SOCIETÀ TOSCANA
DI
Scienze Naturali
RESIDENTE IN PISA

ATTI
DELLA
SOCIETÀ TOSCANA
DI
SCIENZE NATURALI

MEMORIE • SERIE B • VOLUME CXXXII • ANNO 2025

Edizioni ETS

ATTI DELLA SOCIETÀ TOSCANA DI SCIENZE NATURALI
MEMORIE

Via Santa Maria, 53 - 56126 Pisa

Rivista di proprietà della Società Toscana di Scienze Naturali. Fondata nel 1875, la rivista pubblica Memorie e Note originali, recensioni, corrispondenze e notiziari nel campo delle Scienze Naturali. È inviata ai soci e depositata in biblioteche corrispondenti. Tutti i contenuti dei volumi a stampa (articoli originali, comunicazioni brevi, notizie e recensioni) sono liberamente disponibili in rete, in conformità all'Open Access, sulle pagine http://www.stsn.it/en/memorie-serie-a.html (Serie A) e http://www.stsn.it/en/memorie-serie-b.html (Serie B).
Journal owned by Società Toscana di Scienze Naturali. Founded in 1875, the journal publishes original papers, short communications, news and book reviews on Natural Sciences. The Journal is sent to Società Toscana di Scienze Naturali members and deposited in selected libraries. All content of the printed version (original papers, short communications, news and book reviews) is freely available online in accordance with the Open Access at http://www.stsn.it/en/memorie-serie-a.html (Serie A) and http://www.stsn.it/en/memorie-serie-b.html (Serie B).

Gli Atti sono pubblicati in due volumi (Serie A - Abiologica, ISSN 0365-7655; Serie B - Biologica, ISSN 0365-7450) all'anno nel mese di dicembre. Possono essere pubblicati ulteriori volumi, definiti Supplementi, su temi specifici.
Atti are published yearly in two Issues (Serie A - Abiological, ISSN 0365-7655; Serie B - Biological, ISSN 0365-7450) in December. Some monographic volumes may be published as Supplementi.

Le lingue usate dalla rivista sono l'inglese o l'italiano // *The languages of the journal are English or Italian.*

Comitato scientifico (*Editorial Board*)
Serie A: G. Bianucci (Pisa, Italia), R. Blanco Chao, (Santiago de Compostela, Spagna), L. Disperati (Siena, Italia), W. Finsinger, (Montpellier, Francia), C. Montomoli (Torino, Italia), A. Oros Sršen (Zagabria, Croazia), E. Pandeli (Firenze, Italia), S. Richiano (Puerto Madrin, Argentina), E. Starnini (Pisa, Italia).
Serie B: A. Aguilella (Valencia, Spain), N.E. Baldaccini (Pisa, Italy), B. Foggi (Firenze, Italy), E. Palagi (Pisa, Italy), G. Paradis (Ajaccio, France), L. Peruzzi (Pisa, Italy), M. Zuffi (Pisa, Italy).

Direttore scientifico (*Editor in Chief*): Paolo Roberto Federici
Comitato di redazione (*Editorial Office*)
Serie A: A. Chelli (*Segretario agli Atti / Editor*)
Serie B: D. Ciccarelli (*Segretario agli Atti / Editor*), G. Astuti, A. Carta, M. D'Antraccoli, L. Peruzzi, F. Roma-Marzio

La corrispondenza deve essere inviata ai Segretari agli Atti (per la Serie A: A. Chelli, Dipartimento di Chimica, Scienze della Vita e della Sostenibilità Ambientale, Parco Area delle Scienze, 157/A - 43124 Parma, email: attia@stsn.it; per la Serie B: D. Ciccarelli, Dipartimento di Biologia, via Derna, 1 - 56126 Pisa, e-mail: attib@stsn.it).
The correspondence must be sent to Editors (for Serie A: A. Chelli, Dipartimento di Chimica, Scienze della Vita e della Sostenibilità Ambientale, Parco Area delle Scienze, 157/A - 43124 Parma, email: attia@stsn.it; for Serie B: D. Ciccarelli, Dipartimento di Biologia, via Derna, 1 - 56126 Pisa, e-mail: attib@stsn.it).

Per ulteriori informazioni / *For further information*: http://www.stsn.it/
Per informazioni editoriali / *For editorial information*: Edizioni ETS - https://www.edizioniets.com/

SOCIETÀ TOSCANA DI SCIENZE NATURALI
Fondata nel (*founded in*) 1874
Via Santa Maria, 53 - 56126 Pisa

Consiglio Direttivo (*Executive Committee*)
(2025-2026)

Presidente	G. Bedini
Vice Presidenti	M. Pappalardo, G. Petroni
Segretario generale	J. Gennai
Segretari agli Atti (Editors)	A. Chelli (Serie A), D. Ciccarelli (Serie B)
Bibliotecario	M. Zuffi
Economo-Cassiere	R. Narducci

Autorizzazione n. 17/56 del 26 luglio 1956, Trib. di Pisa
Direttore responsabile (Editor in Chief): Paolo Roberto Federici

© Copyright 2025-2026 by Società Toscana di Scienze Naturali.
Per tutti gli articoli pubblicati (articoli originali, comunicazioni brevi, notizie e recensioni) gli autori trasferiscono i diritti d'autore e di pubblicazione alla rivista.
For all published articles (original papers, short communications, news and book reviews) the authors transfer copyright and publishing rights to the Journal.

Tutti gli articoli pubblicati sugli Atti (articoli originali, comunicazioni brevi, notizie e recensioni) sono rilasciati con licenza CC BY 4.0. Essi possono essere condivisi e adattati, a condizione che venga dato credito adeguato, e possono essere utilizzati anche per scopi commerciali.
All published articles in Atti (original papers, short communications, news and book reviews) are released under CCL BY 4.0. They can be shared and adapted, provided that adequate credit is given, for any purpose, even commercially.

Atti Soc. Tosc. Sci. Nat., Mem., Serie B, 132 (2025)
pagg. 17-24; figg. 6; tabb. 1; *doi: 10.2424/ASTSN.M.B.2025.02*
CC-BY 4.0

Daniela Ciccarelli [1], Paola De Giorgi [1], Alessio Mo [2], Ugo Macchia [3]

RESURVEYING DUNE VEGETATION OF THE WWF NATURE RESERVE "DUNES OF FORTE DEI MARMI" (LUCCA): WHAT HAS CHANGED IN 20 YEARS?

Abstract - D. Ciccarelli, P. De Giorgi, A. Mo, U. Macchia, *Resurveying dune vegetation of the WWF Nature Reserve "Dunes of Forte dei Marmi" (Lucca): What has changed in 20 years?*

Coastal dune ecosystems play a crucial role in shoreline protection, erosion control, and biodiversity conservation but are increasingly threatened by human activities and climate change. In Italy, their conservation status is critical, with most classified as Unfavorable-Bad under the EU Habitats Directive. In this study, we resurveyed the last remaining coastal dune habitats in northern Tuscany (WWF Nature Reserve "Dunes of Forte dei Marmi", Lucca) approximately 20 years after an initial vegetation survey. Our findings confirmed the persistence of shifting coastal dunes and coastal dune grasslands but revealed significant changes in plant community composition, particularly within dune grasslands. This habitat exhibited increased species richness, decreased evenness, and higher dominance, alongside the colonization of ruderal species, suggesting intensified disturbance. Despite considerable anthropogenic pressures – this site is situated between two beach resorts and bordered inland by a road running parallel to the coast- the persistence of dune habitats is an encouraging result, underscoring the importance of conservation efforts. Even simple protective measures, like fencing to prevent trampling, can help safeguard these fragile ecosystems. Beyond their ecological significance, these dunes serve as a valuable site for environmental education, promoting awareness of coastal ecosystem conservation.

Key words - coastal dunes, monitoring, Habitat Directive, Tuscany, Italy

Riassunto - D. Ciccarelli, P. De Giorgi, A. Mo, U. Macchia, *Il ricampionamento della vegetazione dunale nell'oasi WWF "Dune di Forte dei Marmi" (Lucca): cosa è cambiato negli ultimi 20 anni?*

Gli ecosistemi dunali costieri svolgono un ruolo fondamentale nella protezione dei litorali, nel controllo dell'erosione costiera e nella conservazione della biodiversità, ma sono sempre più minacciati dalle attività umane e dai cambiamenti climatici. In Italia, il loro stato di conservazione è critico e, secondo la Direttiva Habitat dell'UE, la maggior parte di essi è classificato come "Sfavorevole-Cattivo". In questo lavoro, abbiamo ricampionato gli unici habitat dunali costieri presenti nella Toscana settentrionale (Oasi WWF "Dune di Forte dei Marmi", Lucca) a circa 20 anni di distanza da un primo studio della vegetazione. I nostri risultati hanno confermato la presenza della vegetazione delle dune mobili e delle zone interdunali, ma hanno messo in evidenza dei cambiamenti significativi nella composizione delle comunità vegetali, in particolare a carico della vegetazione interdunale. Questo habitat, infatti, ha registrato un aumento della ricchezza specifica, una diminuzione dell'equità e una maggiore dominanza, oltre a una crescita di specie ruderali, segnale di un'intensificazione del disturbo ambientale. Nonostante le forti pressioni antropiche – il sito si trova tra due stabilimenti balneari ed è delimitato verso l'interno da una strada che decorre parallela alla costa – la persistenza degli habitat dunali rappresenta un risultato incoraggiante, a conferma dell'importanza delle azioni di conservazione. Anche semplici misure protettive, come la recinzione per limitare il calpestio, si sono dimostrate efficaci nel preservare questi fragili ecosistemi. Oltre al loro valore ecologico, queste dune costituiscono un prezioso strumento per l'educazione ambientale, contribuendo a sensibilizzare l'opinione pubblica sull'importanza della tutela degli ecosistemi costieri.

Parole chiave - dune costiere, monitoraggio, Direttiva Habitat, Toscana, Italia

Introduction

Coastal dunes, located at the interface between land and sea known as the Coastal Transition Zone (CTZ), play a vital role in preserving shorelines and mitigating coastal erosion (Maun, 2009). These ecosystems support distinctive flora and fauna, offering services like coastal defense, groundwater storage, and habitat provision (IUCN, 2022; Pérez-Maqueo *et al.*, 2013). Coastal vegetation is exposed to various environmental stressors, including fluctuations in soil temperature and moisture, wind, water retention capacity, marine aerosols, variable salinity levels, and nutrient availability (Doing, 1985; Ciccarelli, 2014; Torca *et al.*, 2019). These factors influence habitat distribution, promoting species adapted to such dynamic conditions, particularly along the Mediterranean sandy coasts (Acosta & Ercole, 2015).

In Italy, the conservation status of coastal dune habitats is critical (Macchia *et al.*, 2005). According to the 4th Report under article 17 of the EU Habitats Directive 92/43/EEC (EEC 1992), 89% of these habitats are classified as having *Unfavorable-Bad* conservation status, while the remaining 11% are considered *Unfavorable-Inadequate* (Prisco *et al.*, 2020). The main pressures and threats stem from human activities such as resource exploitation, tourism, and urbanization, along with rising sea levels and coastal flooding (Hes-

[1] Dipartimento di Biologia, Università di Pisa, Via Derna 1, 56126, Pisa, Italy
[2] Orto e Museo Botanico, Università di Pisa, Via Luca Ghini 13, 56126, Pisa, Italy
[3] Oasi WWF Dune di Forte dei Marmi, c/o Macchia, via Ridolfi 33, 56124 Pisa Italy
Corresponding author: Daniela Ciccarelli (daniela.ciccarelli@unipi.it) - ORCID: Daniela Ciccarelli: https://orcid.org/0000-0001-9715-9779

lenfeld *et al.*, 2004; Mo *et al.*, 2021; Oppenheimer *et al.*, 2022). Effective management of these ecosystems requires a comprehensive understanding of their natural dynamics, the impact of human activities, and the stabilizing role of vegetation, ensuring a balance between habitat conservation and sustainable resource use (Alessandrini *et al.*, 2024).

To achieve this, long-term vegetation monitoring is essential (Del Vecchio *et al.*, 2015; Sperandii *et al.*, 2019). Resurveying studies, which involve resampling historically surveyed vegetation plots, are increasingly employed to track temporal changes in plant communities across various ecosystems, including coastal dune habitats (Knollová *et al.*, 2024; Acosta *et al.*, 2025). Within this framework, we focused on the last remaining stretch of coastline with dune habitats in northern Tuscany. This area is of high conservation interest, as it hosts several EU-protected coastal habitats, including "Embryonic shifting dunes" (EU 2110), "Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)" (EU 2120), "*Crucianellion maritimae* fixed beach dunes" (EU 2210), and "Coastal dunes with *Juniperus* spp." (EU *2250) (Macchia, 2000; Macchia *et al.*, 1994).Given the availability of a detailed vegetation survey conducted approximately 20 years ago (Balderi, 2003), we carried out a resampling effort to investigate temporal changes in species composition and community structure.

Materials and methods

Study site

The study area, known as the WWF Oasis "Dunes of Forte dei Marmi", is situated in the locality of Vittoria Apuana, near Forte dei Marmi (Lucca) and spans approximately 31,740 m^2. Formerly designated as an ANPIL (Local Nature Conservation Area), it represents the only remaining coastal dune systems north of Viareggio along the Tuscan coastline in Italy (Macchia *et al.*, 1994; Macchia, 2000). Covering about 500 m in length and 175 m in width, this stable coastline hosts characteristic psammophilous vegetation typical of sandy shores (Fig. 1). Due to its location between two bathing establishments, the area is highly impacted by human activity, and the natural psammophilous plant succession is interrupted by a coastal road running parallel to the shoreline. During summer, the sand dunes experience heavy trampling and beach cleaning. In response to the ecological significance of this site, WWF Italy secured a lease for the area in 1995, implementing the installation of fencing and pathways to mitigate trampling (Macchia, 2000). A comprehensive floristic and vegetational study conducted between 2002 and 2003 (Balderi, 2003) documented the presence of endemic species and habitats protected under the 92/43/EEC Directive (EEC 1992), including "Embryonic shifting dunes" (EU 2110), "Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)" (EU 2120), "*Crucianellion maritimae* fixed beach dunes" (EU 2210), and "Coastal dunes with *Juniperus* spp." (EU *2250).

Vegetation Sampling and Data Analysis

In spring 2023, we conducted a resurvey of the vegetation in this protected area by randomly placing 17 plots, each measuring 2 × 2 m^2, and visually estimating the percentage cover (range: 0-100%) of each vascular plant species. We were unable to strictly adhere to the resurveying procedure, which requires re-sampling historically surveyed vegetation plots (Acosta *et al.*, 2025), due to the lack of georeferenced positions for the old plots. However, considering the size of the study site, we deemed a random sampling approach to be both sufficient and representative. Plant nomenclature followed the Portal to the Flora of Italy (https://dryades.units.it/floritaly/).

To identify and classify plant communities, we performed a Cluster Analysis (CA). The species abundance matrix (17 plots ×30 species) was subjected to a square-root transformation to balance the highest and lowest coverage values. A similarity matrix was then constructed using the Bray-Curtis similarity index, which is appropriate for biological data with many zero values. This similarity matrix was used for CA, applying average-linkage clustering. Each plot was subsequently classified according to the European Nature Information System (EUNIS) classification (https://eunis.eea.europa.eu/habitats.jsp), a system particularly well-suited for characterizing the complex and dynamic habitat mosaics typical of dune environments, especially in areas affected by disturbance (Maccherini *et al.*, 2020). Specifically, we used the third classification level, which is generally broader than EU habitat classifications it is based primarily on physiognomic and physical attributes. All plots were categorized into two main EUNIS habitats: N14 - Mediterranean, Macaronesian and Black Sea shifting coastal dune, which includes EU habitats 2110 and 2120; N16 - Mediterranean and Macaronesian coastal dune grassland (grey dune), which includes EU habitats 2210 and 2230 (*Malcolmietalia* dune grasslands).

To assess changes in the ecological status of coastal dunes over the past two decades, we compared our findings with data from 25 plots of the same size (2 × 2 m^2) surveyed in the early 2000s (Table S1). A comparative species abundance matrix (42 plots×44 species) was constructed, and a similarity matrix was generated using the Bray-Curtis similarity index. We then applied a permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001), based on

Figure 1. Map showing costal dunes of "Dunes of Forte dei Marmi" (modified from Google Satellite). In the top right, the map of Italy with the geographical location of the study area (asterisk).

Bray-Curti's similarity matrix, to evaluate the effects of two fixed factors: EUNIS habitat type (N14 vs. N16) and sampling period (past vs. present) on plant community composition. The significance of each factor in plant species composition was tested using a null model based on 999 permutations. Cluster analysis and PERMANOVA were conducted using PRIMER v.7 and PERMANOVA+ (PRIMER-E Ltd, Plymouth, UK; Clarke & Gorley, 2015).

To analyze shifts in species richness and diversity over time, we used Hill numbers (Hill, 1973), calculated using the following equation:

$$q_D = \left(\sum_{i=1}^{s} p_i^q \right)^{\frac{1}{1-q}}$$

where is the total number of species within a plot, p_i is the abundance of a species within each plot and q takes values of 0, 1 or 2. When q = 0, ^0D represents species richness; for q = 1, ^1D equals the exponential of Shannon diversity; and when q =2, ^2D corresponds to the inverse of Simpson diversity. Hill numbers were calculated for each habitat (N14 and N16) and each time (past and present). Differences in ^0D, ^1D, and ^2D between habitats and across time were assessed using the Wilcoxon rank sum test. Box-and-whisker plots were used to visualize variations in Hill numbers across habitats and years.

Rank-abundance curves were constructed to show the relative abundance of species within each habitat, with comparisons made across time within the same habitat. Hill number calculations, Wilcox on rank sum tests, box-and-whicker plots, and rank-abundance curves were conducted using "vegan" and "ggplot2" packages within the R software framework (version 4.4.1, R Core Team, 2025).

Results

Plant Communities

A total of 30 vascular plant species were recorded across the 17 sampled plots (Table S1). Cluster analysis identified two main groups: one comprised three plots corresponding to the N14 habitat, while the re-

maining plots represented the N16 habitat (Fig. 2). PERMANOVA analysis demonstrated that both the habitat group factor and the year explained a significant proportion of the variation in species composition ($p = 0.001$). Additionally, the interaction between habitat and year was also significant ($p = 0.002$), underscoring the temporal shifts in community structure (see Table 1 for details).

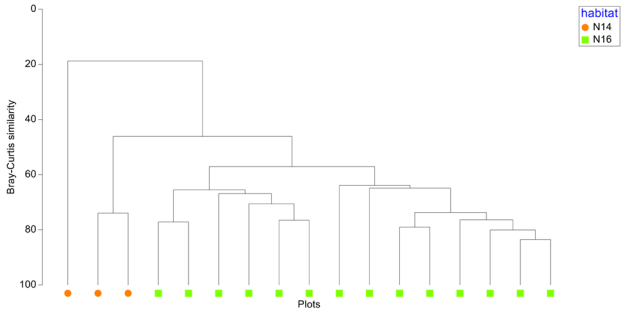

Figure 2. Dendrogram from the cluster analysis of the species abundance matrix (17 plots × 30 species), based on the Bray-Curtis similarity among plots. Different habitats are represented by distinct symbols and colors.

Table 1. Summary of PERMANOVA analysis (based on 999 permutations). Habitat group: 2 levels, fixed factor. Year group: 2 levels, fixed factor.

Source of variation	d.f.	SS	MS	Pseudo-F	P
habitat	1	9446.9	9446.9	6.3979	0.001
year	1	10946	10946	7.4135	0.001
habitat × year	1	6525.4	6525.4	4.4193	0.002
Residuals	38	56109	1476.6		
Total	41	1.02E+05			

d.f. = degrees of freedom, SS = sum of squares, MS = mean squares.

Biodiversity Indices

For the N14 habitat, the Hill numbers (D = 0, 1 or 2) did not differ significantly between the past and present (Fig. 3). Species richness (q0 Hill number) per plot increased slightly, from 7.07 ± 3.10 in the past to 8.67 ± 1.53 in the present. Similarly, exponential Shannon diversity (q1 Hill number) increased from 5.16 ± 2.35 to 7.62 ± 1.15, while the inverse Simpson diversity (q2 Hill number) showed a slight decrease from 0.26 ± 0.11 to 0.15 ± 0.02.

In contrast, all Hill numbers for N16 habitat revealed significant differences between past and present (Fig. 4). Species richness (q0) increased markedly from 8.45 ± 1.86 to 13.07 ± 2.43 ($p < 0.001$). However, exponential Shannon diversity (q1) decreased significantly from 5.92 ± 1.32 to 2.31 ± 2.64 ($p = 0.002$), while inverse Simpson diversity (q2) showed a significant increase from 0.22 ± 0.05 to 0.69 ± 0.32 ($p = 0.017$).

Rank-abundance Curves

The rank-abundance curves for the N14 habitat (Fig. 5) revealed that *Thinopyrum junceum* (L.) Á.Löve was the most abundant species in the past, with a relative abundance (rel. ab.) of 12.20, followed by *Convolvulus soldanella* L. and *Solidago virgaurea* L. subsp. *litoralis* (Savi) Briq. & Cavill. (rel. ab. = 11.41). The latter is an endemic species restricted to eastern Liguria and Tuscany (Nardi *et al.*, 2018). In the present, the most abundant species is *Lomelosia rutifolia* (Vahl) Avino & P.Caputo (rel. ab. = 17.14), followed by *Cyperus capitatus* Vand. (rel. ab. = 11.43), *Seseli tortuosum* L. (rel. ab. = 11.43), and *Thinopyrum junceum* (rel. ab. = 11.43).While the overall shape of the rank-abundance curves remains similar between the two time periods, the current dataset shows a higher dominance of the leading species compared to the past. For the N16 habitat (Fig. 6), the rank-abundance curves show more pronounced differences. In the past, *Lomelosia rutifolia* (rel. ab. = 30.60) was the dominant species, followed by *Seseli tortuosum* (rel. ab. = 23.99), and *Hypochaeris radicata* L. (rel. ab. = 7.44). In the present, the most abundant species is *Helichrysum stoechas* (L.) Moench (rel. ab. = 12.15), followed by *Seseli tortuosum* (rel. ab. = 8.88), *Cyperus capitatus* (rel. ab. = 7.48), and *Silene canescens* Ten. (rel. ab. = 6.54). Unlike N14, the rank-abundance curves for N16 exhibit steeper slopes in the past, indicating greater differences in relative abundance among the top three species. Notably, the dominant species in the past had higher relative abundance values compared to the present.

All the most abundant species identified in both habitats and across both time periods are psammophilous plants, characteristic of Mediterranean coastal dune ecosystems (Acosta & Ercole, 2015).

Discussion

The resurvey conducted at the WWF nature reserve "Dunes of Forte dei Marmi" led to several key findings: (i) vegetation sampling confirmed the continued presence of the same habitats – N14 (shifting coastal dunes) and N16 (coastal dune grasslands) – originally recorded in the early 2000s; (ii) changes in plant community composition were evident over time, particularly in terms of species abundance and dominance; (iii) habitat N16 exhibited more marked shifts in biodiversity and structure compared to N14.

The persistence of both habitat types after nearly two decades is a positive outcome, underscoring the importance of conservation efforts. Simple actions such as fencing to limit trampling can significantly contribute to the preservation of these sensitive environments. In habitat N14, diversity indices remained relatively stable over time. Nevertheless, rank-abundance curves revealed a shift in species dominance and abundance.

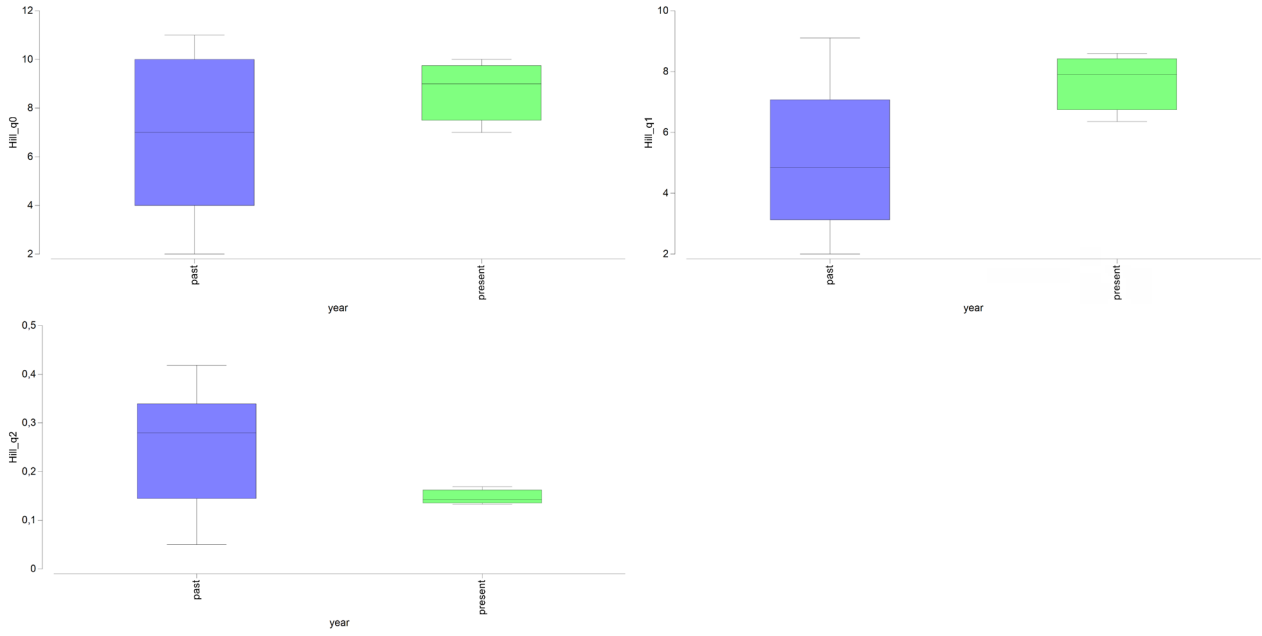

Figure 3. Boxplots of the three Hill numbers for the N14 habitat (shifting coastal dunes). Past (purple) and present (light green) plots are compared for each Hill number.

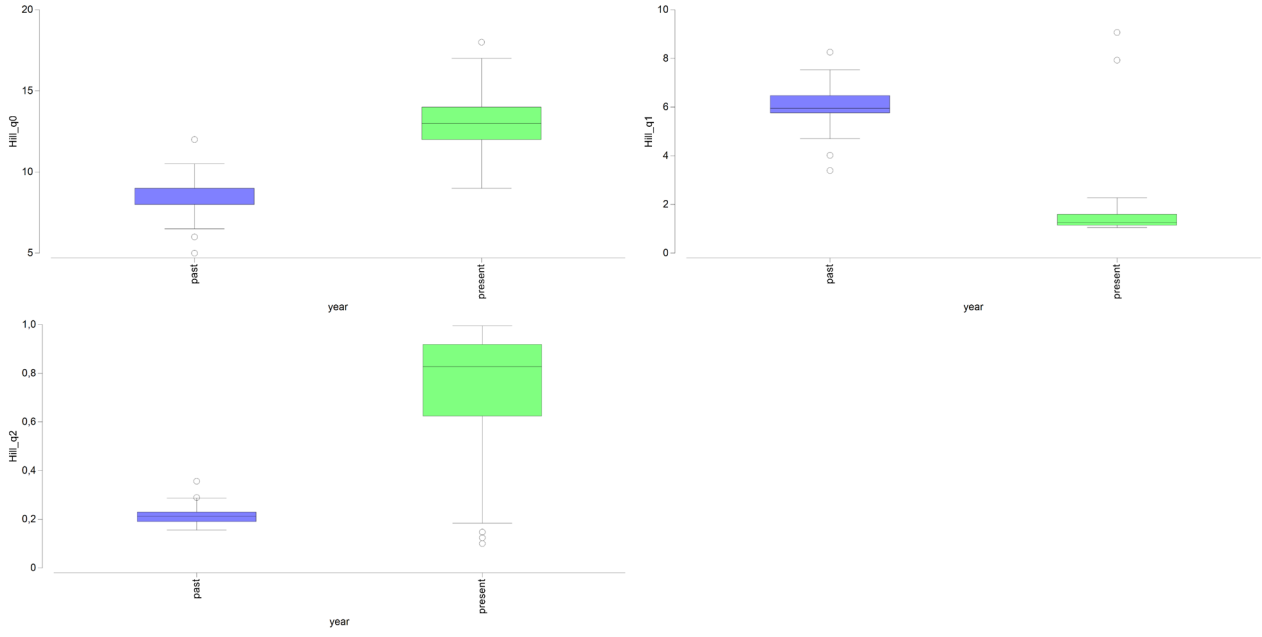

Figure 4. Boxplots of the three Hill numbers for the N16 habitat (coastal dune grasslands). Past (purple) and present (light green) plots are compared for each Hill number.

The increasing presence of *Lomelosia rutifolia* – a diagnostic species of the "*Crucianellion maritimae* fixed beach dunes" (EU 2210) – may indicate the beginning of a transition toward more mature dune vegetation. Additionally, there was an increase in species evenness (q1 Hill number) and a reduction in dominance (q2 Hill number).

In contrast, habitat N16 experienced more pronounced changes, including shifts in species composition. Rank-abundance curves suggest that, in the past, the habitat was characterized by fewer, highly dominant species. At present, those dominant species have declined, and the community now includes several new taxa, such as *Festuca fasciculate* Forssk. and

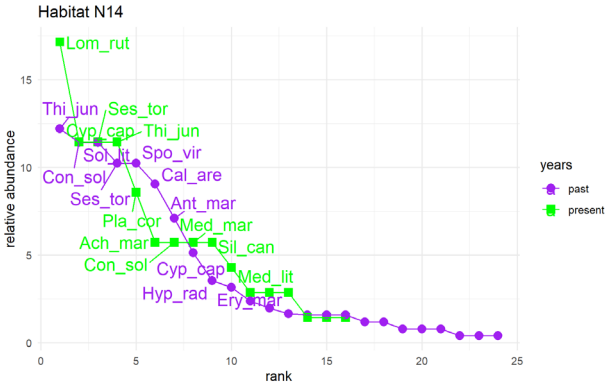

Figure 5. Range-abundance curves for the N14 habitat (shifting coastal dunes), comparing past (circle) and present (quadrat) species distribution.

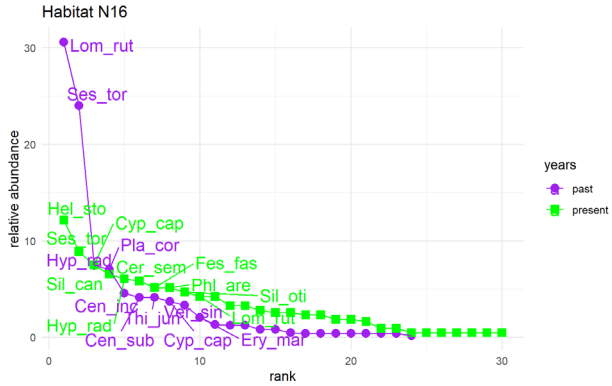

Figure 6. Range-abundance curves for the N16 habitat (coastal dune grasslands), comparing past (circle) and present (quadrat) species distribution.

Phleum arenarium L., many of which are ruderals that were not previously recorded (see Table S1). In this habitat, species richness (q0 Hill number) has significantly increased, while evenness (q1 Hill number) has decreased, and dominance (q2 Hill number) has risen. Importantly, this increase in richness is not necessarily a sign of ecological improvement, as it likely reflects the encroachment of ruderal species and the development of disturbance-driven annual grasslands. Comparable patterns have been reported in other Mediterranean coastal systems (Carboni *et al.*, 2010; Ciccarelli *et al.*, accepted).

Another aspect that warrants attention is the presence of *Yucca gloriosa* L. within the site and *Carpobrotus* sp. along its southern boundary. Both species are widely recognized as invasive aliens in Tuscan coastal ecosystems and are commonly introduced for ornamental purposes (Lazzaro *et al.*, 2020). Targeted monitoring should be implemented to track their spread and evaluate the most suitable management strategy – whether eradication, containment, or long-term control (Cini *et al.*, 2024; Lozano *et al.*, 2024).

From a methodological perspective, a limitation of this study was the inability to relocate the exact original plots. However, given the dynamic nature of dune systems, this limitation can be partially offset by ensuring adequate replication across the study area. To facilitate comparison with historical data, we limited our analysis to the original4 m² plots, a size considered appropriate for sampling herbaceous dune vegetation (Ciccarelli & Bona, 2022).

In conclusion, this coastal dune system is subject to strong anthropogenic pressure, being situated between two beach resorts and bordered in land by a road running parallel to the shoreline. As a result, natural psammophilous succession is inevitably interrupted, preventing further development of plant communities. Nonetheless, the conservation of this small remnant of coastal habitat remains important – not only for its ecological value but also as an educational resource that can raise public awareness about the significance of coastal vegetation and dune ecosystems. Long-term monitoring, public engagement, and coordinated conservation strategies will be critical to ensuring the persistence of these vulnerable systems into the future.

ACKNOWLEDGEMENTS

The authors express their gratitude to the students from University of Pisa that collaborated to sample vegetation.

REFERENCES

ACOSTA A.T.R., DI BIASE L., SARMATI S. *et al.*, 2025. *ReSurveyDunes – a data resource of resurveyed coastal dune vegetation plots in Italy.* Vegetation Ecology and Diversity 62: e139539. https://doi.org/10.3897/ved.139539

ACOSTA A., ERCOLE S. (eds), 2015. *Gli habitat delle coste sabbiose italiane: ecologia e problematiche di conservazione.* Serie Rapporti 215/2015. ISPRA, Roma.

ALESSANDRINI V., BERTONI D., RANGEL-BUITRAGO N., CICCARELLI D., 2024. *Implementing a vegetation-based risk index to support management actions in Mediterranean coastal dunes.* Ocean and Coastal Management 252: 107105. https://doi.org/10.1016/j.ocecoaman.2024.107105

ANDERSON M.J., 2001. *A new method for non-parametric multivariate analysis of variance.* Australian Ecology 26 (1): 32-46. https://doi.org/10.1111/j.1442-9993.2001.01070.pp.x

BALDERI C., 2003. *Vegetazione psammofila e retrodunale dell'Oasi WWF di Vittoria Apuana (Forte dei Marmi - Lucca).* Tesi di laurea in Scienze Naturali. Anno accademico 2002-2003. Alma Mater Studiorum, Università di Bologna.

CARBONI M., SANTORO R., ACOSTA A.T.R., 2010. *Are some communities of the coastal dune zonation more susceptible to alien plant invasion?* Journal of Plant Ecology 3 (2): 139-147. https://doi.org/10.1093/jpe/rtp037

CICCARELLI D., 2014. *Mediterranean coastal sand dune vegetation: Influence of natural and anthropogenic factors.* Environmental Management 54: 194-204. https://doi.org/10.1007/s00267-014-0290-2

CICCARELLI D., BONA C., 2022. *Exploring the functional strategies adopted by coastal plants along an ecological gradient using morpho-functional traits.* Estuaries and Coasts 45: 114-129. https://doi.org/10.1007/s12237-021-00945-y

CICCARELLI D., SAVIOZZI S., WOLFF-COUTINHO J., ORAZI D., BERTACCHI A., 2025. *Long-term vegetation dynamics and management challenges in coastal dunes: Insights from a resurvey of two Mediterranean sites in Italy.* Regional Studies in Marine Sciences (accepted).

CINI E., MARZIALETTI F., PATERNI M., BERTON A., ACOSTA A.T.R., CICCARELLI D., 2024. *Integrating UAV imagery and machine learning via Geographic Object Based Image Analysis (GEOBIA) for enhanced monitoring of* Yucca gloriosa *in Mediterranean coastal dunes.* Ocean and Coastal Management 258: 107377. https://doi.org/10.1016/j.ocecoaman.2024.107377

CLARKE K.R., GORLEY R.N., 2015. *PRIMER v7: User manual/tutorial.* Primer-E Ltd, Plymouth.

DEL VECCHIO S., PRISCO I., ACOSTA A.T.R., STANISCI A., 2015. *Changes in plant species composition of coastal dune habitats over a 20-year period.* AoB Plants 7. https://doi.org/10.1093/aobpla/plv018

DOING H., 1985. *Coastal fore-dune zonation and succession in various parts of the world.* Vegetatio 61: 65-75.

EEC, 1992. *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.* Official Journal of the European Union 206: 7-50.

HESLENFELD P., JUNGERIUS P.D., KLIJN J.A., 2014. *Chapter 20. European coastal dunes: Ecological values, threats, opportunities and policy development.* In: Martínez M.L., Psuty N.P. (eds), *Coastal dunes. Ecology and conservation*: 335-351. Springer-Verlag, Berlin.

HILL M.O., 1973. *Diversity and evenness: A unifying notation and its consequences.* Ecology 54: 427-432. https://doi.org/10.2307/1934352

IUCN, 2022. *Red list. State of the World's species*. IUCN, Gland.

KNOLLOVÁ I., CHYTRÝ M., BRUELHEIDE H. *et al.*, 2024. *ReSurveyEurope: A database of resurveyed vegetation plots in Europe.* Journal of Vegetation Science 35 (2): e13235. https://doi.org/10.1111/jvs.13235

LAZZARO L., BOLPAGNI R., BUFFA G. *et al.*, 2020. *Impact of invasive alien plants on native plant communities and Natura 2000 habitats: State of the art, gap analysis and perspective in Italy.* Journal of Environmental Management 274: 111140. https://doi.org/10.1016/j.jenvman.2020.111140

LOZANO V., MARZIALETTI F., ACOSTA A.T.R. *et al.*, 2024. *Prioritizing management actions for invasive non-native plants through expert-based knowledge and species distribution models.* Ecological Indicators 166: 112279. https://doi.org/10.1016/j.ecolind.2024.112279

MACCHERINI S., BACARO G., TORDONI E. *et al.*, 2020. *Enough is enough? Searching for the optimal sample size to monitor European Habitats: A case study from coastal sand dunes.* Diversity 12: 138. https://doi.org/10.3390/d12040138

MACCHIA U., 2000. *Un'area dunale protetta del WWF a Forte dei Marmi (LU).* Uccelli d'Italia 1-2: 81-85.

MACCHIA U., PRANZINI E., TOMEI P.E., 2005. *Le dune costiere in Italia, la natura e il paesaggio.* Ed. Felici, Pisa.

MACCHIA U., SOLDANO A., SOLDANO S., 1994. *Le dune, natura e poesia.* Poliedizioni, Euromedia, Massa.

MAUN M.A., 2009. *The biology of coastal sand dunes.* Oxford University Press, Oxford.

MO A., D'ANTRACCOLI M., BEDINI G., CICCARELLI D., 2021. *The role of plants in the face of marine litter invasion: A case study in an Italian protected area.* Marine Pollution Bulletin 169: 112544.

NARDI F.D., PUSTAHIJA F., ANDREUCCI A. *et al.*, 2018. *Does* Solidago litoralis *(Asteraceae) merit specific rank? Insights from cytogenetic, molecular and ecological data.* Phytotaxa 346 (2): 121-140. https://doi.org/10.11646/phytotaxa.346.2.1

OPPENHEIMER M., GLAVOVIC B.C., HINKEL J. *et al.*, 2022. *Sea level rise and implications for low-lying islands, coasts and communities.* In: Pörtner H.-O., Roberts D.C., Masson-Delmotte V. *et al.* (eds), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate:* 321-445. Cambridge University Press, Cambridge and New York. https://doi.org/10.1017/9781009157964

PÉREZ-MAQUEO O., MARTÍNEZ M.L., LITHGOW D., MENDOZA-GONZÁLEZ G., FEAGIN R.A., GALLEGO-FERNÁNDEZ J.B., 2013. *Chapter 18. The coasts and their costs.* In: Martínez M.L., Gallego-Fernández J.B., Hesp P.A. (eds), *Restoration of coastal dunes*: 289-304. Springer-Verlag, Berlin.

PRISCO I., ANGIOLINI C., ASSINI S. *et al.*, 2020. *Conservation status of Italian coastal dune habitats in the light of the 4th Monitoring Report (92/43/EEC Habitats Directive).* Plant Sociology 57: 55-64. https://doi.org/10.3897/pls2020571/05

R CORE TEAM, 2025. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna. http://www.R-project.org/

SPERANDII M.G., BAZZICHETTO M., GATTI F., ACOSTA A.T.R., 2019. *Back into the past: Resurveying random plots to track community changes in Italian coastal dunes.* Ecological Indicators 96: 572-578. https://doi.org/10.1016/j.ecolind.2018.09.039

TORCA M., CAMPOS J.A., HERRERA M., 2019. *Changes in plant diversity patterns along dune zonation in south Atlantic European coasts.* Estuarine, Coastal and Shelf Science 218: 39-47. https://doi.org/10.1016/j.ecss.2018.11.016

(ms. pres. 11 marzo 2025; ult. bozze 4 settembre 2025)

SUPPLEMENT S1

Table S1. Floristic inventory obtained from 25 plots (2 × 2 m^2 size) surveyed in the early 2000s (Balderi, 2003) and 17 plots surveyed in 2023.

Family	Taxonomic unit	2003	2023
Amaryllidaceae	*Pancratium maritimum* L.	×	
Asteraceae	*Achillea maritima* (L.) Ehrend. & Y.P.Guosubsp. *maritima*		×
	Ambrosia psilostachya DC.	×	
	Anthemis maritima L.	×	
	Centaurea aplolepa Moretti subsp. *subciliata* (DC.) Arcang.	×	
	Helichrysum stoechas (L.) Moench	×	×
	Hypochaeris radicata L.	×	×
	Senecio vulgaris		×
	Solidago virgaurea L. subsp *litoralis* (Savi) Briq. & Cavill.	×	
Apiaceae	*Echinophora spinosa* L.	×	×
	Eryngium maritimum L.	×	×
	Seseli tortuosum L.	×	×
Caprifoliaceae	*Lomelosia rutifolia* (Vahl) Avino & P.Caputo	×	×
Caryophyllaceae	*Cerastium semidecandrum* L.		×
	Petrorhagia saxifraga (L.) Link subsp. *saxifraga*		×
	Silene canescens Ten.	×	×
	Silene cretica L.	×	
	Silene otites (L.) Wibel subsp. *otites*		×
Chenopodiaceae	*Salsola tragus* L.	×	
Convolvulaceae	*Convolvulus soldanella* L.	×	×
Cyperaceae	*Scirpoides holoschoenus* (L.) Soják		×
Euphorbiaceae	*Euphorbia peplis* L.	×	
Fabaceae	*Medicago littoralis* Rohde ex Loisel.	×	×
	Medicago marina L.	×	×
Lamiaceae	*Clinopodium nepeta* (L.) Kuntze	×	
	Teucrium capitatum L. subsp. *capitatum*		×
Onagranaceae	*Oenothera* sp.	×	
Orobanchaceae	*Odontites luteus* (L.) Clairv. *s.l.*	×	
Plantaginaceae	*Plantago coronopus* L.	×	×
	Plantago lanceolata L.	×	×
Poaceae	*Calamagrostis arenaria* (L.) Roth subsp. *arundinacea* (Husn.) Banfi, Galasso & Bartolucci	×	
	Cenchrus spinifex Cav.	×	
	Cyperus capitatus Vand.	×	×
	Festuca fasciculata Forssk.		×
	Imperata cylindrica (L.) Raeusch.		×
	Lagurus ovatus L.	×	×
	Phleum arenarium L.		×
	Sporobolus pungens (Schreb.) Kunth	×	×
	Thinopyrum junceum (L.) Á.Löve	×	×
	Xantium orientale L.	×	
Ranunculaceae	*Clematis vitalba* L.		×
Rosaceae	*Poterium sanguisorba* L.		×
Rubiaceae	*Sherardia arvensis* L.		×
Scrophulariaceae	*Verbascum sinuatum* L.	×	×