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The Vascular Flora of Italian Volcanic Lake Calderas: A Comprehensive Floristic Study

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Abstract

A comprehensive floristic study on the vascular flora of the 11 Italian volcanic lake calderas is presented. Despite encompassing one of the Mediterranean's major freshwater systems, floristic research in these areas has proved fragmented and often outdated. By integrating literature data with original data from new floristic surveys, a total of 1182 spontaneous plant taxa were recorded, including 152 alien plants. Six taxa represent regional novelties and 102 are new for the study area, while 48 taxa reported before 1950 were not confirmed locally. From a conservation perspective, 27 taxa of national interest were reported, including two species classified as Critically Endangered (*Isoëtes sabatina*, *Vicia incisa*) and four Endangered (*Carex vulpina*, *Baldellia ranunculoides*, *Hippuris vulgaris*, *Hydrocotyle vulgaris*) according to IUCN criteria, along with 50 taxa listed on regional red lists. Floristic richness varies notably, from 124 taxa in the caldera of Lake Giulianello to 756 in Lake Bracciano, reflecting differences in caldera size, degree of anthropogenic impact and availability of previous botanical data. These results significantly enrich the floristic knowledge of the calderas of Italian volcanic lakes and may represent a solid reference for future naturalistic research in these areas.

Keywords: alien and native species; plant diversity; floristic data; volcanic lakes; Italy

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1. Introduction

Wetlands, including natural lakes, artificial basins and extensive fluvial systems, are among the world's most important habitats for the essential ecosystem services they provide, including water supply, trophic and energy resources, groundwater recharge and water purification. So vital are these functions that wetlands have earned the nickname "nature's kidneys" [1]. They are characterized by a high proportion of threatened species and distinctive plant and animal biodiversity [2–4]. Furthermore, wetlands are crucial habitats for multiple human activities (e.g., fishing, tourism, sport) and contribute directly to human well-being [5,6]. Despite their importance, wetland conservation is increasingly threatened by anthropic pressures that compromise their structure, function and biodiversity [7].

Crater lakes, formed within volcanic calderas, are among the most ecologically and geologically distinctive aquatic systems on the planet. Their origin, often linked to high-energy volcanic events, results in enclosed basins with unique limnological features, such as stratification and high mineral content. These lakes attracted attention not only for their geophysical dynamics but also for their potential to host isolated and specialized plant and animal communities. Well-studied volcanic lakes, such as Crater Lake in Oregon [8], Lake Toba in Indonesia [9,10] and Lake Atitlán in Guatemala [11], underline the global relevance of these systems in research on paleoclimate, endemisms and ecosystem resilience. Yet, despite their scientific appeal, the floristic biodiversity of volcanic lakes remains incompletely known. Existing botanical studies are geographically sparse and often rather dated, as exemplified by the early survey on Crater Lake in Oregon [8], on Wonchi crater lake in Ethiopia [12] and on Tagimaucia crater in Fiji [13]. These contributions, while valuable, underscore the lack of systematic and updated studies on plant communities in volcanic lakes.

In the Italian context, volcanic lakes are especially significant, accounting for 94% of the freshwater volume in central and southern Italy and 80% of deep lake surfaces along the Mediterranean coastline [14]. Their hydrological and geomorphological importance is matched by their ecological potential, particularly as reservoirs of plant diversity. A recent literature review on the vascular flora of Italian volcanic lakes [15] confirmed their high floristic richness and emphasized their role in the conservation of the plant biodiversity in the territory. However, this review has also shown marked temporal and spatial heterogeneity in the available data. Indeed, most of botanical surveys date back to the 19th century and focus on single plant taxa or limited areas, leaving entire lakes and their surrounding habitats insufficiently explored. This fragmented plant knowledge on Italian volcanic lakes highlights the need for more comprehensive and up-to-date floristic surveys. The present study aims to address this gap by providing a detailed description and analysis of the vascular flora of the Italian caldera lakes. Specifically, it aimed to (1) determine the overall floristic richness of these systems and compare it with expected values derived from species–area relationships and national reference parameters, (2) document floristic novelties, including newly recorded and rare lacustrine taxa, (3) assess the conservation value of this flora through the identification of species listed in national and regional IUCN Red Lists, with particular attention to narrow endemics and critically endangered taxa, (4) investigate historical floristic records in order to identify both unconfirmed species and newly observed taxa of particular interest and, finally, (5) examine the presence and distribution of alien species within the reference territory.

2. Materials and Methods

2.1. Study Area

The study area includes 11 Italian volcanic calderas associated with the main volcanic lakes present in Italy (Figure 1), spanning a total of 381.58 km^2, of which 195.28 km^2 correspond to lake surfaces. Each caldera, outlined using topographic criteria, includes the lake basin and its surrounding area within the caldera limit. These calderas are distributed between 40.9° and 42.6° latitude across central and southern Italy, specifically in Lazio (calderas of Mezzano, Bolsena, Vico, Monterosi, Bracciano, Martignano, Albano, Nemi, Giulianello), Campania (caldera of Averno) and Basilicata (caldera of Monticchio) (Figure 1). Elevation ranges from 1 m a.s.l. at Lake d'Averno to 658 m at Monticchio lakes (Lake Grande, Lake Piccolo), while caldera surfaces vary from 0.42 km^2 at Lake Giulianello to 223.6 km^2 at Lake Bolsena, the largest volcanic lake in Europe.

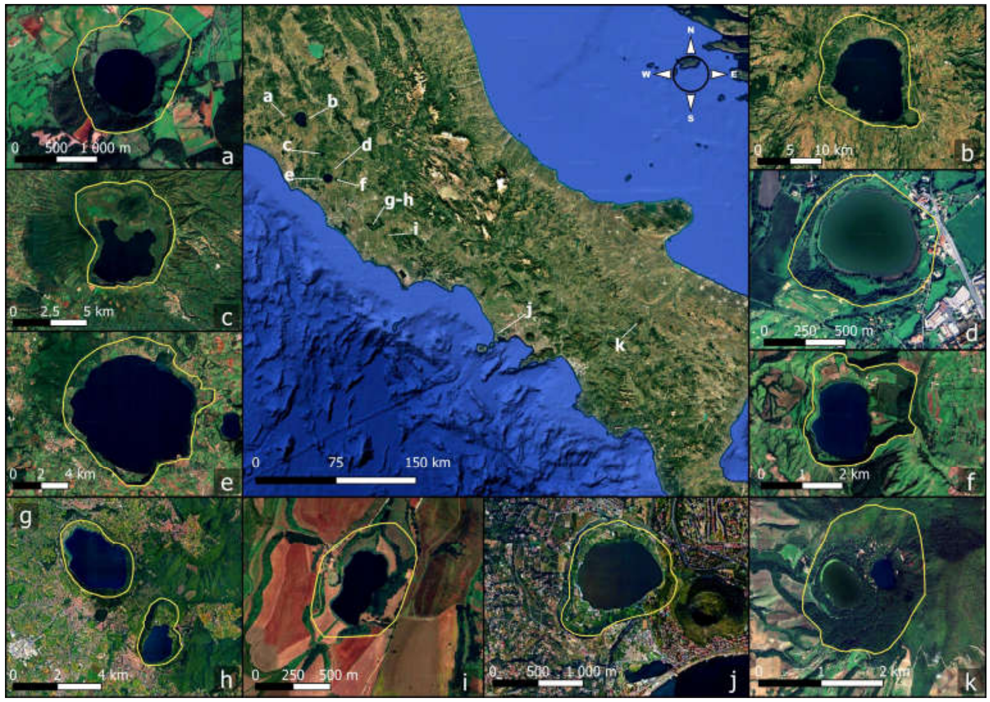

Figure 1. Study area including the main Italian volcanic lake calderas. The letters (**a**–**k**) correspond to each caldera. The limit of each caldera is defined by a yellow line ((**a**) = Mezzano, (**b**) = Bolsena, (**c**) = Vico, (**d**) = Monterosi, (**e**) = Bracciano, (**f**) = Martignano, (**g**) = Albano, (**h**) = Nemi, (**i**) = Giulianello, (**j**) = Averno, (**k**) = Monticchio). Base map is Google Maps 2025 (C).

2.2. Floristic Inventory

Prior to the fieldwork, all the available floristic data found in scientific literature relating to the study area was thoroughly examined to define the knowledge base on already locally reported plant taxa and identify the main existing floristic gaps [16–71].

Floristic samplings were carried out across the Italian volcanic lake calderas from 2023 to 2025 during the main period of plant growth there (i.e., from April to October). All major habitats present within each caldera (aquatic and lake shores, uncultivated lands, woods) were investigated to sample different types of vegetation and thus ensure adequate local floristic knowledge.

Taxonomical identification of critical or potentially rare/novelties taxa was carried out in laboratory under a stereomicroscope (Stemi 305, ZEISS, Oberkochen, Germany) using dichotomous keys of the Flora of Italy [72] and/or by consulting reference herbarium specimens. Exsiccate of the most critical and representative plants of the volcanic lake system analyzed were deposited at the Herbarium of the Roma Tre University (URT). Additional specimens are preserved in a personal collection (Herb. Pinzani) together with photographic documentation of the most relevant plant taxa.

Based on both the plant taxa recorded in this investigation and those extracted from the literature, a comprehensive floristic inventory was compiled on the study area. Angiosperm families were arranged following the APG IV (2016) classification system [73], with genera species and subspecies listed alphabetically within each family. Verification of each taxa occurrence was based on national and regional checklists [74–77]. For each taxa listed was reported life form (therophyte, hemicryptophyte, geophytes, hydrophytes, helophytes, chamaephytes, nanophanerophytes, phanerophytes), and chorotype, following the Flora of Italy [72]. The chorotypes were grouped as follows: Italian endemic, Stenomediterranean, Euromediterranean, Eurasiatic, Atlantic, Boreal and Multizonal, from which the aliens were separated. Furthermore, each taxon was also attributed as follows: endemicity status [77], category in the national [78,79] and regional [80] IUCN Red Lists, the caldera in which each taxon was found and whether it is a floristic novelty/confirmation/disappearance for that caldera compared to previous records documented in the literature. To assess whether the observed floristic richness in the study area deviated from expected patterns based on comparable Italian areas, the species–area relationship (SAR) model proposed by Arrhenius [81] was applied:

$$S = cA^{z} \quad (1)$$

The predicted number (S) of total, native and alien taxa present in the study area (A) was estimated applying the coefficients empirically derived for Italy by D'Antraccoli et al. [82]: c values of 241.2 for total taxa and 10.1 for alien taxa, alongside z coefficients of 0.281 and 0.404, respectively.

To ensure more accurate SAR estimates, the area used in the calculation was obtained by subtracting the extension of the water body (see Table 1) from the area of the caldera, as most lake areas consist of deep, vegetation-free waters. However, since vascular aquatic plants are mainly confined to shallow depths, a 5-meter-wide riparian buffer along the entire lake perimeters was added to the effective area.

Table 1. For each caldera, the following is reported: total number of plant taxa extracted by literature, number of new plant taxa recorded in this study compared to literature, total number of plant taxa, number of alien taxa, area, depth and elevation of the lake included in the caldera and area of the caldera.

Caldera	Taxa By Literature (n)	New Taxa (n)	Total Taxa (n)	Alien Taxa (n)	Lake Area (km²)	Lake Depth (m)	Lake Elevation (m)	Caldera Area (km²)
Lake Mezzano	19	154	173	17	0.48	38	452	1.54
Lake Bolsena	52	277	329	35	113.50	151	305	223.56
Lake Vico	708	12	720	47	12.93	48	510	40.68
Lake Monterosi	126	49	175	21	0.30	6	253	0.54
Lake Bracciano	692	64	756	89	56.76	165	160	89.82
Lake Martignano	19	150	169	21	2.44	60	305	5.86
Lake Albano	61	140	206	42	6.00	170	293	9.46
Lake Nemi	83	152	235	29	1.67	33	325	5.5
Lake Giulianello	5	119	124	12	0.12	10	235	0.42
Lake d'Averno	64	102	166	20	0.54	35	1	1.38
Lakes Monticchio	151	72	223	17	0.54	38	658	3.82
ALL	1080	102	1182	152	195.28	/	/	381.58

All the analyses and graphs were performed using R Studio (vers. 2023.12.1+402) program [83].

3. Results

This study produced a complete and updated inventory of the vascular flora of the Italian volcanic lake calderas (Supplementary Materials S1). A total of 1182 taxa were reported in the study area, taking into consideration both records extracted from the literature and collected through current floristic samplings. The predicted total number of taxa and of alien taxa, according to SAR predictions, is 1047 and 84, respectively.

A comparison between plant taxa recorded in this study and those documented in previous investigations revealed a significant increase in floristic richness across all calderas. The highest increase was observed in Bolsena (+277 taxa), followed by Mezzano (+154), Nemi (+152) and Martignano (+150) calderas. Notably, Lake Giulianello showed the most remarkable relative increase, with the number of recorded taxa rising from just five in previous studies to 124 in the present survey (Table 1). Among the newly recorded taxa, four represent first regional reports for Lazio (*Crepis foetida* subsp. *rhoeadifolia*, *Epilobium ciliatum*, *Miscanthus sinensis*, *Oxalis dillenii*) and two for Basilicata (*Ligustrum sinense*, *Mahonia aquifolium*). Compared to the floristic knowledge on the entire study area, 102 taxa were newly documented in the current investigation. In addition, 18 taxa reported prior to 1950 were confirmed, while 48 taxa, though reliably documented in the past, were not found.

Considering the entire flora recorded in the study area, the most represented families are Asteraceae (140 taxa), Poaceae (114) and Fabaceae (107), followed by Lamiaceae (51), Brassicaceae (48) and Rosaceae (36), while at the genus level, the most represented are *Trifolium* (27 taxa), *Vicia* (20), *Carex* (19) and *Ranunculus* (15).

The analysis of the biological spectrum (Figure 2) revealed that herbaceous plants, especially hemicryptophytes (32%), therophytes (33%) and geophytes (14%), constitute the dominant life forms (Figure 2). Concerning the chorological spectrum (Figure 3), the most frequent chorotypes are Eurasiatic (23%), Multizonal (20%) and Eurimediterranean (21%). The Italian endemismsare 16 (1.3%): *Acer cappadocicum* subsp. *lobelii*, *Adenocarpus complicatus* subsp. *samniticus*, *Alnus cordata*, *Centaurea nigrescens* subsp. *neapolitana*, *Crocus biflorus*, *Digitalis micrantha*, *Drymochloa drymeja* subsp. *exaltata*, *Echinops siculus*, *Helichrysum litoreum*, *Helleborus viridis* subsp. *bocconei*, *Isoëtes sabatina*, *Knautia calycina*, *Linaria purpurea*, *Salvia haematodes*, *Senecio ovatus* subsp. *stabianus* and *Vicia ochroleuca* subsp. *ochroleuca*.

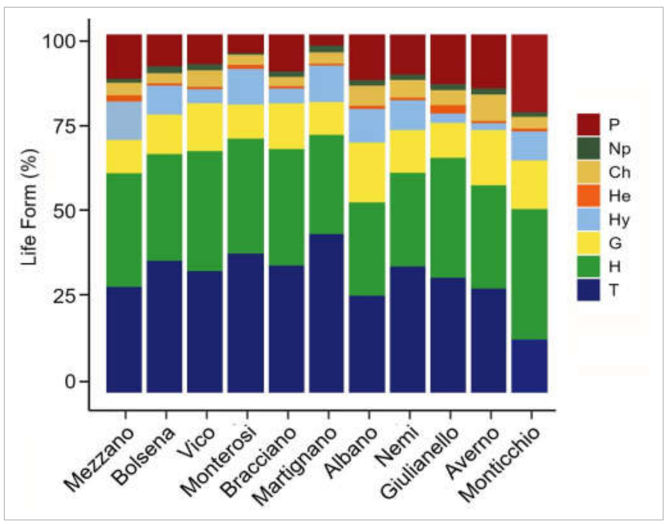

Figure 2. Life form spectrum for each caldera. T = Therophytes, H = Hemicryptophytes, G = Geophytes, Hy = Hydrophytes, He = Helophytes, Ch = Chamaephytes, Np = Nanophanerophytes, P = Phanerophytes.

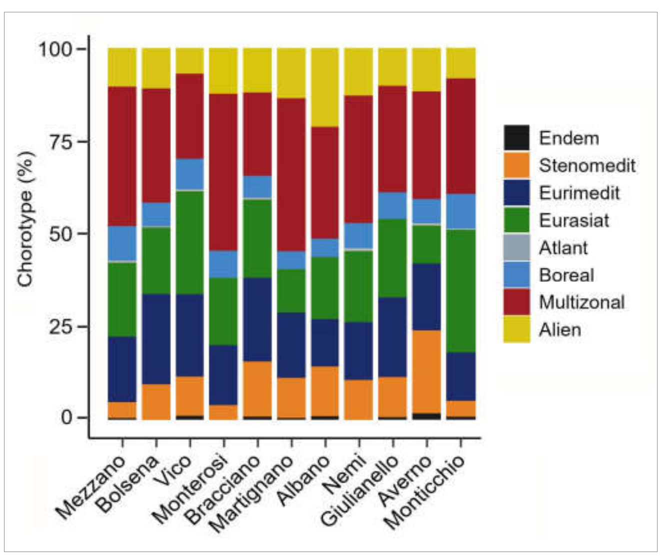

Figure 3. Chorological spectrum for each caldera. Endem = Italian endemics, Stenomedit = Stenomediterraneans, Euromedit = Euromediterraneans, Eurasiat = Eurasiatics, Atlant = Atlantics, Boreal = Boreals, Multizonal = Multizonals, Alien = alien plant species.

As regards alien plants, they represent about 13% (152 taxa) of the flora recorded in the study area. The calderas with the highest proportion of alien plants relative to the native plants are those of Albano, Martignano and Nemi, although the greatest absolute number was recorded in the caldera of Lake Bracciano (89) (Table 1). Moreover, Monterosi and Martignano show the highest combined proportion of multizonal and alien species, exceeding 50% of the total flora, while Vico and Monticchio exhibit the lowest proportions of aliens with 7% and 8%, respectively.

4. Discussion

The total plant taxa recorded in the study area (1182 taxa) exceed the number predicted by the species–area relationship (1047) developed by D'Antraccoli et al. (2024) [82], highlighting the high floristic richness of the calderas investigated. This means that the floristic diversity observed in the study area surpasses the average values reported for Italy in areas of comparable area.

The floristic richness documented in the present study not only exceeds the species–area expectations for Italy but also appears to surpass the diversity reported in previous surveys of volcanic calderas globally. This discrepancy may, at least in part, reflect an objectively higher floristic richness in the investigated area, possibly driven by its biogeographic context, habitat heterogeneity or ecological connectivity. For instance, the early botanical assessments of Crater Lake in Oregon [8] and Tagimaucia crater in Fiji [13] recorded substantially lower numbers of vascular plant taxa. Such differences may largely stem from the considerably smaller surface areas investigated in those studies, as well as from contrasting climatic conditions, such as the cooler, more temperate climate of Crater Lake or the insular tropical regime of Tagimaucia, which may influence species richness and composition. Similarly, the inventory conducted at Wonchi crater lake in Ethiopia [12] likely underrepresents the true floristic diversity due to the partial exploration of the surrounding terrain and the absence of comprehensive sampling protocols. These considerations underscore the importance of systematic and spatially extensive surveys in volcanic landscapes, where microhabitat heterogeneity and ecological isolation can foster elevated levels of plant diversity. The results presented here thus contribute a more refined and quantitatively robust perspective on the biodiversity potential of volcanic calderas, highlighting the need for renewed botanical attention to these ecologically distinctive systems.

Six plant species recorded during this study represent novelties at the regional level: *Crepis foetida* subsp. *rhoeadifolia*, *Epilobium ciliatum*, *Miscanthus sinensis* and *Oxalis dillenii* are new for Lazio, whereas *Ligustrum sinense* and *Mahonia aquifolium* are new for Basilicata. Some plants strictly linked to lacustrine habitats are rare at the regional level, such as *Ceratophyllum submersum* subsp. *submersum*, *Potamogeton berchtoldii*, *P. polygonifolius*, *Nymphaea alba* subsp. *alba*, *Nuphar lutea*, *Ludwigia palustris*, *Sparganium emersum*, *Carex paniculata* subsp. *paniculata*, *Eleocharis acicularis* and *Cladium mariscus*.

There are 27 taxa of conservation interest at the national level according to the IUCN Red Lists for Italy (Rossi et al., 2013, 2020) [78,79], 15 of which are categorized as Least Concern (LC) (for more details, see Supplementary Material S1), four Near Threatened (NT) (*Molineriella minuta*, *Ranunculus baudotii*, *Utricularia australis*, *Zannichellia palustris*), two Vulnerable (VU) (*Butomus umbellatus*, *Euphorbia palustris*), four Endangered (EN) (*Carex vulpina*, *Baldellia ranunculoides*, *Hippuris vulgaris*, *Hydrocotyle vulgaris*) and two Critically Endangered (CE) (*Isoëtes sabatina*, *Vicia incisa*). Additionally, 50 species are included in the Regional IUCN Red Lists (Conti 1997) [75] (for more details, see Supplementary Material S1). Of significant interest is the presence of the critically endangered *Isoëtes sabatina*, a small, rooted aquatic fern narrow endemic in Italy (Troìa & Azzella, 2013) [55]. This species was exclusively recorded along the southeastern shore of Lake Bracciano, where it grows on a sandy substrate in clear, nutrient-poor waters at depths ranging from 0.5 to 2.5 m.

The taxa reported in the literature before 1950 and not confirmed in this study mainly concern flora recorded in the early 20th century within the calderas of Averno, Monticchio and Vico, with fewer occurrences documented in the other calderas (see Supplementary Material S1). Some of these taxa are species associated with wet or aquatic habitats, such as *Groenlandia densa*, *Helosciadium crassipes*, *Hydrocharis morsus-ranae*, *Lemna trisulca* and *Sparganium neglectum*. However, other taxa linked to different habitats (e.g., *Asplenium obovatum* subsp. *billotii*, *Cystopteris dickieana*, *Oeosporangium pteridioides*, *Solenopsis laurentia*) were also not found in this study.

The life form spectrum calculated on the total flora of the volcanic calderas showed a nearly equal proportion of therophytes and hemicryptophytes, resulting in an H/T ratio close to 1. This pattern reflects a Mediterranean bioclimate with significant oceanic to subcontinental influences, likely shaped by climatic and altitudinal gradients across the examined calderas (Table 1). However, when analyzing each caldera, notable variability in H/T ratios emerges, highlighting distinct microclimatic as well as environmental conditions. In particular, the higher H/T ratio observed at Monticchio is typical of well-preserved Apennine forest areas, as in the case of Casentino National Forest Park [84] and the Alpe della Luna [85], whereas the high proportion of therophytes in the calderas of Martignano and Nemi is likely linked to the presence of open habitats and significant environmental instability associated with anthropogenic disturbance, which favors the establishment of short-lived species [86–88].

The chorological spectrum calculated on the total flora showed the dominance of Eurasian and Euromediterranean taxa and the relatively low presence of Stenomediterranean taxa, reflecting the marked oceanic to subcontinental influences. The scarcity of boreal elements is linked to the relatively low altitude of the calderas and the absence of significant mountain chains. Notably, multizonal and alien species account for over one third of the total flora, indicating a high and general degree of anthropic disturbance. Indeed, such disturbance generates environmental instability, reducing ecosystem resistance, and facilitates the spread of these taxa, which often outcompete successfully native taxa under these ecological conditions [89–92]. The link between human-induced disturbance and biological invasion is well-established [93–95]. The presence of alien taxa exceeds expectations by 81%, positioning the level of biological invasion of the study area closer to that recorded in semi-natural areas of comparable size (e.g., +22% in lower Sieve Valley [96], +53% in Cerbaie Hills [97]) than in more highly urbanized areas (e.g., +207% in Municipality of Empoli [98]). It should be noted that the progressive environmental degradation over the past century in the study area driven by human pressures, such as water over-exploitation, water and soil pollution, mechanical mowing and tourism, has likely compromised the integrity of these calderas and, consequently, their associated flora, also favoring the gradual entry of alien species. Moreover, the high presence of alien plants considered as invasive in Italy [75,91,99], such as *Ailanthus altissima*, *Amorpha fruticosa* and *Arundo donax*, represent a considerable threat to the conservation of the native flora. Particularly notable is the presence of the American macrophyte *Ludwigia hexapetala* at Lake Bracciano, which was the subject of recent studies due to its strong impact on native plant communities [100–102]. Although this species was only recently recorded in Lake Bracciano [53,66] and not in the other calderas investigated, it is now widely distributed across multiple sectors of this lake. Its high vegetative reproduction and diverse growth forms enable it to competitively colonize both aquatic and riparian environments. Finally, the finding of invasive alien plants that are currently widespread in the majority of the caldera investigated (e.g., *Dysphania ambrosioides*, *Erigeron bonariensis*, *E. sumatrensis*, *Symphyotrichum squamatum*, *Xanthium orientale*), but which were absent or found only sporadically in the past, highlights a recent increase in biological pollution in the areas investigated and, consequently, a general deterioration in their environmental conservation status.

5. Conclusions

This study provides an extensive overview of the vascular flora associated with Italian volcanic lake calderas, contributing to a better understanding of their plant diversity. The identification of 1182 taxa, including 152 alien species, reflects the notable richness of these habitats as well as their exposure to anthropic pressures. Although floristic knowledge varies among calderas, the number of new plant taxa recorded in this study confirms the importance of continuing floristic research in these constantly changing environments.

This pattern highlights the importance of implementing conservation strategies aimed at mitigating biodiversity loss and protecting native flora. Additionally, the confirmation of rare and threatened species highlights the floristic relevance of these calderas. Future research should focus on long-term monitoring, habitat-specific conservation measures and the management of invasive plants to support the ecological resilience of these valuable ecosystems.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments12090327/s1.

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Data Availability Statement: The complete floristic inventory and information about floristic records are available in Supplementary Materials.

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