

DataLake: a georeferenced dataset of vascular plants from freshwater lakes of central-southern Italy

Lorenzo Pinzani,^{1,2*} Dario Di Lernia,¹ Simona Ceschin^{1,2}

¹Department of Science, University of Roma Tre, Rome; ²NBFC-National Biodiversity Future Center, Palermo, Italy

Abstract

Freshwater lakes are fundamental ecosystems that provide essential ecosystem services for humans and support high plant diversity, often including specialized and rare species. Nevertheless, in Italy, botanical knowledge of lake ecosystems remains fragmented, and floristic data are scattered across heterogeneous sources. *DataLake* is a dataset designed to integrate and standardize existing floristic knowledge on aquatic and riparian vascular plants occurring in 30 natural freshwater lakes of central-southern Italy. Records included in *DataLake* derive from both literature sources and original field surveys conducted by the authors. Overall, *DataLake* comprises 5140 georeferenced floristic records referring to 213 taxa, 97 genera and 43 families. The dataset highlights a markedly uneven distribution of taxa and records among lakes, with large tectonic and volcanic basins accounting for the highest floristic richness and number of records. The taxonomic composition is dominated by Cyperaceae, Potamogetonaceae and Juncaceae, while at the species level *Myriophyllum spicatum* L., *Ceratophyllum demersum* L., *Phragmites australis* (Cav.) Trin. ex Steud., *Potamogeton perfoliatus* L. and *Stuckenia pectinata* (L.) Börner are the most frequently recorded taxa. A substantial proportion of taxa is included in regional (39% of the dataset) and national (10.8%) conservation risk categories, underlining the role of lacustrine ecosystems as important reservoirs for plant species of conservation concern. Alien species were recorded in 14 lakes, and among these, 12 taxa are classified as invasive, including *Paspalum distichum* L., *Elodea canadensis* Michx. and *Bidens frondosa* L.. Biological and chorological spectra reflect the strong ecological dependence of lacustrine plant species on hydrological conditions, with dominance of hydrophytes and helophytes and multizonal taxa. By integrating heterogeneous floristic data into a single, coherent and openly accessible resource, *DataLake* provides a solid reference base for future floristic research, as well as for supporting long-term monitoring activities and actions aimed at conserving natural Mediterranean freshwater lake ecosystems.

Key words: freshwater lakes; floristic dataset; Mediterranean region; biodiversity data; aquatic plants; riparian plants.

Correspondence to: lorenzo.pinzani@uniroma3.it

Introduction

Inland water ecosystems, such as freshwater lakes, are unique and fundamental ecosystems as they provide essential ecosystem services for humans and preserve high biodiversity (Wetzel, 2001; Kalf, 2002). Despite their importance, lake ecosystems are highly vulnerable environments, and the conservation of their biodiversity is seriously threatened by hydrological alteration, eutrophication, water pollution, bank modification and biological invasions (Jeppesen *et al.*, 2010; Bornette and Puijalon, 2011).

Despite the numerous botanical studies conducted on Italian natural freshwater lakes, floristic data on aquatic and riparian plants of these lakes remains fragmentary and unevenly accessible, particularly in the central and southern Italian regions. The available data, often characterized by low spatial accuracy, are scattered among historical publications, dated records, local studies, grey literature and taxonomic treatments targeting specific taxa. As a result, floristic knowledge is often limited to species lists that simply indicate the presence of a species in a lake without specifying its distribution and spatial frequency. Recent studies have attempted to collect and

update scattered floristic knowledge into single contributions focusing on a subset of natural lakes in Italy, particularly Italian volcanic lakes (Pinzani *et al.*, 2025a, 2025b).

In this context, the elaboration of a georeferenced floristic dataset that includes all available floristic data on natural freshwater lakes of different origins in central and southern Italy would represent a fundamental step towards a comprehensive botanical knowledge of these lakes. Recent efforts have similarly focused on integrating vegetation data from Italian freshwater systems, such as the PONDY database on vegetation of Italian ponds (Cannucci *et al.*, 2025), highlighting the growing importance of structured and accessible datasets on biodiversity of inland water ecosystems. Within this framework, *DataLake* was developed as a database containing all available floristic data on aquatic and riparian vascular plants from 30 natural freshwater lakes in central-southern Italy. *DataLake* was created by integrating original field data with records extracted from available botanical literature. Particular attention was paid to spatial data relating to single species recorded, georeferencing them to define as accurately as possible the distribution of each species at each lake considered, without being limited to indicating their presence/absence in each lake.

METHODS

Study area

The dataset includes floristic records from 30 freshwater lakes located in central-southern Italy (Fig. 1). The study area spans a wide latitudinal range encompassing peninsular Italy and includes lakes of different origins: volcanic, karst, glacial, alluvial, tectonic and landslide-dammed lakes (Tab. 1). Only natural lakes were considered, excluding artificial reservoirs and heavily modified water

bodies, paying to attention on systems where the plant record reflects the natural ecological gradients rather than recent engineering interventions.

Lake selection was primarily driven by the availability of floristic data in botanical literature. For each lake, all accessible floristic sources referring to aquatic and riparian vascular plants surveyed were screened, with no temporal restriction, allowing the inclusion of both historical and recent records for each lake, in addition to original data collected in the field by the authors.

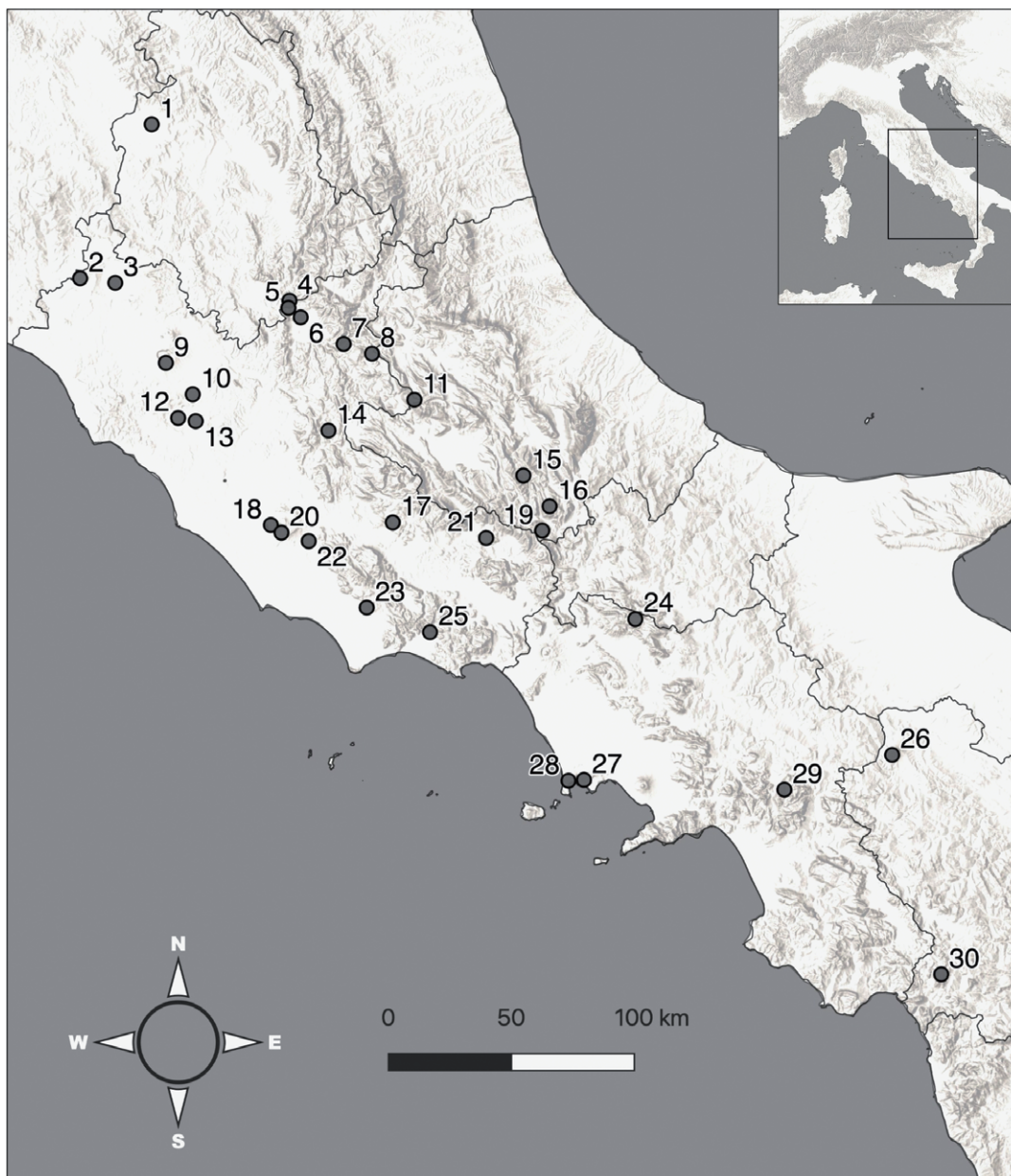


Fig. 1. Location of the 30 natural freshwater lakes included in *DataLake* across central-southern Italy. Lake numbering follows a north-south latitudinal gradient: 1. Trasimeno; 2. Mezzano; 3. Bolsena; 4. Piediluco; 5. Ventina; 6. Lungo-Ripasottile; 7. Paterno; 8. Rascino; 9. Vico; 10. Monterosi; 11. Duchessa; 12. Bracciano; 13. Martignano; 14. Percile; 15. Scanno; 16. Pantaniello; 17. Canterno; 18. Albano; 19. Vivo; 20. Nemi; 21. Posta Fibreno; 22. Giulianello; 23. Vescovo; 24. Matese; 25. Sette Cannelle; 26. Monticchio; 27. Astroni; 28. Averno; 29. Laceno; 30. Laudemio.

Data sources and selection

To ensure that the dataset included only vascular plant species strictly linked to lake ecosystem, Ellenberg autoecological index values for humidity (I_H) (Ellenberg *et al.*, 1992) were applied as species selection criterion. The values adapted to the Italian vascular flora by Guarino and La Rosa (2019) were considered. On a scale of increasing hydrophilicity ranging from 1 to 12, only taxa with $I_H \geq 8$ were retained, corresponding to species ecologically linked to aquatic, semi-aquatic or riparian habitats. This threshold excludes facultative or moderately hygrophilous plants, focusing instead on taxa whose distribution and persistence depend directly on permanent water or high soil humidity.

Taxonomic nomenclature of the species followed Bartolucci *et al.* (2024) and Galasso *et al.* (2024), with updates from the Portal of the Flora of Italy (2025). Synonyms and outdated names reported in the original sources were harmonized accordingly, allowing the integration of historical and recent records under a unified taxonomic framework thereby ensuring consistency among heterogeneous sources. Life forms and chorotypes were attributed to each species following Pignatti *et al.* (2017-2019). In addition, conservation status was attributed according to the National Red Lists (Rossi *et al.*, 2013, Orsenigo *et al.*, 2020) and Regional Red Lists (Conti, 1997), while endemism status was assigned following Bartolucci *et al.* (2024).

Georeferencing

All species records included in *DataLake* were georeferenced to ensure spatial consistency and usability for spatial analyses. Original field data were georeferenced in situ using GPS devices, providing high spatial accuracy. Bibliographic records were georeferenced based on locality descriptions reported in the original sources. In the case of historical data, when possible, locality information was cross-validated with contemporary maps to reduce spatial uncertainty and to assign coordinates consistent with current geographic references.

Georeferencing was carried out with particular attention to spatial accuracy. For each record, an explicit estimate of spatial uncertainty was assigned and stored, allowing differences in positional precision among records to be documented and accounted for in subsequent analyses. Seven spatial accuracy classes were defined (100, 500, 1000, 2000, 5000, 6000 and 7000 m), reflecting increasing levels of uncertainty associated with the original data source and the level of detail provided in the locality description.

When records referred generically to a lake without further spatial details (e.g., Lake Bracciano), geographic coordinates were assigned to the centroid of the lake polygon. In these cases, spatial accuracy was estimated using the mean radius of the lake calculat-

Tab. 1. For each of the 30 natural freshwater Italian lakes included in *DataLake*, geographic information (Italian region, latitude and longitude), geological origin, elevation, surface and floristic richness are reported. The floristic richness refers to the number of taxa and records of vascular plants.

Lake	Region	Coordinates	Origin	Elevation (m)	Surface (km ²)	Taxa (n)	Record (n)	Reference (n)
Trasimeno	Umbria	43.144, 12.107	Tectonic	257	128.0	144	1577	41
Piediluco	Umbria	42.533, 12.758	Alluvial	375	1.58	54	67	2
Mezzano	Lazio	42.611, 11.769	Volcanic	452	0.9	52	154	10
Bolsena	Lazio	42.595, 11.935	Volcanic	305	113.0	64	296	13
Ventina	Lazio	42.508, 12.753	Alluvial	378	0.12	26	49	12
Lungo - Ripasottile	Lazio	42.475, 12.811	Alluvial	370	1.4	43	52	5
Paterno	Lazio	42.382, 13.014	Karst	430	0.03	1	2	2
Rascino	Lazio	42.348, 13.148	Karst	1146	0.1	24	65	7
Vico	Lazio	42.316, 12.174	Volcanic	510	12.9	84	668	14
Monterosi	Lazio	42.206, 12.301	Volcanic	243	0.3	51	126	8
Duchessa	Lazio	42.187, 13.348	Glacial	1788	0.04	5	9	0
Bracciano	Lazio	42.123, 12.232	Volcanic	164	57.5	85	473	19
Martignano	Lazio	42.112, 12.315	Volcanic	207	2.26	35	257	11
Percile	Lazio	42.079, 12.942	Karst	650	9	20	35	4
Canterno	Lazio	41.756, 13.246	Karst	541	1.6	31	64	9
Albano	Lazio	41.747, 12.670	Volcanic	293	5.9	47	138	9
Nemi	Lazio	41.720, 12.720	Volcanic	316	1.7	39	200	10
Posta Fibreno	Lazio	41.701, 13.687	Karst	288	0.3	71	204	14
Giulianello	Lazio	41.690, 12.849	Volcanic	235	0.12	26	51	4
Vescovo	Lazio	41.455, 13.123	Karst	30	0.05	15	30	5
Sette Cannelle	Lazio	41.368, 13.422	Karst	115	0.04	11	14	3
Matese	Campania	41.414, 14.392	Karst	1014	5.0	47	218	3
Astroni	Campania	40.842, 14.149	Volcanic	116	0.3	15	32	7
Averno	Campania	40.839, 14.076	Volcanic	2	0.55	13	22	7
Laceno	Campania	40.807, 15.096	Karst	1050	0.2	5	5	0
Monticchio	Basilicata	40.931, 15.605	Volcanic	823	0.54	71	307	9
Laudemio	Basilicata	40.143, 15.837	Glacial	1525	0.02	5	9	2
Scanno	Abruzzo	41.921, 13.863	Landslide	922	0.93	4	5	2
Pantaniello	Abruzzo	41.813, 13.987	Glacial	1818	0.03	8	8	2
Vivo	Abruzzo	41.727, 13.952	Glacial	1591	0.05	3	3	2

ed from its surface area, in order to represent the maximum distance between the assigned point and any potential original observation site along the lake perimeter. This approach was applied consistently to all those plant records whose original source did not provide more precise spatial information. For large lakes (e.g., Lake Bolsena and Lake Trasimeno), this resulted in spatial uncertainty values of several kilometers.

DataLake structure

DataLake is organized as a tabular database developed in Microsoft Excel (Office 365), in which each row represents a single georeferenced record of a vascular plant taxon at a given lake. In this context, a record is defined as a single georeferenced report of a plant taxon associated with metadata (e.g., source, date, spatial uncertainty). Records derive from both bibliographic sources and original field surveys and are integrated within a unified structure that preserves information on data provenance.

DataLake includes two main Excel sheets: record and metadata sheets. The “record sheet” contains floristic records accompanied by information related to taxonomic identity, spatial coordinates, collection time, record source and some characteristics on the taxa (life form, chorotype, Ellenberg indicator value for humidity, alien status, IUCN categories). The “metadata sheet” includes meaning, units and reference sources of all database fields reported in the “record sheet”.

This database structure allows for the integration of floristic

data recorded at different times and with different spatial accuracy within the same coherent information framework. It also supports the possibility of filtering, aggregating and analyzing data at multiple levels. The full matrix with all collected data is deposited in the Zenodo repository (10.5281/zenodo.18630469) (Pinzani *et al.*, 2026).

RESULTS AND DISCUSSION

DataLake comprises 5140 georeferenced records of vascular plants recorded in 30 natural freshwater lakes of central-southern Italy (Fig. 1, Tab. 1). Of these, 767 records (15%) derive from unpublished field data collected by the authors, whereas the remaining part (85%) were extracted and georeferenced from 135 bibliographic references (*List SI*). The temporal distribution of records shows a marked increase in sampling intensity from the second half of the 20th century onwards, with a peak in the most recent decades (Fig. 2). Richness of taxa and records is unevenly distributed among the investigated lakes and, more clearly, among lake types. Volcanic lakes account for the highest number of records (n=2724), followed by tectonic lakes (n=1577), whereas karst (n=637) and alluvial lakes (n=168) contribute substantially fewer records. Glacial (n=29) and landslide-dammed lakes (n=5) are represented by very limited data overall (Tab. 1). This pattern primarily reflects differences in data availability among lake origins. In addition, records for tectonic lakes are largely concentrated

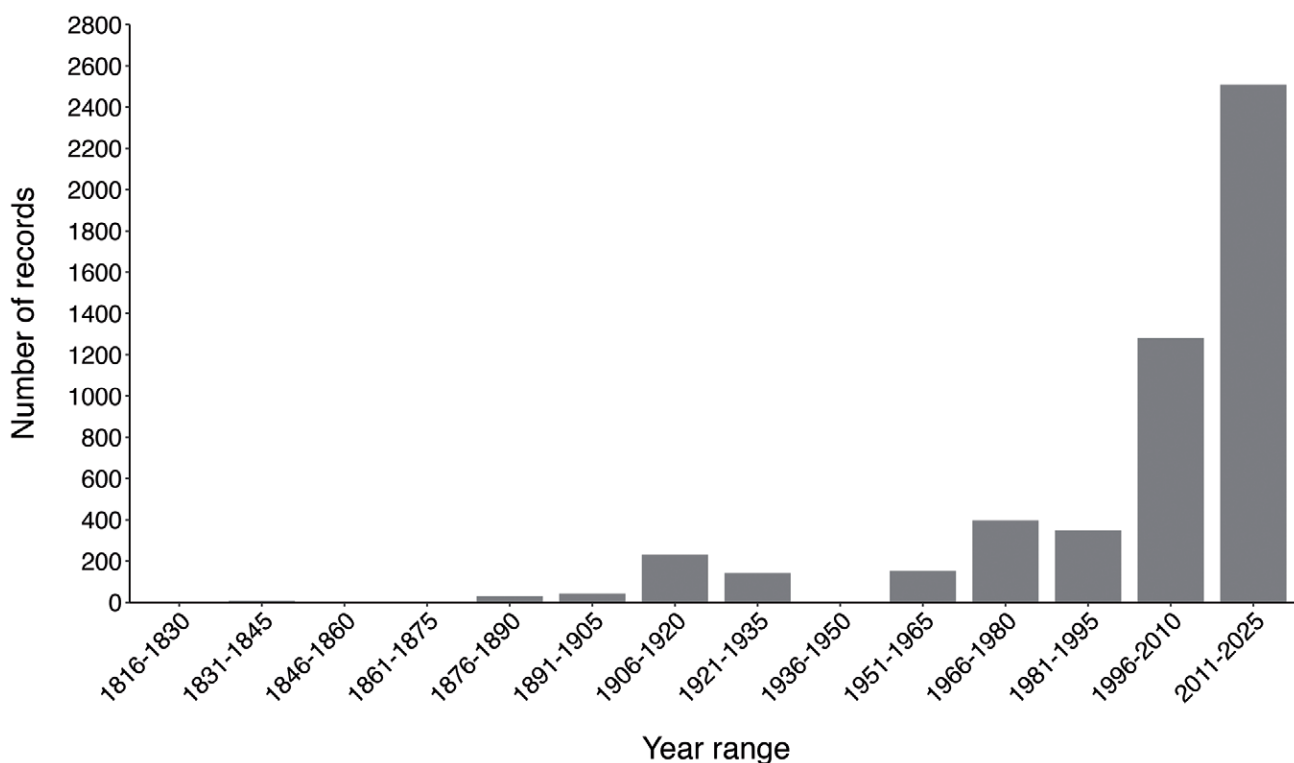


Fig. 2. Temporal distribution of records relating to vascular plants included in *DataLake*. Records are grouped by 15-year intervals from the first reports in the 19th century to the current year. The bars indicate the number of georeferenced records for each temporal range.

in a single major basin (Lake Trasimeno), while volcanic lakes are represented by multiple water bodies with substantial data coverage (Tab. 1, Fig. S1). Consequently, patterns observed at the lake-type level should be interpreted with caution, given the uneven representation of records across geological origins.

The spatial accuracy of the records is high overall. In fact, of the 5140 records included in *DataLake*, 2907 records (56.5%) are associated with a low spatial uncertainty of 100 m, based on GPS data or very detailed information on the floristic sampling site. Records with intermediate spatial accuracy include 327 records (6.3%) with an uncertainty of 2000 m, generally corresponding to sites defined on a sub-lake or municipal scale. Less precise records were primarily associated with generic lake-level locality descriptions. The least accurate records, falling into the 5000 m class and above, count 1050 records (20.4%), and are mainly associated with generic descriptions of sites around the largest lakes.

The 5140 georeferenced records included in *DataLake* correspond to 213 taxa, 97 genera and 43 families. Consistent with the aquatic and riparian environments considered, the taxonomic composition is dominated by families typical of these habitats, with Potamogetonaceae, Cyperaceae, Poaceae, Juncaceae, Hydrocharitaceae, Haloragaceae and Salicaceae accounting for the highest number of taxa and records (Fig. 3). Although dominance was defined at the overall dataset level, the contribution of the most representative families varies across lake types (Fig. S1). In tectonic lakes, record richness is strongly concentrated in a limited number of dominant families, largely reflecting the weight of a single basin. In contrast, volcanic lakes show a more even distribution of records among the dominant families across multiple systems. Karst and alluvial lakes display intermediate patterns, whereas glacial and landslide-dammed lakes, due to their very low

record numbers, do not allow robust family-level comparisons.

At the genus level, *Potamogeton*, *Myriophyllum* and *Ceratophyllum* are the dominant genera in the aquatic habitats, while *Juncus* and *Carex* along the riparian ones. At the species level, *Myriophyllum spicatum*, *Ceratophyllum demersum*, *Phragmites australis*, *Potamogeton perfoliatus* and *Stuckenia pectinata* are the most frequently recorded species.

From a conservation perspective, the dataset is particularly relevant. A total of 84 taxa (39% of the dataset) are included in regional risk categories according to Conti *et al.* (1997), corresponding to 1366 records (27%). In addition, 23 taxa (10.6% of the total) are listed in national IUCN risk categories according to Orsenigo *et al.* (2020), accounting for 268 records (Tab. S1). These results highlight the vulnerability of the aquatic and riparian flora associated with Italian freshwater lakes and emphasize the role of lacustrine ecosystems as important reservoirs for plant species of conservation concern. By documenting the spatial distribution and frequency of threatened taxa across multiple lake systems, *DataLake* provides a valuable base for planning conservation actions, monitoring activities and future assessments of floristic changes.

Alien species were recorded in 14 lakes (47%) and account for 19 taxa (8.9% of the total flora), represented by 249 records (4.8%). Among these, 12 taxa are classified as invasive, including *Paspalum distichum*, *Elodea canadensis* and *Bidens frondosa*. Their presence across multiple lake systems underlines the relevance of the dataset for documenting biological invasions in freshwater environments and for supporting long-term monitoring activities.

The biological spectrum is mainly characterized by hydrophytes and helophytes, with hemicryptophytes also contributing substantially, while therophytes, geophytes and phanero-

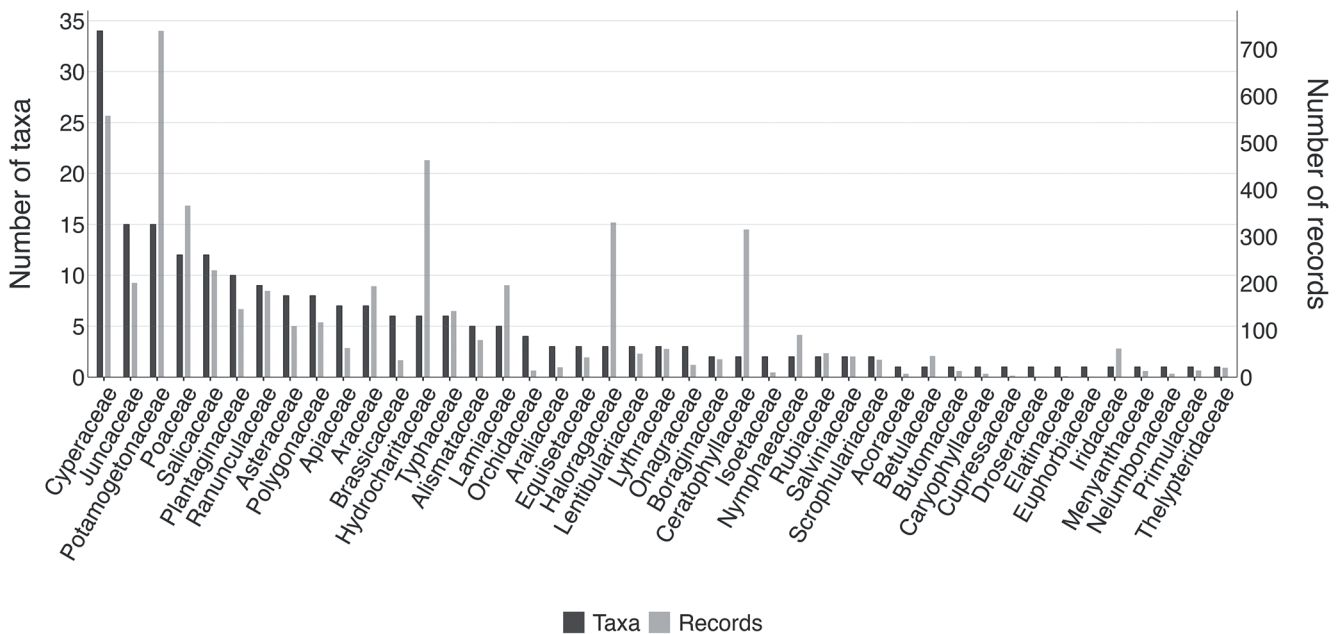


Fig. 3. Distribution of taxa and records among vascular plant families in *DataLake*. Families represented by very low numbers of records may appear absent at the adopted graphical scale due to their minimal contribution.

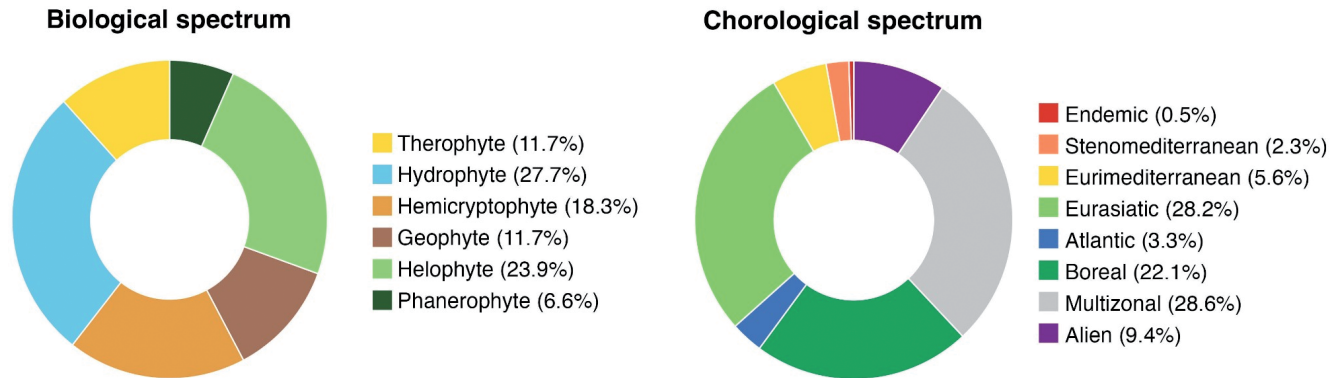


Fig. 4. Biological and chorological spectra of plant taxa included in *DataLake*.

phytes occur less frequently (Fig. 4). The chorological spectrum is dominated by Multizonal, Eurasiatic and Boreal taxa, followed by Aliens, Euromediterraneans, Atlantics, Stenomediterraneans and Endemics (Fig. 4). The observed biological and chorological patterns are consistent with the strong ecological dependence of aquatic and riparian plant species on hydrological conditions rather than on regional climatic constraints. In freshwater lake environments, as commonly observed in other inland water bodies, the buffering effect of water availability tends to reduce the influence of macroclimatic factors, favoring the prevalence of multizonal taxa over strictly Mediterranean ones (Wetzel, 2001; Bornette and Puijalon, 2011).

CONCLUSIONS

DataLake provides a georeferenced dataset on aquatic and riparian vascular plants from 30 natural freshwater lakes in central-southern Italy. Thanks to the comprehensive floristic data available in *DataLake*, it was possible to document how the aquatic and riparian flora of these lakes is rich in species but also vulnerable, as evidenced by a significant percentage of species of conservation interest, as well as of invasive alien species that pose a real local threat to the conservation of the native plant biodiversity.

It should be noted that the importance of this digital database lies in summarizing in a unique, coherent, standardized and easily accessible resource, floristic data from heterogeneous sources across time and space for the lakes considered.

Despite differences in the representativeness of the various types of lakes investigated, the dataset provides a comprehensive and well-documented overview of the diversity of vascular plants associated with natural Mediterranean freshwater lakes in central and southern Italy. Therefore, *DataLake* can provide a solid reference base for future floristic research, as well as for supporting long-term monitoring activities and actions aimed at conserving natural lake ecosystems of the Mediterranean.

REFERENCES

Bartolucci F, Peruzzi L, Galasso G, Alessandrini A, Ardenghi NMG, Bacchetta G, et al., 2024. A second update to the checklist of the vascular flora native to Italy. *Plant Biosyst* 158:219-296.

Bornette G, Puijalon S, 2011. Response of aquatic plants to abiotic factors: a review. *Aquatic Sci* 73:1-14.

Cannucci S, Bolpagni R, Bonari G, Candini F, Dalla Vecchia A, Fanfarillo E, et al., 2025. Dive into the Italian PONDY dataset: pond vegetation data and water physico-chemical parameters. *Veg Ecol Divers* 62:e176891.

Conti F, Manzi A, Pedrotti F, 1997. [Liste Rosse Regionali delle Piante d'Italia] [in Italian]. Camerino, WWF Italia, Società Botanica Italiana.

Ellenberg H, Weber HE, Düll R, Wirth V, Werner W, Paulissen D, 1992. [Zeigerwerte von Pflanzen in Mitteleuropa] [Book in German]. *Scripta Geobotanica* 18. Göttingen, Erich Goltze Verlag.

Galasso G, Conti F, Peruzzi L, Alessandrini A, Ardenghi NMG, Bacchetta G, et al., 2024. A second update to the checklist of the vascular flora alien to Italy. *Plant Biosyst* 158:297-340.

Guarino R, La Rosa M, 2019. [Flora d'Italia digitale]. [in Italian]. In: Pignatti S, Guarino R, La Rosa M (eds.), *Flora d'Italia*. Bologna, Edagricole.

Jeppesen E, Moss B, Bennion H, Carvalho L, DeMeester L, Feuchtmayr H, et al., 2010. Interaction of climate change and eutrophication, p. 119-151. In: Kernan M, Battarbee R, Moss B (eds.), *Climate change impacts on freshwater ecosystems*. Oxford, Wiley-Blackwell.

Kalff J, 2002. *Limnology: inland water ecosystems*. Upper Saddle River, Prentice Hall.

Orsenigo S, Fenu G, Gargano D, Montagnani C, Abeli T, Alessandrini A, et al., 2020. Red list of threatened vascular plants in Italy. *Plant Biosyst* 155:310-335.

Pignatti S, 2017-2019. [Flora d'Italia] [in Italian]. Vol. 1-3. Bologna, Edagricole.

Pinzani L, Di Lernia D, Pelella E, Ceschin S, 2025a. The vascular flora of Italian volcanic lake calderas: a comprehensive floristic study. *Environments* 12:327.

Pinzani L, Di Lernia D, Ceschin S, 2026. *DataLake: a georeferenced dataset of vascular plants from freshwater lakes of central-southern Italy* [Dataset]. Zenodo 18630469.

Pinzani L, Pelella E, Azzella MM, Ceschin S, 2025b. A bibliographic review on vascular flora of Italian volcanic lakes. *Inland Waters* 15:2475684.

Portal to the Flora of Italy, 2025. Version 2025.2. Accessed: 1 Dec 2025. Available from: <https://dryades.units.it/floritaly/>
Rossi G, Montagnani C, Gargano D, Peruzzi L, Abeli T, Ravera S, et al., 2013. [Lista Rossa della Flora Italiana. 1. Policy Species e altre

specie minacciate].[in Italian]. Rome, Comitato Italiano IUCN e Ministero dell'Ambiente e della Tutela del Territorio e del Mare.
Wetzel RG, 2001. Limnology: lake and river ecosystems. San Diego, Academic Press.

Online supplementary material:

List S1. Complete list of bibliographic references consulted for the extraction and georeferencing of records included in DataLake.

Fig. S1. Percentage of records for the ten most represented vascular plant families in DataLake.

Tab. S1. Vascular plant taxa in DataLake included in national and/or regional Red Lists.

Received: 3 January 2026; Accepted: 26 February 2026.

Contributions: Lorenzo Pinzani, conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing - original draft. Dario Di Lernia, investigation, data curation. Simona Ceschin, conceptualization, supervision, investigation, writing - review & editing. All authors read and approved the final version of the manuscript.

Conflict of interest: the authors declare no conflict of interest.

Data availability: DataLake: a georeferenced dataset of vascular plants from freshwater lakes of central-southern Italy is openly available on Zenodo at: <https://doi.org/10.5281/zenodo.18630469>

Acknowledgements: the authors acknowledge the support of NBFC to Department of Science-University of Roma Tre, funded by the Italian Ministry of University and Research, PNRR, Missione 4 Componente 2, "Dalla Ricerca all'Impresa", Investimento 1.4, Project CN00000033.

Publisher's note: all claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher; the editors and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0).

Environmental and community constraints on *Elodea nuttallii*: implications for early season control in an urban stretch of the Po River (NW Italy)

Marta Zoppi,^{1,2} Gianluca Vacca,^{1,2*} Guido Badino,¹ Sabrina Basile,¹ Rossano Bolpagni,³ Alice Dalla Vecchia,³ Elisa Falasco,^{1,2} Francesca Bona^{1,2}

¹Department of Life Sciences and Systems Biology, University of Turin; ²Alpstream - Alpine Stream Research Center/Parco del Monviso, Ostana (CN); ³Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Italy

Abstract

Invasive aquatic macrophytes represent an increasing concern for freshwater ecosystems, where they alter biodiversity, ecosystem functioning, and water-related services. Among them, the submerged species *Elodea nuttallii* has rapidly expanded across many European waterbodies, yet its ecology in regulated lowland rivers remains insufficiently explored, particularly compared to that in artificial canals, ponds, and lakes. This study investigates the environmental, hydrological, and biotic factors shaping the occurrence and distribution of *E. nuttallii* in an urban river system. Field surveys conducted in 2025 documented macrophyte assemblages and habitat conditions in the Po River, the longest Italian river, flowing through the city of Turin. A total of 150 presence-absence points for *E. nuttallii* were recorded, spaced at least 200 meters apart, along the urban stretch of the river, collecting information on temperature, dissolved oxygen, pH, conductivity, as well as the presence of other macrophytes and the extent of plant populations. The results show that most vegetated patches are dominated by *E. nuttallii*, which is associated with depositional areas characterised by soft sediments and significantly related to the presence of *Myriophyllum spicatum*, as demonstrated by Phi correlation analysis. Although interspecific competition appears to limit *E. nuttallii*'s relative abundance during the seasonal macrophyte community peak, when its mean relative cover drops from 89.2% to 60%, its extended vegetative season likely contributes to its persistence. Moreover, substrate type emerged as the primary abiotic factor shaping spatial distribution in a regulated lowland river, with sand and silt providing optimal conditions for its establishment. We further highlight the need for early season and site-specific management interventions. Given the ecological and recreational significance of the Po River and its role as a dispersal corridor, understanding the invasion dynamics of *E. nuttallii* is critical for informing management strategies, particularly in light of its designation as an EU-priority alien invasive species.

Key words: Invasive alien species; waterweed management; biotic interactions; physical and chemical variables; lotic regulated ecosystem.

Correspondence to: gianluca.vacca@unito.it

Introduction

The spread of invasive alien species (IAS) is a major threat to freshwater ecosystems worldwide, driving biodiversity loss, habitat alteration, and disruption of ecosystem structure and functioning (IPBES, 2023; IUCN, 2023). Aquatic environments are particularly vulnerable to plant invasions, which are often triggered by human introduction and facilitated by hydrological connectivity, thereby promoting the rapid dispersal of propagules (Bolpagni, 2021). Once established, alien macrophytes can alter sediment dynamics, nutrient cycling, and light availability, often displacing native communities (Bouma *et al.*, 2010; Emery-Butcher *et al.*, 2020; Tasker *et al.*, 2022).

In this context, the genus *Elodea* (Hydrocharitaceae) comprises some of the most widespread invasive submerged macrophytes in temperate regions. *Elodea nuttallii* (Planch.) H. St. John has shown remarkable invasive success across Europe, frequently replacing or co-occurring with the earlier established *Elodea canadensis* Michx. (Steen *et al.*, 2019; Buldrini *et al.*, 2023). *Elodea nuttallii* thrives in

a wide range of lentic and low-flow environments, exhibiting high phenotypic plasticity and tolerance to light, nutrient, and hydrodynamic conditions (Atapaththu and Asaeda, 2015; Szabó *et al.*, 2019). Its ability to form dense monospecific stands allows it to alter natural ecosystems and interfere with ecosystem services such as navigation, recreation, and water abstraction (Kelly *et al.*, 2015; Millane *et al.*, 2016). Due to its impacts, *E. nuttallii* is listed as an IAS of Union Concern under EU Regulation 1143/2014, requiring prevention, early detection, control and eradication measures. Previous studies show that *E. nuttallii* distribution and spread are regulated by abiotic gradients (nutrients, hydrodynamics), biotic interactions with other invasive species and native flora, and physiological plasticity that enables survival across diverse freshwater habitats, e.g., lakes and canals, as well as under laboratory conditions (Atapaththu and Asaeda, 2015; Crane *et al.*, 2022; Bučar *et al.*, 2024). Despite growing evidence that *E. nuttallii* thrives in regulated and artificial systems, where human pressures amplify ecological dynamics, and local communities directly perceive the impacts of invasive species, knowledge remains limited of long-term distribu-

tion dynamics in urban river systems (Grudnik and Germ, 2013).

In Italy, *E. nuttallii* has been recorded since the late 20th century (Desfayes, 1995; Selvaggi and Dellavedova, 2016) and has since spread across northern and central regions, especially in artificial canals, streams, and lakes (Bolpagni *et al.*, 2017). Buldrini *et al.* (2023) identified the Po River basin as a priority area for studying the invasion dynamics of *Elodea* species, due to its dual role as both a natural barrier and a dispersal corridor, facilitated by a dense network of artificial canals, connecting northern and central Italy. In this context, studies focusing on *E. nuttallii* populations within the Po River, particularly in its upper reaches, are crucial for understanding the species' ecological performance, as well as for supporting effective monitoring and management strategies aimed at limiting its spread and ecological impact, as required by the EU legislation.

The city of Turin (North-West Italy) is the biggest city crossed by the longest Italian river, the Po River. This river provides important ecosystem services, both through direct use for water-based activities (e.g., fishing, rowing) and through its high landscape value, supporting leisure and recreational opportunities in the surrounding riverside parks and walking areas. In 2022, this river stretch experienced a major invasion event by *E. nuttallii*, which thrived under conditions of extremely low water flow, stable sunny weather, and high nutrient concentrations (ENEA, 2022; Aree pro-

tette Po Piemontese, 2023). Management interventions, primarily manual harvesting, were implemented at the peak of the season (Regione Piemonte, 2023), reducing its biomass, although the species re-established in persistent patches over the following three years.

This study investigates the ecological factors influencing *E. nuttallii*'s occurrence and distribution in an urban section of the Po River. The specific objectives were to: i) assess its distribution during the growing season; ii) identify the environmental, hydrological, and biotic factors driving its spatial patterns; and iii) provide management recommendations tailored to the regulated lotic system. Overall, this study offers new insights into the invasion dynamics of *E. nuttallii* within an urban river ecosystem subject to substantial human pressures and contributes to improving management strategies for this EU-listed IAS.

METHODS

Study area

The study took place in an urban stretch of the Po River in Turin (NW Italy; Fig. 1). Turin is the first major city downstream of the river's source, located approximately 90 km away. Here, the

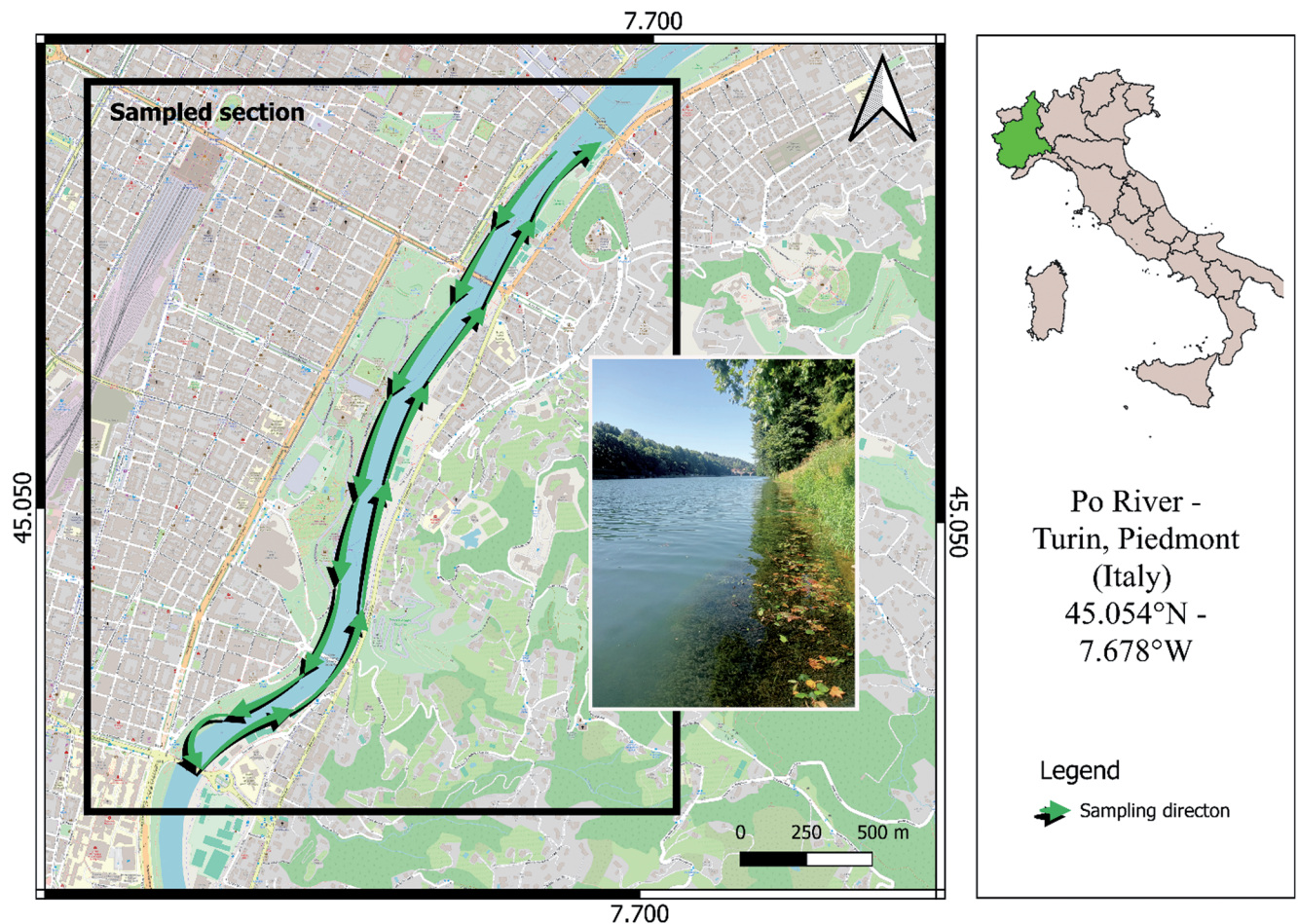


Fig. 1. Map of the sampling area and surveyed section of the Po River. (WGS84 - UTM Zone 32N- EPSG:32632; on QGIS 3.40.13 <http://tile.openstreetmap.org/{z}/{x}/{y}.png>).

river has the characteristics of a lowland river, approximately 100 m wide and up to 5 m deep. Riverbanks are largely artificial, and the flow is regulated by a downstream weir to maintain sufficient water depth for river navigation and to manage flood events. *Elodea nuttallii* was first documented in this area in 2022, during a major invasion event (Regione Piemonte, 2024). Possible introduction pathways include the discharge of water from aquariums, accidental transport, use of machinery for mowing aquatic vegetation, and transport by water birds.

Field surveys

Five surveys were carried out from June to September 2025, covering the entire vegetative season of *E. nuttallii*. Before June, intense rainfall and flood events prevented the establishment of a stable macrophyte community (see ARPA Piemonte (2024) hydrological portal for more details). A 3 km stretch of the river was surveyed by motorboat once a month (twice in August) at 30 random sites, each at least 200 metres apart and equally divided between locations with and without *E. nuttallii* (Fig. 1) At each site, presence/absence of *E. nuttallii* and co-occurring macrophytes, patch size, and proportional cover of *E. nuttallii* within each patch were recorded, along with substrate type and water depth (ISPRA, 2007). Macrophyte patches exhibited well-defined boundaries, permitting stand-level sampling and individual surface area measurements. Macrophyte identification and nomenclature followed the Portal to the Flora of Italy (<https://dryades.units.it/floritaly/>). The type of substrate was classified as artificial, depositional (sand and silt), transitional (gravel), or transport (cobble). Similarly, we classified the type of bank as natural, semi-natural, or artificial. Water temperature, dissolved oxygen (DO; % and mg L⁻¹), pH, and electrical conductivity (EC; μS cm⁻¹) were measured using a multiparametric probe (Manta+ 20, Solinst Eureka) at all sites. Two water samples were collected at the beginning and at the end of the river stretch on each sampling occasion to determine total suspended solids (TSS) (IRSA, 2004) and nutrient concentrations (N-NO₃⁻ and P-PO₄⁻; assay kits LCK 339 and LCK 349 - Hach, The Netherlands) in the laboratory. Further information on the sampling sites and protocol can be found in *Supplementary Material 1 (SM1)*.

The solar exposure of the banks was estimated retrospectively using the SunCalc web application (SunCalc, 2025). To estimate flow velocity, the channel width of each river section was first measured using standard OpenStreetMap (OSM; Fig. 1) in QGIS software (version 3.40.13, <https://qgis.org/download/>). The depth of the water in the middle of the Po River was obtained from the ARPA Piemonte (2024) hydrological portal, and these two parameters were used to calculate the cross-sectional area. Flow discharge for the corresponding sites was retrieved from ARPA Piemonte. Flow velocity was then computed for each sampling date as the ratio between discharge and cross-sectional area:

$$v = Q/A \quad (\text{Eq. 1})$$

v = flow velocity; Q = flow discharge; A = cross section area

Data analysis

Substrate preference was assessed by comparing the proportion of *E. nuttallii* occurrences across substrate categories (artificial, depositional, transport, and transitional). Patch extent of *E. nuttallii* was estimated using recorded size classes (e.g., < 3×3 m, > 3×3 m, > 6×6 m, > 10×10 m). For each patch, the minimum and maximum

area corresponding to the size class were calculated (0-9 m², 9-36 m², 36-100 m², > 100 m²), and the mean of these two values was used to estimate the average patch area. Data analysis and graphics were produced in R (R Core Team, 2022). To assess the influence of the measured environmental variables on the presence and absence of *E. nuttallii*, a Generalized Additive Model (GAM) with a binomial family and logit link was applied. Prior to model fitting, potential collinearity among environmental variables was evaluated using pairwise correlations and variance inflation factors (VIF), and highly collinear variables were removed (i.e., saturation percentage of dissolved oxygen). The remaining environmental parameters were included as smooth covariates in the model. Categories with a low number of observations were excluded to avoid biasing the results. This approach enabled us to highlight the limitations imposed by the environmental conditions at the site. Conversely, to assess the influence of environmental parameters on the extent of the target species, a Principal Component Analysis (PCA) was first conducted on the measured environmental variables. This approach allowed us to reduce collinearity and identify the key environmental factors shaping the patches of *E. nuttallii*. Subsequently, a GAM was performed between the scores of the first two principal components (PC1 and PC2) and the relative percentage cover of *E. nuttallii*. Lastly, to assess the correlation between the observed species, a Phi coefficient analysis was conducted, which is suitable for binary data (0 and 1). A schematic workflow of data analysis is reported in *Fig. S1*.

RESULTS

Overall water quality reflected a typical lowland river, sampled in a phase of moderate flow and low turbidity. There were no signs of serious eutrophication or anoxia, but moderate trophic enrichment was observed (2.40-2.61 mg N-NO₃⁻ L⁻¹). Moreover, peaks of pH >9 and DO% >90 suggest intense photosynthetic activity, typical of a slightly eutrophic system. In the area, fine substrate prevailed and shading from the terrestrial canopy was absent or partial. The weather and environmental conditions remained largely stable throughout the study period, with fluctuations mainly in conductivity and temperature, and particularly toward the end of the study period (*Tab. S1*). *Elodea nuttallii* mostly occurred within 10 m of the banks, at depths between 0.5 and 3 m. Larger stands were found along the left bank, where artificial sections are interspersed with natural and semi-natural sections. This bank is exposed to the southeast and is characterised by higher mean water temperatures in June and July, compared to the right bank. The main environmental parameters measured showed no evident difference between sites where *E. nuttallii* was present or absent, as indicated by the GAM (Fig. 2a). However, the PCA revealed that PC2 was strongly influenced by temperature (*Tab. 1*) and significantly positively associated with percentage cover of *E. nuttallii* ($p=0.005$; *Tab. 2*). Electrical conductivity at sites with *E. nuttallii* patches showed a narrower range compared to sites where the species was absent, while dissolved oxygen and pH were similarly distributed between the two groups. As indicated by the GAM analysis (*Tab. 3*), the relationship between *E. nuttallii* presence and substrate type, especially sand-silt substrate, was significant ($p=0.019$). The preference of *E. nuttallii* for different sediment types was further graphically analysed: sand accounted for ~38% of all sites but 47% of *E. nuttallii* occurrences, whereas gravel (27.5% of all sites) accounted for 23.5% of occurrences, and cobble presented fewer occurrences (Fig. 2b).

Aquatic vegetation occurred mainly in extensive patches concentrated along the right bank of the river, which is predominantly artificial and exposed to the northwest (*Supplementary Material 1*). Vegetation cover increased from approximately 10 m² in June to 100 m² by the end of August, then decreased in September (Fig. 3). The absolute cover of *E. nuttallii* showed a similar temporal pattern, reaching its maximum at the end of August. In contrast, the mean

relative cover of *E. nuttallii* (relative to the whole macrophyte cover) decreased over the season, from 89.2% in June to 60% at the end of August, indicating an increasing contribution of other macrophyte species during peak biomass. Overall, *E. nuttallii* was the dominant macrophyte in most patches, accounting for approximately 70% of the total vegetation cover, and reaching 100% cover in approximately 14% of patches. Nevertheless, Fig. 3 highlights a mid-summer

Tab. 1. Loadings of environmental variables on the first four principal components (PCs) from the PCA. Values in parentheses indicate the proportion of variance explained by each component. Loadings with higher absolute values indicate stronger contributions of the variable to the respective PC.

	PC1 (40%)	PC2 (32%)	PC3 (19%)	PC4 (6%)
Conductivity	-0.72	0.14	0.22	0.64
Dissolved oxygen	-0.40	0.04	-0.90	-0.15
Temperature	-0.22	0.80	0.21	-0.56
pH	0.52	0.57	-0.30	0.59

Tab. 2. Summary table of the GAM analysis of the ordinal extent class of *Elodea nuttallii* as a function of PC1 and PC2 of the environmental PCA. The ordinal response was modelled using quasibinomial(link = “log”).

	Estimate	Std. Error	t-value	Pr(> t)
PC1	0.207	0.151	1.369	0.175
PC2	0.505	0.176	2.873	0.005**

**Statistically significant at $p < 0.05$.

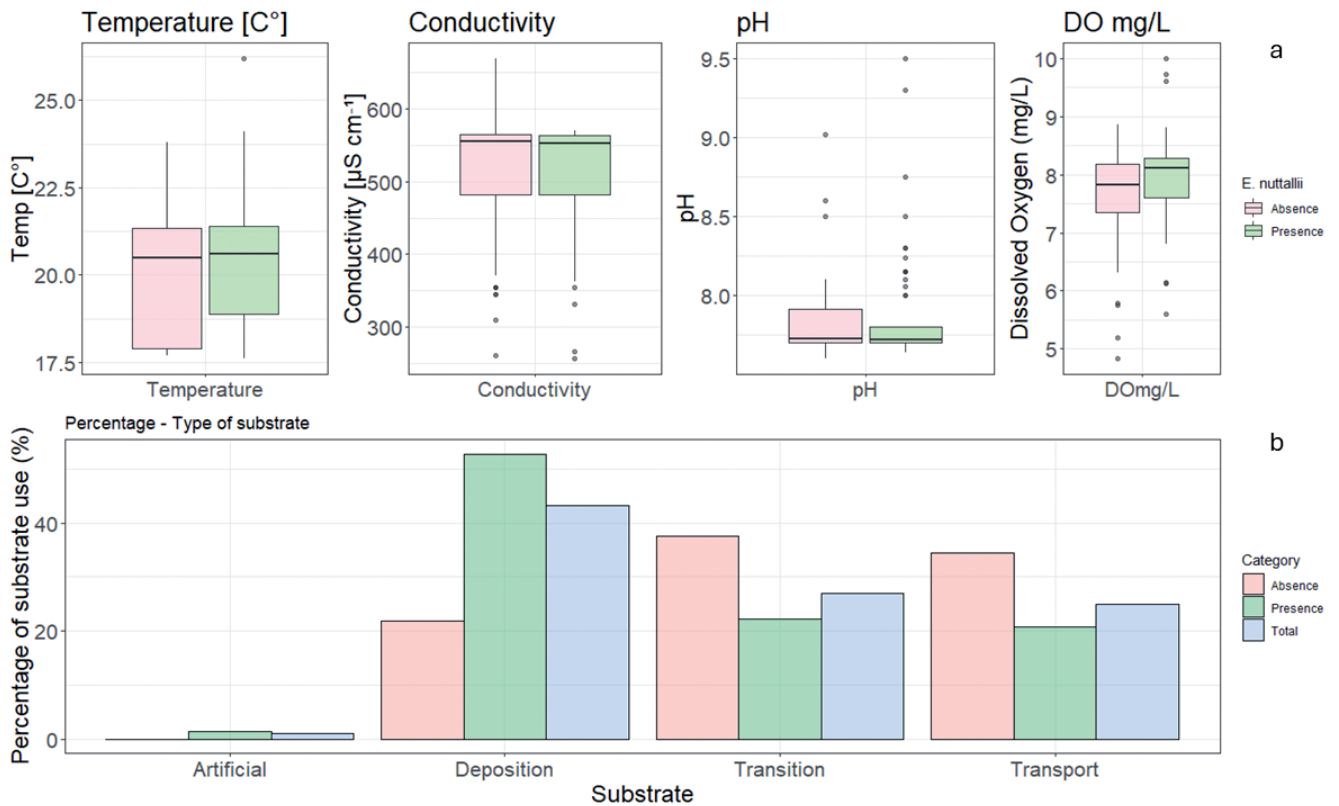


Fig. 2. Abiotic parameters in relation to the presence or absence of *Elodea nuttallii*. a) Boxplots summarising the physical parameters of water where *E. nuttallii* is present and where it is absent. b) Occurrence of *E. nuttallii* based on the type of substrate.

Tab. 3. Results of the GAM analysis between presence/absence of *Elodea nuttalli* and type of substrate, type of bank and environmental parameters. Binomial family with logit link; smooth terms included without modification of complexity (AIC values checked). Other macrophyte species were included in the GAM but are not displayed, since their results are indicated in the heatmap of the Phi correlation analysis.

	Estimate	Std. Error	Z value	Pr (> z)
Gravel	0.447	1.500	0.298	0.765
Sand with pebbles	1.601	1.495	1.071	0.284
Sandy-silt	3.697	1.581	2.338	0.019**
Semi-natural bank	1.328	1.244	1.077	0.286
	Eff	Ref. df	Chi.sq	p-value
Temperature	4.729	5.781	7.818	0.287
Conductivity	1.000	1.000	0.379	0.518
pH	2.647	3.243	2.306	0.699
Dissolved oxygen (mg L ⁻¹)	1.000	1.000	2.765	0.065

**Statistically significant at $p < 0.05$.

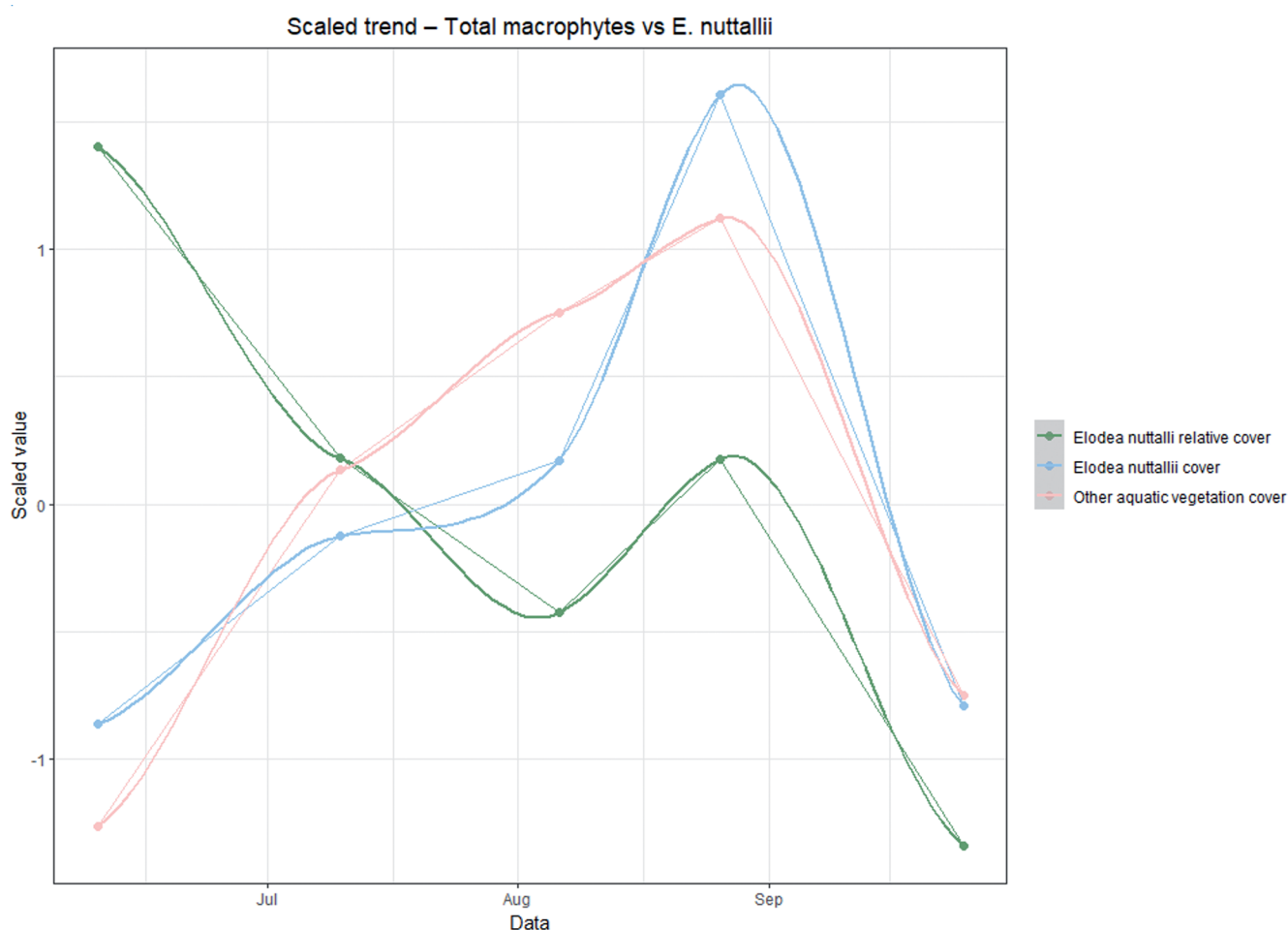


Fig. 3. Temporal trend of aquatic vegetation. The figure illustrates changes over time in *Elodea nuttallii* relative (%) and absolute (m²) cover, alongside the absolute cover (m²) of other macrophytes. Variables were scaled to enable comparison, and smoothed trends (geom_smooth, ggplot2) were used to emphasize overall temporal patterns.

decline in its relative dominance, despite sustained absolute cover. This pattern suggests that *E. nuttallii* has a longer period of high abundance compared to other macrophytes, being already well established and dominant early in the season, when other species are still present at low abundance, and maintaining high cover later into the summer.

In patches with multiple species, *E. nuttallii* co-occurred with *Stuckenia pectinata* (L.) Börner, *Potamogeton crispus* L., *Potamogeton natans* L., *Callitriche stagnalis* Scop., and *Lemna* spp., in order of abundance. Additionally, no significant association between *E. nuttallii* and *Myriophyllum spicatum* was observed based on Phi correlation analysis (including only co-occurring macrophyte species; Fig. S2). However, *M. spicatum* was present in approximately 70% of the cases where *E. nuttallii* occurred.

DISCUSSION

Hydrological and environmental drivers

Our study confirms the extensive presence of *E. nuttallii* in the examined stretch. We observed no clear relationships with DO, pH, or water depth, unlike previous studies that identified strong associations between *E. nuttallii* distribution and abiotic parameters, based on multi-year field surveys or controlled laboratory experiments (Grudnik and Germ, 2013; Atapaththu and Asaeda, 2015; Bučar *et al.*, 2024). However, PCA revealed that temperature has a strong influence, indicating that it is an important component of the environmental gradient associated with species extent. Nevertheless, this result is not entirely consistent with previous studies (Grudnik *et al.*, 2014; Qui *et al.*, 2025). These contrasting findings support evidence that the species exhibits broad ecological tolerance and high phenotypic plasticity (Kolada *et al.*, 2022). Even water depth was not a limiting factor for *E. nuttallii*, which was recorded here at depths ranging from 0.5 to 3 m, while previous studies reported it in narrower depth ranges (0.3–1 m; Bučar *et al.*, 2024) or over 1 m (Grudnik and Germ, 2013). In the present study, *E. nuttallii* was mostly present at conductivity values ranging from 256 to 570 $\mu\text{S cm}^{-1}$, while it was absent at higher conductivity levels. However, this pattern is not consistent across all sites. Specifically, *E. nuttallii* was not present in some locations within the same conductivity range. According to literature data, the species can tolerate and even thrive at conductivities exceeding 700 $\mu\text{S cm}^{-1}$ (Bučar *et al.*, 2024).

In contrast, substrate type emerged as a determinant of the presence of *E. nuttallii*, as suggested by the GAM and confirmed by the barplot. Soft sediments such as silt, sand, and fine gravel promote anchorage and nutrient uptake by macrophytes (Kuriata-Potasznik *et al.*, 2018; Gao and Hu, 2023). These substrates typically occur in depositional zones, where reduced flow energy allows fine sediments and organic matter to accumulate. Such environments favour macrophyte establishment and can create positive feedback loops in which dense stands further enhance sedimentation and habitat stability (Grudnik *et al.*, 2014; Buccheri *et al.*, 2019; Emery-Butcher *et al.*, 2020). Accordingly, along the Oglio River, Bolpagni *et al.* (2017) observed that the dammed stretches, characterised by fine sediments, are widely colonised by rooted macrophytes typical of slow-moving/lentic conditions (e.g. *Vallisneria spiralis* L., *Potamogeton* spp., and *M. spicatum*), which are characteristic plants of lacustrine systems rather than rivers.

Although *E. nuttallii* was found in depositional zones where

current velocity is reduced, all the stands were nonetheless exposed directly to the main river channel. This stretch of the Po River lacks secondary channels or refugia that typically protect submerged vegetation from flow stress. Under such conditions, *E. nuttallii* appears capable of maintaining growth and structural integrity even under lotic conditions. Nonetheless, flow velocities estimated during the vegetative period were relatively low (0.07–0.27 m s^{-1}), reflecting summer low-flow conditions. Notably, these values are substantially higher than the thresholds at which stress responses have been reported for *E. nuttallii* in the literature. Atapaththu and Asaeda (2015), for example, observed that flow velocities as low as 0.02–0.03 m s^{-1} can induce marked morphological and physiological stress responses in *E. nuttallii* (e.g., reduced shoot elongation, increased radial expansion, and altered cellulose, lignin, and chlorophyll content). These adaptive traits are interpreted as mechanisms to reduce drag and mechanical damage, enabling the species to persist in mildly turbulent environments. In contrast, in our study *E. nuttallii* was able to maintain growth and structural integrity at considerably higher velocities, suggesting a greater tolerance to moderate current stress than previously documented. This tolerance may enable the species to persist even in mildly turbulent environments, supporting its ability to colonize open-channel habitats such as those of the Po River, where summer hydrodynamic conditions are not extreme but still impose mechanical constraints on macrophyte establishment.

Overall, while *E. nuttallii* tolerates a wide range of environmental conditions, our data indicate that substrate type represents the primary determinant of its spatial distribution in lotic habitats at the local scale.

Interspecific competition

The relative homogeneity of water parameters across sites and the observed mid-season decline in *E. nuttallii* cover suggest that competition with other macrophytes can be a major factor shaping its distribution pattern. In the studied stretch of the Po River, *E. nuttallii* is the first macrophyte to establish extensively in spring, colonizing suitable substrates before other species begin their vegetative development. This early establishment is likely linked to its low temperature requirement for active growth, ranging between 8.2 and 12.0°C (Kunii, 1981), and it is supported by previous research in other European catchments (Wang *et al.*, 2019; Bučar *et al.*, 2024). This phenological advantage enables rapid colonization of suitable substrates before the emergence of other species. However, as temperature rises, co-occurring macrophytes, and particularly *M. spicatum*, which initiates growth above 15°C (Xiao *et al.*, 2010; Arts *et al.*, 2022), become more competitive. This leads to a reduction in *E. nuttallii* dominance during the peak of the growing season, although it remains abundant (above 50%) in most stands. Towards late summer, when many other species begin to senesce, *E. nuttallii* resumes growth, extending its vegetative period beyond that of native species. This pattern of early establishment, mid-season competitive limitation, and late-season resurgence reflects a temporal niche differentiation that promotes long-term persistence and dominance of *E. nuttallii* in mixed macrophyte assemblages. Such dynamics underline the importance of biotic interactions and seasonal timing in understanding and managing the spread of this invasive aquatic plant.

The specific mechanisms of competition remain uncertain. The reduction of invader success due to functional similarities with native species has been well documented in the scientific literature (Petruzzella *et al.*, 2018). In this study, *E. nuttallii* co-

occurred with other rooted submerged macrophytes exhibiting overlapping ecological niches and similar resource-use strategies. *Myriophyllum spicatum*, which co-occurred with *E. nuttallii* in ~70% of the stands, is known to produce allelochemicals that can inhibit the growth and photosynthetic performance of phytoplankton and herbivores (Gross *et al.*, 2012; Jeong *et al.*, 2021), but no allelopathic effects on plants are recorded in the literature. On the other hand, the association between the two species suggests that their coexistence may reflect an ecologically relevant relationship: *E. nuttallii* may tolerate competitive or inhibitory effects exerted by *M. spicatum*, and their frequent co-occurrence indicates that additional ecological factors may promote or facilitate their association. Further experimental work would be needed to disentangle the relative importance of allelopathy, functional overlap, and other biotic factors in shaping the distribution patterns of *E. nuttallii* within regulated lowland river ecosystems.

Management strategies and suggestions

Preventing the introduction and spread of *E. nuttallii* is a legal requirement across the EU, given its listing as an IAS of Union Concern (Regulation EU 1143/2014 and subsequent Commission Implementing Regulations). In Turin, a major invasion event occurred in 2022, when *E. nuttallii* rapidly outcompeted native macrophytes and occupied extensive areas of the Po River. The proliferation was likely favoured by reduced hydrological flow and stable sunny weather and elevated nutrient concentrations, which created suitable conditions for its establishment and expansion. To limit the infestation, a large-scale manual removal was carried out at the peak of the growing season, leading to substantial operational costs, high labour demand, and a considerable volume of biomass requiring disposal. Our findings underscore the importance of targeted, seasonally informed management, for which we propose the following measures:

- A. Early season removal.** This approach offers several advantages:
1. Selective removal: *E. nuttallii* accounted for ~90% of vegetation cover in June, allowing effective targeting with minimal disturbance to native plants;
 2. Lower biomass volume: early season harvesting reduces handling and disposal costs relative to peak biomass removal;
 3. Reduced regrowth: harvesting during the initial regeneration phase can substantially limit total seasonal biomass and regrowth capacity of *E. nuttallii* (Di Nino *et al.*, 2005);
 4. Cost efficiency: bioeconomic analyses (Marbuah *et al.*, 2019) demonstrate that early intervention minimizes management costs and ecological damages associated with invasive aquatic plants.
- B. Prioritization of removal areas.** Management efforts should focus on the areas experiencing high depositional processes, where *E. nuttallii* typically establishes, as well as on banks exposed to strong afternoon sunlight (Fig. S3).

CONCLUSIONS

This study characterizes the distribution and seasonal dynamics of *E. nuttallii* in a regulated urban stretch of the Po River. While it provides detailed insights at a local scale, it does not capture basin-wide invasion dynamics. Furthermore, the study was conducted over a single vegetative season, limiting its long-

term generalization, particularly given the potential climate dependence of *E. nuttallii* abundance and phenology. Despite these limitations, the results are robust for the year studied. Although *E. nuttallii* is the dominant species across much of the area, monospecific stands are less frequent than mixed assemblages with native macrophytes. Its temporal pattern -early colonization, mid-season limitation by competitors, and late-season recovery- suggests competitive interactions among macrophytes and a comparatively long vegetative season. Indeed, in the target site the species requires lower temperature for active growth compared to native macrophytes, yet it becomes limited by interspecific competition during the seasonal peak, highlighting the combined role of abiotic and biotic factors. On the other hand, substrate type emerged as the primary abiotic factor shaping spatial distribution, with sand and silt providing optimal conditions for its establishment. Water physicochemical parameters showed very limited influence, confirming the broad tolerance and adaptability of this IAS. Based on these findings, effective management strategies should focus on mechanical control early in the growing season, prioritizing depositional areas along the left riverbank to prevent large-scale proliferation and reduce intervention costs such as those incurred during the 2022 invasion event. By integrating ecological insight with practical management considerations, this study contributes to improving invasive macrophytes control within urban river restoration frameworks. In this regard, river management cannot ignore the ecological preferences of invasive macrophytes, given that the exploitation of water resources (such as river damming) may encourage their spread and affirmation. Future research should incorporate multi-year monitoring and expanded spatial coverage to better capture the responses of *E. nuttallii* to a wide range of environmental and climatic conditions and to more clearly identify the main drivers of its invasion dynamics. In addition, interactions with native macrophytes should be analysed in greater detail.

REFERENCES

- Aree protette Po Piemontese, 2023. [La vegetazione acquatica del Po. La minaccia delle specie esotiche invasive. *Elodea nuttallii*: biologia della specie ed azioni a contrasto]. [in Italian]. Accessed: 7 January 2026. Available from: <https://www.parcopiemontese.it/news-dettaglio.php?id=74773>
- ARPA Piemonte, 2025. [Idrologia – Acque superficiali]. [in Italian]. Accessed: 7 January 2026. Available from: <https://www.arpa.piemonte.it/temi/acqua/idrologia-acque-superficiali>
- Arts GHP, Smeden J, Wolters MF, Belgers JDM, Matser AM, Hommen U, et al., 2022. Seasonal dynamics of the macrophyte test species *Myriophyllum spicatum* over two years in experimental ditches for population modelling application in risk assessment. *Integr Environ Assess Manag* 18:1375-1386.
- Atapaththu KSS, Asaeda T, 2015. Growth and stress responses of Nuttall's waterweed *Elodea nuttallii* (Planch) St. John to water movements. *Hydrobiologia* 747:217-233.
- Bolpagni R, 2021. Towards global dominance of invasive alien plants in freshwater ecosystems: the dawn of the Exocene? *Hydrobiologia* 848:2259-2279.
- Bolpagni R, Racchetti E, Laini A, 2016. Fragmentation and groundwater supply as major drivers of algal and plant diversity and relative cover dynamics along a highly modified lowland river. *Sci Total Environ* 568:875-884.

- Bolpagni R, Azzella MM, Agostinelli C, Beghi A, Bettoni E, Brusa G, et al., 2017. Integrating the Water Framework Directive into the Habitats Directive: Analysis of distribution patterns of lacustrine EU habitats in lakes of Lombardy (northern Italy). *J Limnol* 76:1627.
- Bouma TJ, De Vries MB, Herman PMJ, 2010. Comparing ecosystem engineering efficiency of two plant species with contrasting growth strategies. *Ecology* 91:2696-2704.
- Bučar M, Rimac A, Šegota V, Vuković N, Alegro A, 2024. Ecology of *Elodea canadensis* Michx. and *Elodea nuttallii* (Planch.) H. St. John—Insights from National Water Monitoring in Croatia. *Plants* 13:1624.
- Buccheri M, Boscutti F, Pellegrini E, Martini F, 2019. [La flora aliena nel Friuli Venezia Giulia]. [Article in Italian]. *Gortania* 40:7-78.
- Buldrini F, Pezzi G, Barbero M, Alessandrini A, Amedei L, Andreatta S, et al., 2023. The invasion history of *Elodea canadensis* and *E. nuttallii* (Hydrocharitaceae) in Italy from herbarium accessions, field records and historical literature. *Biol Invasions* 25:827-846.
- Crane K, Kregting L, Coughlan NE, Cuthbert RN, Ricciardi A, MacIsaac HJ, et al., 2022. Abiotic and biotic correlates of the occurrence, extent and cover of invasive aquatic *Elodea nuttallii*. *Freshwater Biol* 67:1559-1570.
- Desfayes M, 1995. [Appunti floristici sulle acque del Trentino e territori circostanti]. [Article in Italian]. *Ann Mus Rov* 10:223-248.
- Di Nino F, Thiébaud G, Muller S, 2005. Response of *Elodea nuttallii* (Planch.) H. St. John to manual harvesting in the North-East of France. *Hydrobiologia* 551:147-157.
- Emery-Butcher HE, Beatty SJ, Robson BJ, 2020. The impacts of invasive ecosystem engineers in freshwaters: A review. *Freshwater Biol* 65:999-1015.
- ENEA, 2022. [Fiume Po: intervento sperimentale di estirpazione della vegetazione esotica]. [in Italian]. Accessed: 7 January 2026. Available from: <https://sostenibilita.enea.it/news/fiume-po-intervento-sperimentale-estirpazione-vegetazione-esotica>
- European Commission, 2014. Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. Available from: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R1143>
- Gao J, Hu W, 2023. A bibliometric analysis of lake restoration with submerged macrophytes. *Water* 15:2411.
- Gross EM, Bakker ES, 2012. The role of plant secondary metabolites in freshwater macrophyte–herbivore interactions: limited or unexplored chemical defences?, pp. 154-169. In: Iason GR, Dicke M, Hartley SE (eds.), *The ecology of plant secondary metabolites: from genes to global processes*. Ecological Reviews. Cambridge University Press, Cambridge.
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2023. Accessed: 7 January 2026. Available from: <https://www.ipbes.net/>
- International Union for Conservation of Nature (IUCN), 2023. Invasive alien species. Accessed: 7 January 2026. Available from: <https://www.iucn.org/our-work/topic/invasive-alien-species>
- IRSA, 2004. [Metodi analitici per le acque – Sezione 2000]. [in Italian]. Manuals and guidelines APAT, 29/2003.
- ISPRA, 2007. [Metodi biologici per le acque superficiali interne – Macrofite]. [in Italian]. Manuali e Linee guida. Rome, ISPRA.
- Jeong S, Yang D, Joo S, Park S, 2021. Allelopathic inhibition effects of *Myriophyllum spicatum* on growths of bloom-forming cyanobacteria and other phytoplankton species in coexistence experiments. *J Plant Biol* 64:501-510.
- Kelly R, Harrod C, Maggs CA, Reid N, 2015. Effects of *Elodea nuttallii* on temperate freshwater plants, microalgae and invertebrates: small differences between invaded and uninvaded areas. *Biol Invasions* 17:2123-2138.
- Marbuah G, Gren IM, Tattersdill K, McKie BG, 2019. Management of an aquatic invasive weed with uncertain benefits and damage costs: The case of *Elodea canadensis* in Sweden. *Water Econ Policy* 5:1850025.
- Grudnik MZ, Germ M, 2013. Spatial pattern of native species *Myriophyllum spicatum* and invasive alien species *Elodea nuttallii* after introduction of the latter one into the Drava River (Slovenia). *Biologia* 68:202-209.
- Grudnik ZM, Jelenko I, Germ M, 2014. Influence of abiotic factors on invasive behaviour of alien species *Elodea nuttallii* in the Drava River (Slovenia). *Ann Limnol-Int J Limnol* 50:1-8.
- Millane M, Caffrey J, O'Flynn C, 2016. Risk Assessment of *Elodea nuttallii* – submission for consideration of Union listing under EU IAS Regulation No. 1143/2014. EU amended template for submission February. Version 1.2.1.
- Kolada A, Pasztaleniec A, Bielczyńska A, Kutyla S, 2022. Taking over the dominance of the macrophyte community by *Elodea nuttallii* (Planch.) H. St. John is poorly reflected in ecological status assessment results. *Aquat Invasions* 17:516-542.
- Kunii H, 1982. The critical water temperature for the active growth of *Elodea nuttallii* (Planch.) St. John. *Jap J Ecol* 32:111-112.
- Kuriata-Potasznik A, Szymczyk S, Pilejczyk D, 2018. Effect of bottom sediments on the nutrient and metal concentration in macrophytes of river-lake systems. *Ann Limnol-Int J Limnol* 54:1.
- Petrzellera A, Manschot J, van Leeuwen CHA, Grutters BMC, Bakker ES, 2018. Mechanisms of Invasion Resistance of Aquatic Plant Communities. *Front Plant Sci* 9:134.
- Qi Y, Zhang Y, Xue J, Zhang Z, Cao J, Yang N, et al., 2025. Future climate change increases the risk of suitable habitats for the invasive macrophyte *Elodea nuttallii*. *Biology* 14:504.
- R Core Team, 2022. R: A Language and Environment for Statistical Computing, version 4.2.0. Available from: <https://search.gesis.org/publication/zis-RCoreTeam.2022R>
- Regione Piemonte, 2023. [Individuazione dei beneficiari e dei progetti inerenti l'eradicazione/gestione delle specie esotiche invasive di interesse unionale, ai sensi della D.G.R. n. 8 - 6354 del 28/12/2022. Riduzione della prenotazione di impegno sul capitolo 140546 e conseguente impegno di spesa sul bilancio di previsione finanziario 2022 - 2024, annualità 2023]. [Regional Law in Italian]. DD 159/A1601C/2023.
- Regione Piemonte, 2024. [Scheda monografica *Elodea nuttallii*]. [in Italian]. Turin, Gruppo di Lavoro Specie Esotiche della Regione Piemonte. Available from: <https://www.regione.piemonte.it/web/media/32551/download>
- Selvaggi A, Dellavedova R, 2016. [Note floristiche piemontesi: 747. *Elodea nuttallii* (Planch.) H. St. John (Hydrocharitaceae)]. In: Selvaggi A, Soldano A, Pascale M, Dellavedova R (eds.), [Note floristiche piemontesi n. 706-773]. [in Italian]. *Riv Piem Stor Nat* 37:349.
- SunCalc, 2025. SunCalc web application. Accessed 7 January 2026. Available from: <https://www.suncalc.org/#/45.0684,7.6831,11/2025.11.21/09:26/1/3>

- Steen B, Cardoso AC, Tsiamis K, Nieto K, Engel J, Gervasini E, 2019. Modelling hot spot areas for the invasive alien plant *Elodea nuttallii* in the EU. *Manag Biol Invasions* 10: 151-170.
- Szabó S, Peeters ETHM., Várbiro G, Borics G, Lukács BA, 2019. Phenotypic plasticity as a clue for invasion success of the submerged aquatic plant *Elodea nuttallii*. *Plant Biol* 21: 54-63.
- Tasker SJ, Foggo A, Bilton DT, 2022. Quantifying the ecological impacts of alien aquatic macrophytes: A global meta-analysis of effects on fish, macroinvertebrate and macrophyte assemblages. *Freshwater Biol* 67:1847-1860.
- Wang Y, Chen X, Liu J, Hong Y, He Q, Yu D, et al., 2019. Greater performance of exotic *Elodea nuttallii* in response to water level may make it a better invader than exotic *Egeria densa* during winter and spring. *Front Plant Sci* 10:144.
- Xiao C, Wang X, Xia J, Liu G, 2010. The effect of temperature, water level and burial depth on seed germination of *Myriophyllum spicatum* and *Potamogeton malaianus*. *Aquat Bot* 92:28-32.

Online supplementary material:

SM1 - Data collected during the five field surveys and protocols.

Fig. S1. Workflow of the statistical analyses for the presence/absence and coverage data of *Elodea nuttallii*.

Fig. S2. Graphical representation of the heatmap of the Phi correlation between macrophyte species including *Elodea nuttallii*.

Fig. S3. Graphical representation of the heatmap showing the priority areas for the management of *Elodea nuttallii*.

Tab. S1. Summary table of mean values for each sampling date.

Received: 9 January 2026; Accepted: 5 February 2026.

Contributions: Marta Zoppi, conceptualization (equal), writing – original draft (lead); methodology (equal). Gianluca Vacca, conceptualization (equal), formal analysis (lead), methodology (equal), writing - review and editing (equal). Guido Badino, writing - review and editing (equal). Sabrina Basile, writing - review and editing (equal); methodology (equal). Rossano Bolpagni, writing - review and editing (equal), methodology (equal). Dalla Vecchia Alice, writing - review and editing (equal), methodology (equal), formal analysis. Elisa Falasco, conceptualization (equal), writing - review and editing (equal). Francesca Bona, conceptualization (equal), writing – review and editing (equal), methodology (equal), project administration.

Conflict of interest: the authors declare no conflicts of interest.

Data availability: all data generated or analysed during this study are included in this published article and its supplementary files.

Acknowledgements: the authors are grateful to the Municipality of Turin - City Maintenance Department and to the Local Police Force for the essential support during the in-situ surveys. The authors acknowledge the NODES project for financing the project and MZ' PhD position.

Funding: this publication is part of the project NODES, which has received funding from the MUR – M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).

Publisher's note: all claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0).