifies habitat composition but also disrupts trophic chains. Therefore, similar impacts to those observed in the Maspalomas dunes are anticipated in other areas with vulnerable bio-geomorphological features where *N. procumbens* have been introduced.

2. Materials and methods

To assess the influence of environmental factors on the expansion of *N. procumbens*, a comparative analysis was performed using abundance data collected during two field campaigns conducted in 2007 and 2023. The differences in abundance values between these years served as the

basis for evaluating correlations with environmental variables at the plot level. The eco-anthropic factors considered in this study were: i) aeolian sediment transport, as an abiotic constraint, given the reduced germination capacity of the species in mobilized substrates (Hegazy et al., 2014); ii) vegetation density, as a biotic limiting factor, represented by native shrub and tree communities within the protected area; iii) trail density per plot, considering the adhesive properties of *N. procumbens* fruits and the potential role of visitor movement in propagule dispersal. Data for the chorological inventory and the analysis of the selected variables were processed using ArcGIS-Pro version 3.5.3, whereas correlation analyses were conducted with SPSS version 29.0.2.0.

2.1. Expansion of *Neurada procumbens*

Chorological cartography of the species based on abundance levels was conducted using the methodology proposed by Panareda (2000), previously applied in the initial distribution analysis of the taxon within the reserve in 2007 (Medina Santamaría, 2007). This approach enabled a diachronic comparison of both the spatial extent and abundance levels of *N. procumbens* across the study period (2007–2023). Both surveys employed a 100×100 m Universal Transverse Mercator (UTM) grid, generated in a GIS geodatabase, covering the entire reserve. To each plot was assigned an abundance level which was assigned to each plot based on field observations, resulting in a tessellation of 417 cells encompassing the full extent of the protected area. Two fields were created in the geodatabase to record abundance values following the applied methodology (Fig. 2).

As an annual species with a phenological cycle dependent on rainfall patterns (Kadmon, 1997), the field campaigns were conducted at the end of winter, coinciding with the flowering phase of the taxon. Transects were carried out in all grid cells, and abundance values were assigned as follows: 1 = isolated individuals, as well as small, spatially discontinuous clusters occurring within areas that are relatively limited in size compared to the grid; 2 = frequent presence. This category applies to grid cells with frequent occurrences, larger aggregations, and some interconnected patches, despite the overall abundance within the cell remaining low; 3 = dominant. This category is applied to grid cells where plant cover is clearly detectable across more than half of the area (Panareda, 2000). These values were integrated into the geodatabase. Differences in abundance between the two sampling years were categorized and numerically coded to support subsequent statistical analyses (Table 1). Categories were ordered based on the abundance increase observed in 2023. Cells with minimal abundance remained in the lowest categories, while those where the species became dominant were placed in the highest. Intermediate categories reflected either stable abundance or increases of one or two levels, with greater increases considered more critical from a management perspective.

2.2. Eco-anthropic factors

To evaluate abiotic constraints, aeolian sediment transport was used as a key indicator. This was assessed through topographic variation detected over the study period, using the amplitude between maximum and minimum elevation values derived from a differencing operation that produced a Digital Elevation Model of Differences (DEMoD). This metric has been validated as an indicator of sediment transport in previous studies by Hesp et al. (2021). Accordingly, Digital Elevation Models (DEMs) for the study area were obtained for the years 2009 and 2023, based on LiDAR flights conducted under the Spanish National Aerial Orthophoto Plan (PNOA). The point cloud density was 0.5 points/m² in 2009 and 5 points/m² in 2023. Ground-classified points (code 2, according to the classification of the American Society for Photogrammetry and Remote Sensing standard (ASPRS) were exported to TIN format to generate DEMs with a spatial resolution of 2 m per pixel. Zonal statistics tools in GIS were used to calculate sediment

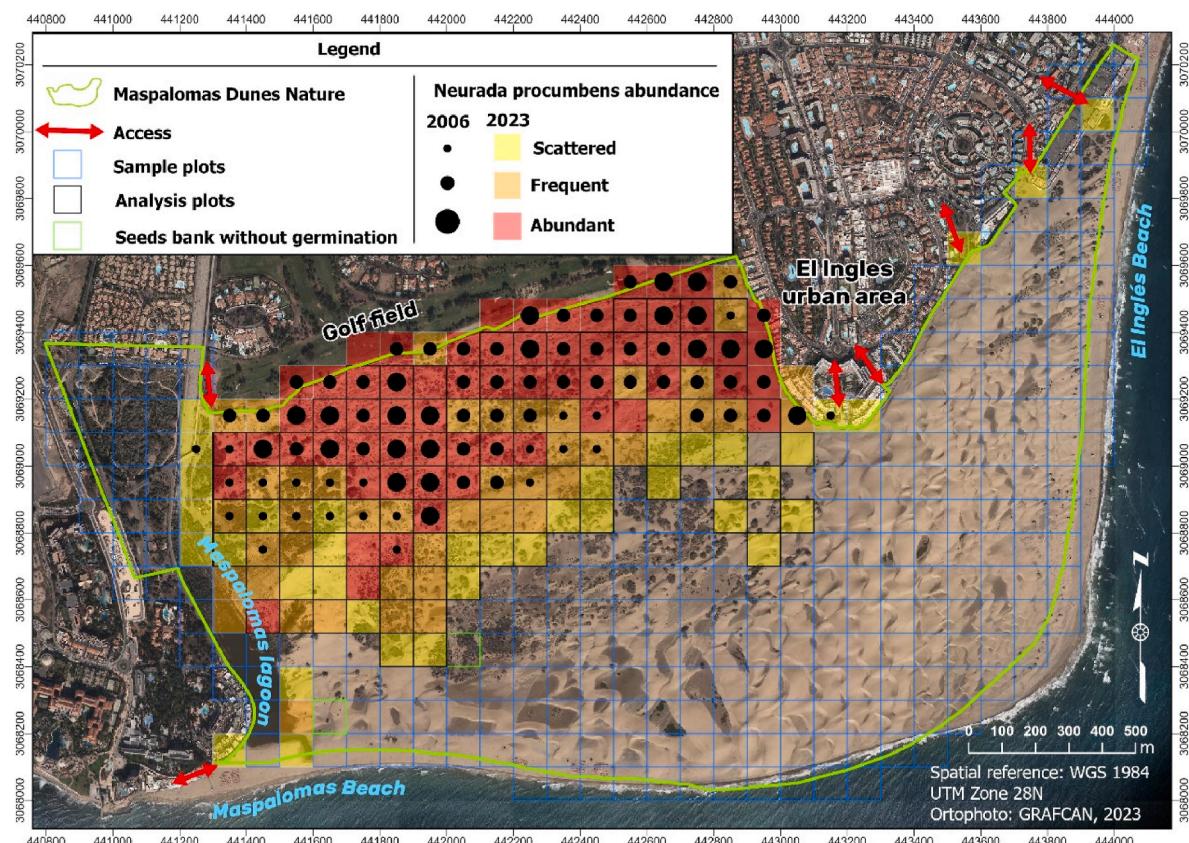


Fig. 2. Sample plots in the study area and results of the chorological cartography in both study years (2006 and 2023).

Table 1

Abundance levels according to Panareda's (2000) classification detected in both sampling years, coding of abundance increase, and number of plots per category.

Abundance 2007	Abundance 2023	Codification	No. of plots
0	1	1	34
1	1	2	4
2	2	3	12
1	2	4	13
2	3	5	30
0	2	6	19
1	3	7	6
3	3	8	21
0	3	9	7

Abundance values: 1 = localized taxon; 2 = frequent taxon; 3 = abundant taxon.

transport values for each 100 × 100-m grid cell.

To assess biotic resistance, vegetation density was classified using the methodology developed for arid aeolian sedimentary systems (García-Romero et al., 2018). Green bands from two aerial orthophotos (also used for trail mapping) were resampled to 1-m resolution. Vegetation was reclassified into 10 classes, with classes 2 and 3 representing vegetative cover. A point cloud was generated from the centroids of the output raster pixels, and a 9 × 9 rectangular neighbourhood analysis was applied to estimate vegetation density.

Given the morphological traits of *N. procumbens* fruits, which favour anthropochorous dispersal (see Fig. 1C), trail networks, both official and informal, within the main dispersal nucleus of the species were analysed as potential vectors. Trail mapping was conducted in GIS using orthophotos from 2006 to 2023, each with a spatial resolution of 10 cm/pixel. The 2006 orthophoto was generated via orthorectification of aerial frames from a LiDAR flight, while the 2023 image was corrected using AI-enhanced techniques from a GSD 11 cm/pixel flight, with a planimetric error below 0.62 m (GRAFCAN, 2024). A geodatabase of polyline

vectors was created from the 2023 orthophoto to delineate trail segments. Modifications were made to reflect changes in the trail network compared to 2006. Kernel density analyses were performed for both trail networks, individually and combined, using a planar method with a 2-m output cell size. Kernel density estimation has been widely applied to assess visitor impact in natural areas (Bumbak et al., 2024; Iqbal et al., 2024; Koju et al., 2019; Nistor et al., 2020; Porras Bernárdez et al., 2019), including service routes within the Maspalomas dune system (Pinardo-Barco et al., 2023).

2.3. Correlation analysis

Nonparametric correlation analyses were conducted using the plots employed in the chorological cartography as spatial reference units. Spearman's non-parametric correlation coefficient offers a robust starting point for exploring relationships among variables (Dormann et al., 2013; Iqbal et al., 2021; Noor et al., 2020) and has been employed in recent vegetation research (Bocianowski et al., 2024), as well as in studies examining correlations between environmental factors and even COVID-19-related indices (Mirahmadizadeh et al., 2021). Its suitability for evaluating monotonic associations between environmental variables and species distribution has led to its broad recommendation in the literature (Liebscher, 2021).

Isolated plots located outside the main expansion nucleus of the species were excluded, as well as those partially outside the dune system (e.g., adjacent to the lagoon, urban areas, or the golf course). This exclusion was justified not only by the absence of aeolian sedimentary dynamics in these plots but also to ensure that vegetation and trail density values covered the entire extent of each plot. For each plot, values for the selected variables were extracted using zonal statistics tools in a GIS environment (ArcGIS-Pro v.3.5.3). The resulting dataset was processed using SPSS statistical software v. 29.0.2.0. to calculate

bivariate correlations (Spearman) between the coded abundance increase values and the eco-anthropic variables.

3. Results

This section presents the comparative outcomes of the chorological inventories and the values obtained for the eco-anthropic factors analysed, followed by the results of the statistical correlation analyses.

3.1. Increase in distribution and abundance of *Neurada procumbens* in the Maspalomas Dunes Special Nature Reserve

An increase in both the distribution and abundance of *N. procumbens* was observed in the reserve. The species expanded from 87 grid cells (100×100 m) in 2007 to 149 cells in 2023, representing 35.7 % of the protected area (Fig. 2). Colonization has progressed southward but remains constrained by interdunal depressions with saline or moist sandy substrates, which are ecologically unsuitable for the species. Additionally, new isolated populations were identified near urban access points to the dune system.

The number of plots corresponding to the observed increases in abundance is presented in Table 1, which includes the coding assigned to the various combinations based on the changes in the abundance of the taxon detected in each plot.

3.2. Eco-anthropic factors

Two zones exhibiting significant NE-SW sediment transport were identified, corresponding to semi-stabilized dune areas. These zones showed the greatest pixel-level elevation changes over the study period,

while changes in other areas were minimal (Fig. 3A). Elevation variation ranged from increases of 9 m to decreases of 8 m, with most values concentrated between ± 1 m. Vegetation density, expressed in points/km², revealed increases in stabilized dune areas dominated by *Tamarix canariensis* communities (Fig. 3B). Conversely, decreases were noted in semi-stabilized dunes, where advancing mobile dunes buried existing vegetation. A 7 % reduction in trail network length was recorded in the main distribution area of the species, from 111,681 m in 2006 to 103,900 m in 2023. Kernel density analysis identified the zones of highest trail density and their spatial overlap across both years (Fig. 3C).

3.3. Correlations analysis

After excluding grid cells that were either partially outside the aeolian sedimentary system or isolated from the main expansion nucleus of the taxon, zonal statistics were performed for a total of 109 plots. Each plot was assigned a coded value based on the observed increase in abundance during the study period. Statistical values were extracted for topographic changes (topographic variation range in centimeters above sea level) as a proxy for aeolian sediment transport, vegetation density (dots/m²) to assess biotic resistance, and trail density (trails length/m²), as an indicator of propagule dispersal. These values were compiled and analysed using SPSS statistical software v. 29.0.2.0. to calculate Spearman bivariate correlations (significance level: $p < 0.001$ or $p < 0.05$, depending on the sample size) with the coded abundance increase values. Correlation analyses revealed significant relationships between abundance increase and several eco-anthropic factors, with the strength and significance varying across different invasion scenarios (Tables 2–5). Table 2 summarizes the most relevant correlations identified across all analysed plots. Table 3 presents the correlations

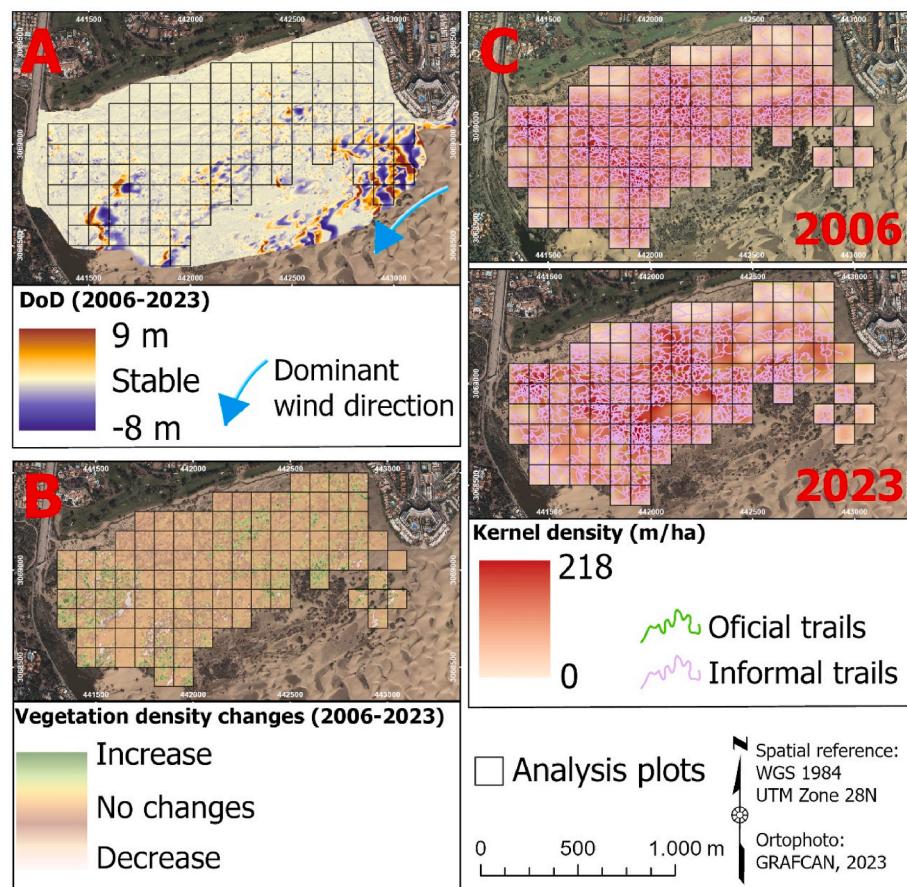


Fig. 3. Eco-anthropic factors analysed. A: sediment transport as an abiotic limiting factor; B: vegetation density as a biotic resistance factor; and C: trail density as a propagule dispersal factor.

Table 2

Bivariate correlations for all the analysis plots. Only correlations with high bilateral significance at the 0.01 level are shown.

Variable	Minimum topographic (deflation areas)	Maximum topographic (dunes)	Elevation range (aeolian sediment transport)	Vegetation minimum (sand sheet)	Vegetation maximum (<i>Tamarix</i> groves)
Spearman correlation (n = 109)	0.350	-0.436	-0.396	0.328	-0.310
Bilateral significance (0.001 level)	<0.001	<0.001	<0.001	<0.001	0.001

Table 3

Correlations for plots without maximum abundance levels. Only correlations with high bilateral significance at the 0.001 level are shown.

Variable	Minimum topographic (deflation areas)	Maximum topographic (dunes)	Elevation range (aeolian sedimentary transport)	Minimum trails accumulation (2006–2023)
Spearman correlation (n = 46)	0.493	-0.523	-0.527	0.449
Bilateral significance (level 0.001)	<0.001	<0.001	<0.001	0.002

Table 4

Correlations for plots with changes in the abundance (2006–2023). Only correlations with high bilateral significance at the 0.05 level are shown.

Variable	Minimum topographic (deflation areas)	Vegetation minimum (sand sheet)	Maximum accumulation of trails (2006–2023)
Spearman correlation n = 64	0.309	0.278	0.270
Bilateral significance (level 0.05)	0.014	0.029	0.034

Table 5

Correlations for plots in which the maximum abundance was identified only in the second survey. Only correlations with high bilateral significance at the 0.001 level are shown.

Variable	Trails range	Trails STD
Spearman correlation (n = 32)	0.482	0.547
Bilateral significance (level 0.001)	0.005	0.001

observed in plots where the maximum abundance level of *Neurada procumbens* has not yet been reached. Table 4 includes the correlations calculated exclusively for plots exhibiting changes in abundance, excluding those with stable abundance levels. Finally, Table 5 reports the correlations corresponding to plots that reached their highest abundance level following the initial chorological survey.

The variables exhibited the highest correlation coefficients with the increase in *N. procumbens* abundance were those related to the abiotic component, although significant correlations were also found with vegetation density. Regarding aeolian sediment transport, negative correlations were observed for maximum topographic values (n = 109, -0.436 correlation with <0.001 bilateral significance at level 0.001), which corresponds with dune's crests of both vegetated and transgressive dunes. Furthermore, a significant negative correlation was identified (n = 109, -0.396 correlation with <0.001 bilateral significance at level 0.001) with the elevation range, which corresponds to areas with the greatest topographic variation due to sediment movement. Conversely, positive correlations were found for minimum topographic values (n = 109, correlation of 0.350 with <0.001 bilateral significance at level 0.001), that correspond to sand sheet and deflation areas. A similar pattern was observed for vegetation density: positive correlations (n = 109, 0.328 correlation with >0.001 bilateral significance at level 0.001) were found between low vegetation density and higher abundance increases, while high vegetation density showed

significant negative correlations to the increase in the abundance of the taxon (n = 109, -0.310 correlation with 0.001 bilateral significance at level 0.001). Additionally, significant negative correlations (n = 109, -0.304 correlation with 0.001 of significance at level 0.001) were identified between trail density and aeolian sediment transport. When analysing plots where new colonization occurred but maximum abundance levels had not yet been reached (Table 3), significant correlations were found between abundance increases and trail accumulation between the two sampling years (n = 46, 0.449 correlation with 0.002 significance at level 0.001), as well as with aeolian sediment transport (n = 46, -0.527 correlation with <0.001 significance at level 0.001).

When considering only those plots where changes in abundance were recorded, 64 samples, all showing abundance increases (Table 4), correlations at the 0.05 level were also found between abundance increases and maximum trail density (n = 64, 0.270 correlation with 0.034 bilateral significance at the level 0.05). However, the highest correlations continued to be those between abundance increases and aeolian sediment transport (n = 64, 0.309 correlation with 0.014 significance at level 0.05), followed by vegetation density (n = 64, 0.278 correlation with 0.29 significance at level 0.05).

In plots where maximum abundance levels were reached after the initial survey (Table 5, 32 plots), correlations were found between the increase in taxon abundance and trail density, specifically with statistical indicators such as the range (i.e. the greatest difference in trail density between 2006 and 2023) (n = 32, 0.482 correlation with 0.005 significance at level 0.001) and the standard deviation of trail densities across both years (n = 32, correlation 0.547 with 0.001 significance at level 0.001).

4. Discussion

The hypothesis of this study was based on the premise that visitor movement acts as a vector for the dispersal of *N. procumbens* propagules, and that a comparative analysis of abundance increases and the evolution of trail density over the study period could provide evidence of this relationship, supported by field observations and previous studies (Hernández Cordero, 2012). However, the correlation obtained between these variables was comparatively lower than that found for abiotic factors. This may be due, in part, to the fact that in areas with high aeolian sediment transport, trails may not be permanent and can be erased by advancing sand, making them undetectable in those zones. This is supported by the negative correlation obtained between maximum sediment transport values and minimum trail density. Additionally, areas with intense sediment transport often contain barchan dunes—aeolian landforms with steep slopes and unstable surfaces—which are less accessible and therefore less frequently used by visitors.

Nevertheless, the presence of new populations disconnected from the main expansion nucleus and their proximity to access points to the natural system provide strong evidence of propagule dispersal from the core area to new zones. The significant correlation between plots with lower trail density and lower abundance levels may suggest that reduced visitor traffic limits the expansion of the species, while, once established, other ecological factors become more influential. The limited significance found in plots where invasion has not reached maximum levels may also be explained by the reduced sample size, which may not be statistically representative.

The geomorphological and vegetation-related factors in the Maspalomas Dune Special Nature Reserve have proven to be particularly important in determining the distribution of this invasive species, both in areas where *N. procumbens* was previously recorded and in newly colonized zones. These findings align with those of Hegazy et al. (2014), who emphasized the importance of substrate stability for the germination success of the species. This was also evident during fieldwork: even in areas with high abundance and dominance of the taxon, seed banks were observed along trails without signs of germination, while coverage was nearly continuous in adjacent areas without trails. This suggests that although human movement may facilitate propagule dispersal, substrate disturbance caused by trampling may limit germination success within the trail area, whereas establishment occurs more readily outside it. The symmetry between positive correlations of abundance increases with minimum sediment transport and negative correlations with maximum transport values indicates that aeolian dynamics are the primary controlling factor for the expansion of *N. procumbens* in the reserve. Given the sediment deficit affecting this part of the dune system (Hernández Calvento, 2006), mainly caused by urban-touristic interference with wind dynamics and dune migration (Hernández-Calvento et al., 2014; García-Romero et al., 2019), biological invasion is unlikely to be reversed without corrective measures. Moreover, as sand input continues to decline and dunes become increasingly stabilized south of the main expansion nucleus, the dominance of the taxon may intensify. Scientific and management efforts are already underway to address sediment deficits in mobile dune areas (Sanromualdo-Collado et al., 2021b), but these measures do not affect the interior zone which is most impacted by *N. procumbens* and where urban infrastructure interferes with natural processes.

The observed negative correlation between high vegetation density and the abundance of *N. procumbens* may be attributable to the alteration of sandy substrates caused by leaf litter deposits from *Tamarix canariensis* stands—the dominant plant community in the area, as well as the shading effect produced by these arboreal formations. Although managers have proposed increasing native vegetation cover as a nature-based solution to contain the expansion of the taxon, the arboreal vegetation in this sector of the dune field is highly dependent on groundwater emergence (Hernández-Cordero et al., 2015c, 2022, Hernández-Cordero et al., 2015c), which limits the feasibility of such interventions.

The chorological cartography produced in this study has been used as a guide for control and eradication measures of *N. procumbens* in the Maspalomas Dune Special Nature Reserve. However, the absence of the species from the Spanish Catalogue of Invasive Alien Species (BOE, 2013) poses challenges for the implementation of corrective actions by reserve managers. Therefore, it is considered necessary to implement control measures based on the removal of individuals during their flowering phase and to monitor the species' expansion, particularly south of the main nucleus and in areas where sand stabilization is increasing. In this regard, the inclusion of *N. procumbens* in the national catalogue of invasive alien species is recommended, based on its documented expansion in the study area. This would facilitate the adoption of urgent monitoring, control, and eradication measures, and support further research into potential biological control strategies.

Regarding the methodological approach, we consider the analysis of environmental factors based on diachronic chorological inventories to

be an appropriate method for guiding lines of action in the management of invasive alien species. Although the chorological cartography of 2023 required six days of fieldwork across 360 ha, this effort was necessary to replicate the methodology used in the initial survey. This allowed for a comparative analysis of abundance values between the two chorological studies, confirming the southward expansion of the taxon from its original distribution area and its colonization of new zones, including sectors of Playa del Inglés and Playa de Maspalomas. These new zones consist of small nuclei with isolated individuals or small clusters, demonstrating the species' colonization capacity over a 15-year period. Notably, these new populations are located near access points between the natural system and adjacent urban areas, suggesting that fruits are transported via footwear and deposited as visitors transition from sandy areas to urbanized zones.

The categorization of abundance changes between 2007 and 2023 (Table 1) presented challenges, particularly in defining intermediate categories. While the lowest (absence in 2007, isolated individuals in 2023) and highest (absence in 2007, abundant in 2023) categories were clearly indicative of minimal and maximal expansion, establishing a scale for intermediate cases was less straightforward. The severity of a biological invasion may be understood not only by the establishment and completion of the germination cycle but also by the taxon's ability to produce propagules (Sylvie and Brisson, 2018). Nonetheless, this study correlates ecological constraints with abundance levels, with maximum abundance generally considered to have the greatest biological impact (Alonso and Castro-Díez, 2015; Vantarová et al., 2023).

Access regulation in restricted areas of the reserve remains a major concern for site managers, although resource limitations continue to pose challenges. Although significant correlations were detected between the increase in taxon abundance and higher trail densities during the early stages of invasion, it is important to consider that the sample reduction performed to carry out this analysis may entail a potential decrease in statistical power. Attention must also be paid to camel rides, which, although limited in spatial extent, may contribute to propagule exchange between zones. Furthermore, while native mammal populations in the Canary Islands are limited, this study did not consider the potential role of introduced species such as European rabbits (*Oryctolagus cuniculus*) and feral cats (*Felis catus*) in fruit and seed dispersal (Dellafore et al., 2010). In this context, it would be valuable to investigate whether the rabbit population in the Maspalomas Nature Reserve plays a role in the dispersal of *Neurada procumbens*. This could involve monitoring individual movements within the reserve and mapping their spatial distribution using dung accumulation as an indicator.

The trail digitization effort in the study area was exhaustive. Although this method has been widely used in research assessing environmental and landscape impacts of informal trail creation (Ballantyne and Pickering, 2015; Barros and Pickering, 2017; Pickering and Norman, 2017), recent advances in machine learning applied to GIS are yielding promising results for automated trail network mapping (Beaupre et al., 2025; McDermaid et al., 2025). It is therefore advisable to further develop these methodologies for trail detection in natural environments. In any case, the methodological approach adopted in this study assumes that greater trail density and accumulation are associated with higher anthropogenic pressure. However, trail usage intensity was not assessed, which would require monitoring access points and visitor numbers—an effort that is difficult to implement given the size and accessibility of the area. Nevertheless, the trail density maps produced in this study are currently being used by reserve managers to determine the placement of monitoring sensors in high-use areas, including both authorized and informal trails.

These findings provide valuable insights for the management of *N. procumbens* in the areas where its presence has been recorded, all of which are characterized by unique biodiversity adapted to these specific environments. The abiotic limitation identified in this study may be particularly relevant for prioritizing management actions in locations outside the species' natural range. In this context, we suggest

prioritizing continuous management efforts in areas with low sediment mobility, while monitoring strategies may be more appropriate in zones with higher sediment transport.

In the case study presented, the vegetation contributing to biotic resistance against invasion is primarily composed of *Tamarix* groves. These tree stands have been found to coincide with access to groundwater emergence zones (Hernández-Cordero et al., 2022). Therefore, the nature-based management measure proposed by local conservation authorities—reforestation with native species—is considered unfeasible, as its success would depend on the condition and location of these groundwater sources. Nevertheless, biotic resistance-based strategies may offer useful insights for managing *N. procumbens* invasions through nature-based solutions in other areas where the species has been identified as exotic.

Additionally, the observed relationship between trail presence and the early stages of the invasion process is considered useful for implementing control measures in other regions, such as the central Australian desert, where evidence of propagule dispersal along trails has also been reported (Albrecht et al., 2002).

5. Conclusions

The methodological approach applied in this study enabled the analysis of the increase in both the distribution and abundance of an invasive exotic plant species, as well as its relationship with environmental factors that condition its expansion within the arid aeolian sedimentary system of the Maspalomas Dunes. Such information is invaluable when defining management strategies to address this issue in protected natural areas.

The results indicate that aeolian sedimentary dynamics are the primary controlling factor for the increase in abundance of *N. procumbens* within the reserve, followed by vegetation density, with additional evidence suggesting anthropochorous propagule transport.

Based on the expansion observed between 2007 and 2023, and the species' ability to form continuous coverage as the dominant herbaceous element in its stratum, the inclusion of *N. procumbens* in the Spanish Catalogue of Invasive Alien Species is strongly recommended. This would facilitate the implementation of direct control and eradication measures, supported by the documented expansion of the taxon in other areas outside its native range, such as the interior deserts of Australia.

Regarding public use of the area, the kernel density analyses allowed for the identification of problematic zones, providing key information for the adoption of visitor control and monitoring measures within the natural reserve. In this context, further research is recommended to develop automated trail network detection methodologies.

CRediT authorship contribution statement

Emilio Medina-Lorenzo: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonio I. Hernández-Cordero:** Visualization, Validation, Funding acquisition, Conceptualization. **Abel Sanromualdo-Collado:** Writing – review & editing, Formal analysis, Data curation. **Leví García-Romero:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This publication is part of the R + D + i Project PID2021-124888OB-I00, funded by the Spanish Ministry of Science and Innovation/State

Research Agency/10.13039/501100011033 and by "ERDF – A way of making Europe", and the PRECOMP01 SD-24/03 project, funded by the University of Las Palmas de Gran Canaria. We also thank the Environmental Department of the Cabildo of Gran Canaria for their collaboration in this study. Emilio Jesús Medina-Lorenzo is a predoctoral researcher funded by the Department of Universities, Science, Innovation and Culture of the Government of the Canary Islands and co-financed by the European Social Fund Plus (FPI2024010084). Leví García Romero is a postdoctoral researcher under the Catalina Ruiz program (APCR2022010005). This work was completed while the first author was a PhD student in the IOCAG Doctoral Program in Oceanography and Global Change of the University of Las Palmas de Gran Canaria (Spain).

Data availability

Data will be made available on request.

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