



Flora and plant communities across a complex network of heavily modified water bodies: geographical patterns, land use and hydrochemical drivers in a temperate overexploited plain

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Received: 9 March 2021 / Revised: 12 March 2022 / Accepted: 14 March 2022 / Published online: 3 April 2022

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Abstract

The decline of freshwater flora due to alteration, reclamation and trophic perturbation of lowland wetlands is among the most relevant issues in biological conservation. The contribution of heavily modified water bodies (HMWBs) in preserving plant diversity is notable, but the underlying ecological mechanisms are not completely explored. To contribute to this debate and expand the knowledge on the role of HMWBs in maintaining wetland biodiversity in overexploited agroecosystems, a canal network of about 1150 km (SE Po valley, N-Italy) was analysed to study the geographical patterns of riparian flora and plant communities, and their land use and hydrochemical drivers. A systematic sampling procedure was adopted by randomly selecting 96 transects (10 m²) along 79 drainage canals. Additionally, 22 transects were sampled for water quality evaluation. Flora was characterised based on species richness and presence of threatened, alien and invasive species. We also studied the contribution of land use and water quality in explaining plant richness and composition. Slope and aspect of canals do not significantly affect plant species composition, whereas the «proximity to protected areas» seems to have a negative influence. Both threatened and alien plants richness decrease approaching protected areas. Among land use types, only agro-zootechnical settlements influence plant species composition, favoring nitrophilous species, as demonstrated by water parameters (the spatial patterns of nitrophilous species mirrored the progressive worsening of canal waters). This work confirms the key role of HMWBs in sustaining plant species diversity in oversimplified landscapes, highlighting complex regulation mechanisms that need further investigations.

Keywords Drainage canals · Plant diversity · Threatened plant species · Alien plant species · Po valley

Introduction

Inland waters are one of the most endangered ecosystems globally (Reid et al. 2019; Dudgeon 2019), and the loss of native freshwater species is one of the hot topics in biological conservation (e.g., Bolpagni et al. 2019; Cantonati et al. 2020; van Rees et al. 2020). This is especially relevant for lowland alluvial areas in so-called developed countries, which are largely dominated by disturbed landscapes mainly devoted to intensive agriculture and scattered urban and industrial areas (Kadoya et al. 2009; Verhoeven and Setter 2009; Bolpagni et al. 2020).

In Europe, for example, from the Industrial Revolution onwards, two centuries of drainage and simplification of lowland aquatic ecosystems have led many wetland plant species to a strong decline, or even regional extinction (e.g., *Aldrovanda vesiculosa* L., *Leucojum aestivum* L., *Marsilea*

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quadrifolia L., *Trapa natans* L., *Viola elatior* Fr., *V. pumila* Chaix; see e.g. Schnittler and Günther 1999; Dorotovičová 2013; Buldrini et al. 2013a, 2015). Here, the process of «ecosystem simplification» has been so intense that, in the last 80 years or so, 66% of the disappeared plant species includes only amphibian or aquatic taxa (Denny 1994; Sager and Clerc 2006).

Thus, it is generally acknowledged that, at least at mid-latitudes, wetland plants are among the most threatened ones (Preston and Croft 1997; Moser et al. 2002) due to habitat loss or trophic enrichment (Riis and Sand-Jensen 2001; Buldrini et al. 2013b; Bolpagni and Piotti 2016). In Italy, and especially in the Po valley, the above-mentioned issues are probably even more relevant than in other areas of the Northern Hemisphere. As is known, Italy is a biodiversity hotspot for macrophytes at a global level (Bolpagni et al. 2018; Murphy et al. 2019) and the reclamation works began in much more ancient times than elsewhere in Europe. The first examples date back to the I millennium B.C., then they continued with ups and downs until the Renaissance and the Enlightenment, ending only in 1970 (Bondesan 1990; Tinarelli and Tosetti 1998; Dallai et al. 2014, 2015). Today, the Po valley is a territory almost completely dominated by intensive farming and widespread urbanization (Romano and Ciabò 2008), with obvious deleterious consequences for wetland diversity (Guareschi et al. 2020).

In areas where multiple human impacts are so pervasive, artificial water bodies like ditches and drainage canals may play fundamental roles in offering habitats to preserve plant richness and diversity (Buldrini and Dallai 2011; Bolpagni et al. 2013, 2018; Dorotovičová 2013). In many cases, canals and other heavily modified water bodies (HMWBs) are among the very few (if not unique) spaces that can host wetland species in agroecosystems, showing moderate to high biological and environmental richness compared to the neighboring semi-natural land uses (Tölgyesi et al. 2022). Nevertheless, it must be borne in mind that drainage canals, due to their typical physiognomy (steep banks and trapezoidal cross section of variable dimensions, proximity to cultivated areas, management necessary to ensure hydraulic purposes), are particularly agriculture-sensitive habitats. Runoff and soil erosion imply the transport of a multitude of nutrients and chemicals (e.g., pesticides, fertilizers) with negative effects on riparian and aquatic biota (Herzon and Helenius 2008).

Even if the potential support of HMWBs to plant diversity and lowlands environmental quality is rather widely recognized, drainage canals are exclusively managed for hydraulic and irrigation purposes (e.g., Bolpagni 2020). For a long time, HMWBs were considered scarcely interesting from a biological viewpoint, being them artificial environments. Hence, data about flora composition, distribution and abundance (especially from a geographical and land use

perspective) are scarce and often published only in grey literature (Dorotovičová 2013; Montanari et al. 2020). All this despite the fact that HMWB networks can take on impressive dimensions, up to 100.000 km for example in Northern Italy (e.g., Bartoli et al. 2003; Bischetti and Chiaradia 2009; Longhi et al. 2010, 2011; Dallai et al. 2015). To improve the great potential of HMWBs in preserving biological diversity in areas strongly impacted by humans, a deeper knowledge about drainage canal ecology is needed. This is essential for developing effective management practices in order to harmonise the active use of canals for irrigation/hydraulic purposes with the conservation of biodiversity and ecosystem services provision.

Bearing all this in mind, the present study aims at expanding the knowledge on the role of HMWBs in maintaining wetland flora and vegetation in overexploited agroecosystems. In this regard, a wide set of hypotheses was tested using the network of the drainage canals of the Bologna plain (northern Italy) as a case study. Specifically, we expected a reduction of species richness together with the increase of slope of the studied canals (H1), but no change in the plant composition as the aspect of canals changes (H2). At the same time, a reduction in endangered plant richness as the distance from protected areas of studied canals increases was assumed (H3), as well as an opposite effect for alien and invasive plants (H4). Finally, a non-negligible role of water quality in driving flora and plant communities was hypothesized, with a progressive reduction of plant richness and an increase of communities' simplification as the canal water quality worsens (H5).

Materials and methods

Study area

The study area includes the lowland sectors of the province of Bologna (Emilia Romagna region, Italy; Fig. 1), situated in the south-eastern part of the Po Valley. The province of Bologna is one of the most productive agricultural and industrial areas of the Po basin and, consequently, one of the most impacted plain areas of Europe (Guareschi et al. 2020). The climate of the study area is continental, with cold winters and hot summers (Köppen climate classification Cfa, see Peel et al. 2007), because the Apennines stop the southern warm winds, and the thermal regulation of the Adriatic Sea is scarce depending on its shallowness. Atmospheric circulation is normally limited, thus relative humidity is high. According to 1981–2010 data, the average annual temperature is 12.4 °C; the hottest month is July (average temperature 31.4 °C) and the coldest month is January (average temperature – 1.1 °C). Annual precipitation is 684 mm,

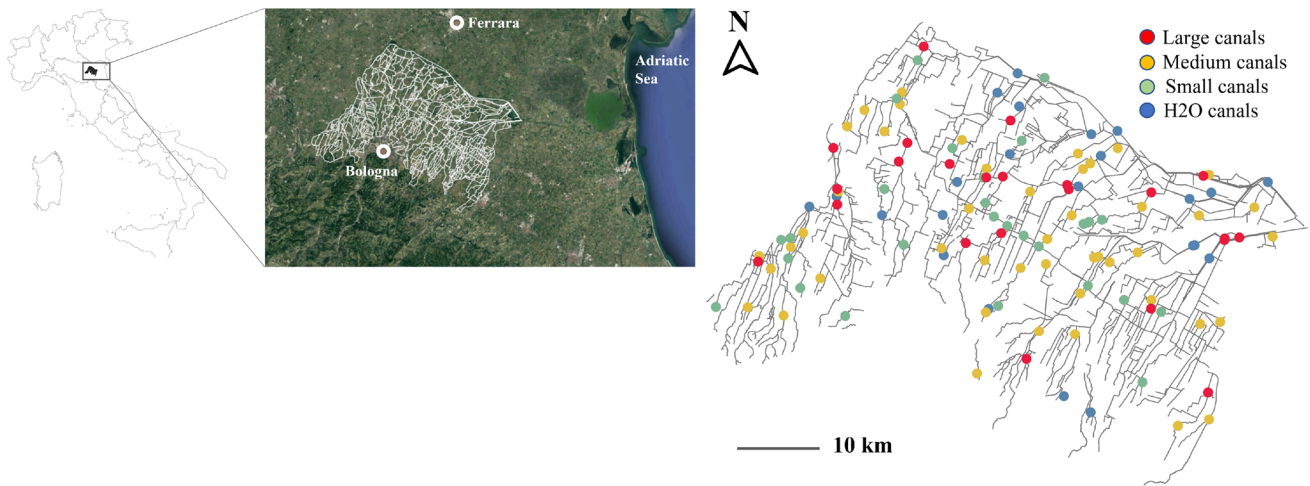


Fig. 1 Map of the study area (Bologna plain, northern Italy) with the indication of the sampling sites. The position of the study area within Italy is also shown

with a maximum in October and a minimum in July (Arpae Emilia-Romagna 2019, <https://simc.arpae.it/dext3r/>).

The River Reno (212 km) and its tributaries (Samoggia, 60 km; Idice, 78 km; Sillaro, 66 km; Santerno, 103 km; Senio, 92 km) are the principal natural water courses of the study area; they rise from the Tuscan-Emilian Apennines and have a torrential regime. However, as normally happens in overexploited alluvial plains, the most important water courses of the study area are artificial ones (i.e., canals built for land drainage and/or irrigation purposes), which are organized in a hydrological network managed by a reclamation consortium called *Consorzio della Bonifica Renana* (hereafter Consortium). The Consortium manages a territory of 3419 km², including 1439 km² of plain areas (coinciding with the study area). The canal network is 1154 km long and is used for both drainage and irrigation purposes. For this reason, all canals undergo periodic changes in their hydrological regime, with higher flows from May to September (crop growing season) and a lean period from November to March (autumn and winter times), apart from exceptional rainy events; smaller canals (with sections less than 1 m) are frequently dry during autumn and winter (Montanari et al. 2020). All the canals in the study area were excavated between 1911 and 1925 (Piccoli 1983; Furlani 2009; Zampighi 2009), therefore they have a certain stability from an environmental and ecological viewpoint, given their age (see also Dorotovičová 2013).

In the studied area, soils are generally calcareous with a prevailing clay-silty texture (Carta dei Suoli dell'Emilia-Romagna, 1:50.000, <https://geo.regione.emilia-romagna.it/cartapedo/>). Along the canals, woody species are practically absent, due to the periodic mowing of banks to permit a better water runoff in case of rainfall. Here, the vegetation is composed by widely spread herbaceous plant species (e.g.,

sub-cosmopolitan, Eurasian, palaeotemperate), whereas more ecologically demanding species (stenotopic, red list species) are very rare (<3% of the total floristic list, cfr. Montanari et al. 2020).

Sampling design

A preliminary inspection of the studied HMWB network was carried out by a GIS approach to identify the prevalent kinds of drainage canals. Ancillary information was provided by the Consortium and Emilia-Romagna Agency for Environmental Protection (Arpae). Based on this survey, canals were grouped in three different classes according to their depth (large, medium and small, i.e., canals with bank-full depths < 2 m, from 2 to 4 m and > 4 m, respectively). By using the random points function of QGIS, 79 canals and 96 sites were randomly selected to be subjected to field investigation.

The number of sites to monitor was defined based on the total length of the three canal depth classes, to obtain an array of sites representative of the entire hydrological network (Chiarucci 2007). Additionally, if two or more sites were selected along the same canal a minimum distance between sites of 2 km was imposed. By this action, 23 large canals (L), 46 medium canals (M), 27 small canals (S) were selected (Fig. 1). In addition, 22 sampling sites were selected according to opportunistic criteria, as they coincide with the closure points of the hydrological sub-basins (here referred to as H₂O). Therefore, the total number of sites considered is 118 (Fig. 1).

In each site, a transect of 10 m × 1 m (composed by 10 contiguous 1 m × 1 m plots) was positioned along the canal bank, parallel to the water flow. Starting from the water-bank interface, the transect was placed to include in the analysis

the first 10 cm of the canal water body and the first 90 cm of the bank slope.

All plant species identified in the transect were recorded, deriving their frequency as the sum of the occurrences in the 10 plots that form each transect. Nomenclature follows Pignatti et al. (2017–2019).

Spatial data

For this study we used:

1. the Land Use Map 2017 (reference scale 1:10.000) by the Emilia-Romagna Region. It is characterized by a minimum patch size of 0.16 ha and a minimum size of 7 m for linear elements. This map was realised by the Region using color (RGB) and infrared orthophotographs TeA of 2017 (20 cm pixel resolution). The classification system used for the legend is Corine Land Cover IV and identifies the categories shown in Table 1 and Supplementary material 1. We merged the aforementioned land use categories into the following macro-categories: «Artificial uses», «Water bodies and inland wetlands», «Wood», «Meadows», «Agricultural area», «Agro-zootechnical settlements».
2. The map of the water catchment areas of all drainage canals in the territory of the Consortium.
3. The map of protected areas in the area studied (regional parks, Natura 2000 sites, local protected areas).
4. The regional map of Military Geographical Institute (IGM) altitude points, grid of 200 m.

Ground data

For the study we also used:

- vegetation data (collected by the Canal Bank Research Group as described in Sampling design),

- water quality data collected by a team of the DISTAL Department of the University of Bologna, from April to October 2019 to provide baseline data for the quality of the water supply to the farms of the area. The selected sampling points coincide with the closure points of 22 sub-basins of the drainage network examined (Fig. 2).

Hydrochemical data

At the H₂O sites, pH and electrical conductivity (EC) were monitored by a portable multiprobe (Hanna instruments) and a water sample was collected using a plastic bottle (1 L) by hand every month (once a month, in the period from April to September 2019; *n* = 6). All the samples were stored in a cooled box (at 4 °C) and then quickly transferred (within 8 h) to the laboratory where they were processed for the subsequent analysis phases. The water samples were then filtered for the determination of the following parameters, according to standard methods (Ottaviani and Bonadonna 2007;

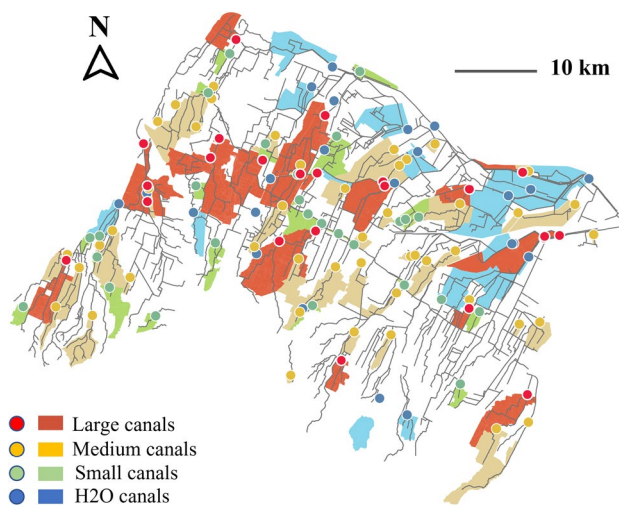


Fig. 2 Map of the sampled transects (colored circles) and their upstream basins (colored areas) (color figure online)

Table 1 Percentage of macro-categories of land use in the upstream basin of each type of canal sampled (L=large canals, M=medium canals, S=small canals, H₂O=canals for which both vegetation and water quality data are available)

Land use macro-categories	Canal type			
	L	M	S	H ₂ O
Artificial surfaces (Ec, Ed, Er, Ia, Ic, Io, Is, It, Qa, Qc, Qi, Qq, Qr, Qs, Qu, Ra, Re, Rf, Ri, Rm, Ro, Rs, Va, Vd, Vg, Vi, Vm, Vs, Vt, Vv, Es)	15.8	13.5	13.5	7.6
Water bodies and inland wetlands (Ac, Aa, Ax, Af, Ar, Av, Zi)	5.2	3.4	2.2	7.9
Wood (Bm, Bp, Bq, Br, Bs, Ta, Tn)	1.5	2.7	0.9	2.5
Meadows (Fs, Pp, Rv, Vp, Vx)	1.8	1.4	1.6	0.7
Agricultural areas (So, Se, Sv, Ze, Zo, Zt, Sn, Cf, Co, Cv, Cl, Cp)	75.1	78.3	81.3	80.6
Agro-zootechnical settlements (Iz)	0.7	0.7	0.5	0.6
Total percentage	100	100	100	100

For the abbreviations of land use categories see Supplementary material 1

APHA 2017): ammonia (NH_4^+), boron (B^{3+}), biochemical oxygen demand (BOD5), calcium (Ca^{2+}), chemical oxygen demand (COD), chlorines (Cl^-), dissolved inorganic carbon (CARB), magnesium (Mg^{2+}), nitrates (NO_3^-), nitrites (NO_2^-), orthophosphates (PO_4^{3-}), potash (K^+), sodium (Na^+), sodium absorption ratio (SAR), sulphates (SO_4^{2-}), and total nitrogen (NT). For each parameter, the minimum, maximum and mean values were determined based on the multitemporal investigation.

Data analyses

To achieve the purpose of the study, the analysis of the flora and plant communities was carried out in relation to both geographical patterns in each transect (slope, bank aspect, land use of upstream basin and proximity to protected areas of each transect) and water quality.

Geographical patterns and species analysis

To calculate the slope of canal types (L, M, S, H_2O), from the regional map of IGM altitude points, we extracted the farthest points within a 2 km radius area around each transect (classified as L, M, S or H_2O). Assuming that the air-line distance between the two selected altitude points was 2 km, the slope was calculated as a percentage of the stretch of canal into which each transect falls. Moreover, the bank aspect was also recorded to verify whether this parameter was able to affect the plant community. This was possible for 104 out of 118 sampled transects, the other lacking properly collection of field information.

We also detected the land use in the upstream basin of each transect using the Land Use Map 2017. We considered an upstream stretch of canal of 2 km at least (up to the entire basin when the stretch of canal was not longer than 10 km). In case there were more than one transect along the same canal, the upstream basin of each transect was identified excluding what was already attributed to the transect placed upstream. We normalised the areas of each land use in each upstream basin to allow fully comparability between them. An upstream basin could not be identified for five transects (NA_01, NA_02, NA_03, SAM_01, SAV_01) because they lied on canals that do not receive water from the surrounding agricultural areas, but only from the urban area of Bologna distant even tens of kilometres (rainwater and city water treatment plant). Therefore, data about upstream basins are available for 113 transects only.

The proximity of transects to protected areas (EU Natura 2000 sites, regional parks, local protected areas) was categorised into four classes: (a) high, if transects fell within a protected area; (b) medium, if transects fell within a buffer of 100 m from a protected area; (c) low, if transects fell within a buffer of 101–500 m from a protected area; (d) scarce, if

transects fell more than 500 m away from a protected area. In addition, the analysis of the presence of alien, invasive and threatened plant species in the transects according to the four proximity classes was performed.

The alien and invasive species were identified according to the classification proposed by Galasso et al. (2018). These authors defined as alien the species whose presence in Italy is due to the intentional or unintentional release by humans, or which have spread to an area where they were not native. Aliens include the naturalised allochthonous species and the allochthonous casual species. The invasive species, a subgroup of the aliens, can reproduce quickly and at considerable distances from the mother plant and this gives them a huge potential as colonisers of vast areas (Pyšek et al. 2004; Galasso et al. 2018). According to Jalas et al. (1972), cryptogenic taxa and archaeophytes (the alien species present in Europe since before 1492) were grouped together with native species. Threatened species were attributed to an IUCN category according to the regional list of rare/threatened plant (Regione Emilia-Romagna 2017).

Inference on geographical patterns

The analysis of transect plant composition in relation to the geographical patterns were obtained first performing a non-metric multidimensional scaling (NMDS) on transect species composition data, then overlaying to the ordination scatterplot the data of the three above mentioned geographic variables (i.e., slope, bank aspect, proximity to protected areas of each transect). NMDS is a robust unconstrained ordination method commonly used in plant ecology (see e.g. Montanari et al. 2020; Chiarucci et al. 2021). Separate analyses were performed for the complete dataset and alien species alone to verify possible significant effects of the geographic variables on the detected species composition. A PERMANOVA was subsequently applied to verify the significance of each relationship recorded with the NMDS. Only to verify significant effects of the land use of the upstream basins (data grouped into macro-categories) on species composition, the fitting function of R with 999 permutations was applied to the NMDS results.

Water quality

The analysis of plant community in relation to water quality was performed applying the NMDS to the species composition of the 17 H_2O transects for which it was possible to identify the upstream basin, separately using presence/absence and abundance data. The PERMANOVA was subsequently applied to verify the significance effect of the water chemical parameters on plant community.

For the study of geographical patterns QGIS version 3.10 was used. All the shape files were aligned to the ETRS 1989

UTM Zone 32N geographical reference system. The shape files with the regional system called UTMRRER were converted with the program Conver_2013 version 2.05.07.

For the comparison of plant species data with geographical patterns, water quality and land use, the software R version 3.6.0 was used (R Core Team 2019).

Results

Canal structural and geographical features

The slope of the canals varied from 0.00% to 0.50%, with only one canal having a higher slope (0.75%; Supplementary material 2). The most frequent slope values—exhibited by 42.4% of the transects—ranged from 0.00% to 0.05%. Conversely, only 4.2% of the transects fell into canals with slopes between 0.40% and 0.50%. The four different canal types investigated showed very similar average slopes, ranging from 0.12% (large, medium and H₂O canals) to 0.14% (small canals; see Supplementary material 3).

Considering the bank aspect of the sampled transects (Table 2), large canals showed a prevalent exposure to north (26%), followed by south (21.7%) and west (17.4%) exposure. Between medium canals, transects were mainly exposed to south-east (28.3%) and north-west (21.7%), whereas small canals to south-west (18.5%), north-west (14.8%) and east (14.8%). The H₂O canals had a predominant south-east (27.3%) and north-west (18.2%) exposure. Overall, a major part of the transects was exposed to south-east (17.8%), north-west (15.3%) and south (12.7%).

The land use classes were distributed fairly uniformly between large, medium and small canals. The most common class was «Irrigated plain arable land», with values ranging from 69.5% in large canals to 75.2% in small canals, followed by «Fruit trees», ranging from 2.9% in large canals to 4.2% in small canals, and «Isolated residential facilities», ranging from 3.5% in large canals to 4.7% in small canals. The land-use classes «canals» and «inland wetlands» had values varying from 0.5% in medium canals to 1.5% in large canals and from 0.1 to 4.3% respectively in small canals and H₂O canals (Supplementary material 4). The analysis of land use according to macro-categories (Table 1) showed that «agricultural areas» was, by far, the most widespread

macro-category of land use: it ranged from 75.1% in large canals to 81.3% in small canals. The next land use macro-category in importance was «artificial surfaces», which varied from 13.5% in small and medium canals to 15.8% in large ones. The macro-category «water bodies and inland wetlands» varied between 2.2% in the upstream basins of small canals and 5.2% of the upstream basins of large canals.

Concerning the «proximity to protected areas» parameter, only 3.4% of the sites fell within regional parks, while 10.2% of the transects belonged to the Natura 2000 network. Of these sites, 2.5% and 6.8% fell in a buffer of 100 m and of 101–500 m from their borders, respectively. Finally, only 0.85% of the sites fell within a local protected area.

Out of 272 total species sampled, 14 were alien, 9 invasive and 7 threatened species (Table 3), equal to 5.5%, 3.3% and 2.6% of the total richness, respectively. Similar results were obtained for the 96 «terrestrial» transects, with a total of 251 species and an alien contribution of 4.8%, while the proportion of invasive and threatened species stood at 2.8%. In the 17 H₂O transects, of the 153 total species, the alien accounted for 5.9%, the invasive and the threatened taxa for 3.3% and 0.6%, respectively. Considering the presence of alien, invasive and threatened (according to IUCN criteria) species, we found that 47.5% of the transects did not host alien or invasive or threatened species, whereas in the remnant 52.5% their presence was subdivided as follows: 17.8% of the transects had 1 threatened species, 0.85% of the transect had 2 threatened species, 26.3% of the transects had 1 alien species, 16.1% of the transects had 1 invasive species, 11.0% of the transects had 2 invasive species, 2.54% of the transects had 3 invasive species, and 0.85% of the transects had 4, 5 or 6 invasive species.

Considering all types of protected areas present in the studied area, we verified that only 4 invasive and 2 threatened species were observed inside them. The largest number of threatened species were recorded outside the buffer of 500 m from protected areas. It should be considered that only 23.7% of the 118 sampled transects fell within or around 500 m from protected areas.

Canal plant composition drivers

The NMDS analysis applied to the species composition data showed a wide dispersion of transects (Fig. 3), that means

Table 2 Frequency of each bank aspect type in 104 of the sampled transects (L=large canals, M=medium canals, S=small canals, H₂O=canals for which both vegetation and water quality data are available)

Canal type	Not recorded	E	N	NE	NW	W	S	SE	SW
L	2	3	6	1	0	4	5	1	1
M	5	3	1	4	10	2	5	13	3
S	6	4	2	2	4	1	2	1	5
H ₂ O	1	3	0	1	4	1	3	6	3
Total	14	13	9	8	18	8	15	21	12

Table 3 Occurrences of alien, invasive and threatened plant species among the canals of Bologna plain (L=large canals, M=medium canals, S=small canals, H₂O=canals for which both vegetation and water quality data are available)

	Species	Canal type			
		L	M	S	H ₂ O
Alien taxa	<i>Acer negundo</i> L.	–	1	–	1
	<i>Erigeron annuus</i> (L.) Desf.	–	2	1	1
	<i>Paspalum distichum</i> L.	–	–	1	–
	<i>Populus deltoides</i> Marshall	–	–	–	1
	<i>Veronica persica</i> Poir.	2	6	10	4
	TOTAL OCCURRENCES	2	9	12	7
	Invasive taxa	<i>Ailanthus altissima</i> (Mill.) Swingle	–	–	–
<i>Amaranthus retroflexus</i> L.		1	–	–	–
<i>Amorpha fruticosa</i> L.		4	2	–	1
<i>Artemisia verlotiorum</i> Lamotte		2	–	–	–
<i>Erigeron canadensis</i> L.		–	2	–	–
<i>Robinia pseudoacacia</i> L.		–	1	1	4
<i>Rumex cristatus</i> DC.		–	–	–	1
<i>Sorghum halepense</i> (L.) Pers.		1	3	1	2
<i>Xanthium orientale</i> L. ssp. <i>italicum</i> (Moretti) Greuter		1	1	–	–
TOTAL OCCURRENCES		9	9	2	11
Threatened taxa	<i>Allium angulosum</i> L. - EN -	–	1	–	–
	<i>Euphorbia palustris</i> L. - EN -	4	2	3	1
	<i>Juncus subnodulosus</i> Schrank - CR -	–	1	–	–
	<i>Nuphar lutea</i> (L.) Sm. - VU -	1	–	–	–
	<i>Samolus valerandi</i> L. - EN -	–	–	1	–
	<i>Schoenoplectus tabernaemontani</i> (C.C. Gmel.) Palla - VU -	–	–	1	–
	<i>Sium latifolium</i> L. - EN -	–	–	1	–
	TOTAL OCCURRENCES	5	4	6	1

IUCN risk categories are also provided (CR=critically endangered, EN=endangered, VU=vulnerable), according to Regione Emilia-Romagna (2017)

a substantial equivalence of plant communities, dominated by generalist herbaceous species typical of disturbed grasslands in all the canal categories considered. Only a few sites (CB_02, CF_01, GR_02, GR_03, NA_03) turned out to be well separated, because they were characterised by a mono-specific dominance of *Phragmites australis* (Cav.) Trin.

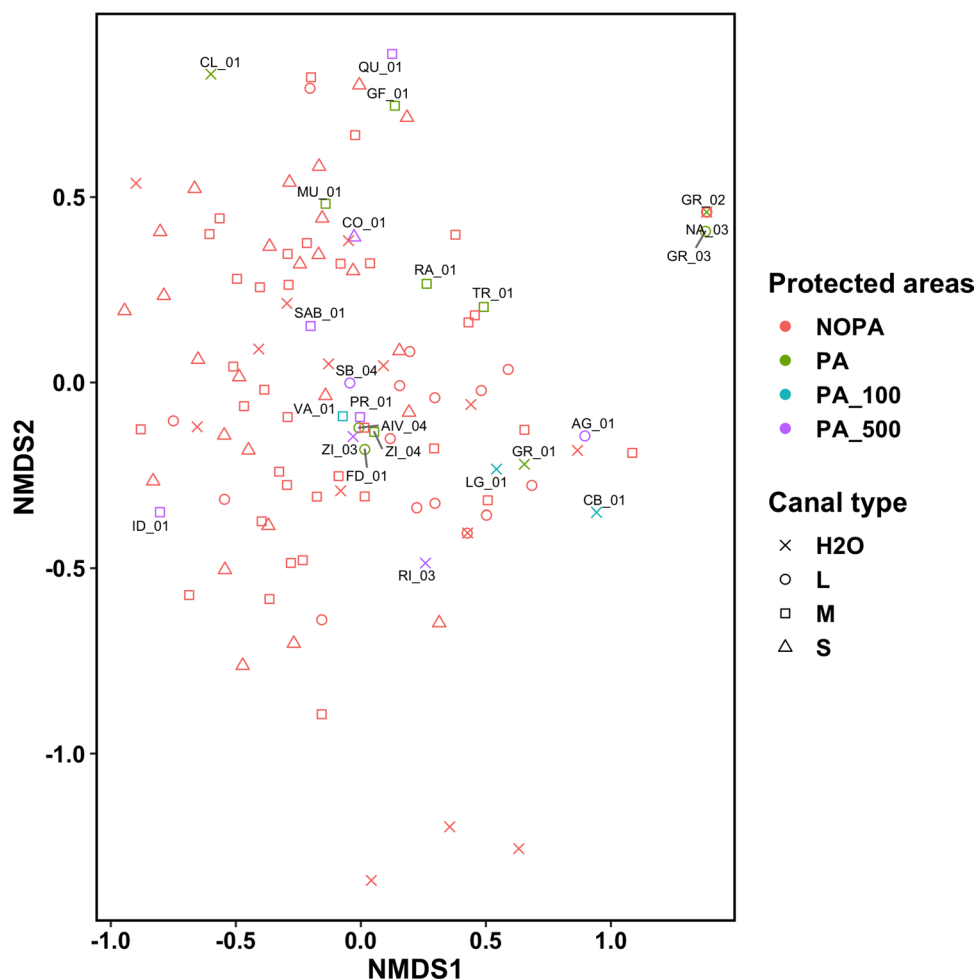
NMDS results excluded a significant influence of slope and bank aspect on plant composition arrangement across transects. Similar evidence was found by the PERMANOVA test (with $P=0.1$ and 0.2 for slope and bank aspect, respectively). Conversely, both the NMDS and PERMANOVA ($P<0.05$) found a significant contribution of the «proximity to protected areas», highlighting a small group of transects with greater similarity (Fig. 3). These transects (ZI_03, ZI_04, FD_01, AIV_04, PR_01 and SB_04) share the following species: *Alopecurus myosuroides* Huds., *Elymus repens* (L.) Gould, *Galium aparine* L., *Geranium columbinum* L., *Lythrum salicaria* L., *P. australis* and *Urtica dioica* L. The same factor (proximity to protected areas) well differentiated two transects (RD_01 and RC_01; see Supplementary material 5) based

on the alien or invasive or threatened species (AIT) components by the presence of two quite rare species in lowlands of northern Italy: *Juncus subnodulosus* Schrank in RD_01 and *Allium angulosum* L. in RC_01 (Fig. 3). Otherwise, the PERMANOVA analysis showed that proximity to protected areas does not influence the presence of AIT between transects ($P>0.1$).

Another two well defined site clusters were identified by NMDS, the former characterised by the recurring presence of *Schoenoplectus lacustris* (L.) Palla, in association with *Acer negundo* L. (MO_02, SB_03) and *Paspalum distichum* L. (DC_01), and the latter by *Veronica persica* Poir. (18.6% of the transects), *Euphorbia palustris* L. (8.5% of the transects), *Sorghum halepense* (L.) Pers. (5.9% of the transects), *Amorpha fruticosa* L. (5.9% of the transects) and *Robinia pseudoacacia* L. (5.1% of the transects).

Land use categories did not result in a clear zonation of species across sites. Exclusively the macro-category «Agro-zootechnical settlements» was related to the presence of two nitrophilous species (*Lysimachia nummularia* L. and *Setaria pumila* (Poir.) Roem. et Schult.; Fig. 4).

Fig. 3 Non-metric multidimensional scaling plot, in which each point represents a single transect of the 118 sampled (stress=0.18). The distances from protected areas (PA) were grouped in 4 classes: inside PA (green), outside in a buffer of 100 m (blue), outside in a buffer from 100 to 500 m (purple), outside more than 500 m (red) (color figure online)



Canal water quality effects

Results confirmed a significant predictive value of pH (in the range 7.2–9.2, and with a mean value of 7.9 pH units), sodium ($11.5\text{--}176.0$, 45.6 mg L^{-1}), sodium adsorption ratio ($1.6\text{--}16.4$, 4.7 mEq L^{-1}), orthophosphates ($0.03\text{--}3.53$, 0.70 mg L^{-1}) and chlorine ($8\text{--}227$, $56\text{ }\mu\text{g L}^{-1}$) for the plant community composition (Fig. 5). As the availability of phosphorus increases (as a proxy for a progressive deterioration in the quality of canal water), a progressive structural simplification of the communities was observed, with a progressive increase in the local representativeness of ruderal plant species. Concerning the abundance data, ammonia (up to 8.1 mg L^{-1}) emerged as a key predictive feature, being associated with canals characterised by *R. pseudoacacia*, *Rubus ulmifolius* Schott, *Sambucus nigra* L. and *U. dioica* (Fig. 6).

Discussion

The present results contribute to better understand the role of HMWBs and land uses in supporting flora and vegetation in a highly anthropized agroecosystem such as the Po Valley. The notable number of species found (272 species) confirms that HMWBs—and artificial waterbodies more in general—can mimic natural environments, representing habitat refugia for some endangered plant species (e.g., *E. palustris*, *J. subnodulosus*, *S. lacustris*), as already seen by Gentili et al. (2010), Buldrini and Santini (2016), Bolpagni (2020) and Guareschi et al. (2020) in the same geographical context. However, the observed links between plant spatial patterns and drivers (e.g., structural, geographical, and quality canal features) were weak, suggesting the probable existence of (neglected) leading factors of canal

Fig. 4 Non-metric multidimensional scaling plot in which each point represents a single transect (stress = 0.20); occurrence data were used applying the Bray–Curtis method. The macro-category of land use upstream of transects significant for the plant composition is indicated by the arrow (Set_Agro_Zoo: Agro-zootechnical settlements; $P \leq 0.05$). The species that mainly characterise the groups of transects are also shown ($P \leq 0.05$): Alt.can: *Althaea cannabina*, Che.alb: *Chenopodium album*, Con.arv: *Convolvulus arvensis*, Dau.car: *Daucus carota*, Ely.rep: *Elymus repens*, Gal.mol: *Galium mollugo*, Gal.ver: *Galium verum*, Hel.ech: *Helminthotheca echinoides*, Lys.num: *Lysimachia nummularia*, Phr.aus: *Phragmites australis*, Pla.lan: *Plantago lanceolata*, Poa.tri: *Poa trivialis*, Pol.avi: *Polygonum aviculare*, Set.pum: *Setaria pumila*, Sil.lat: *Silene latifolia*, Urt.dio: *Urtica dioica*

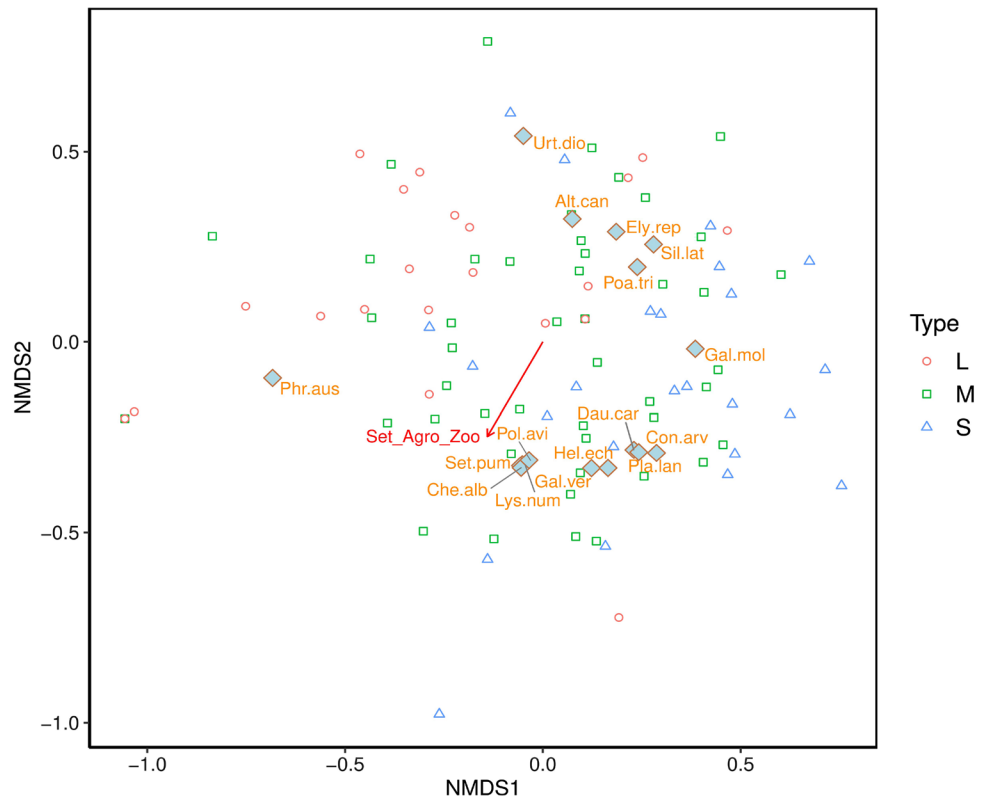
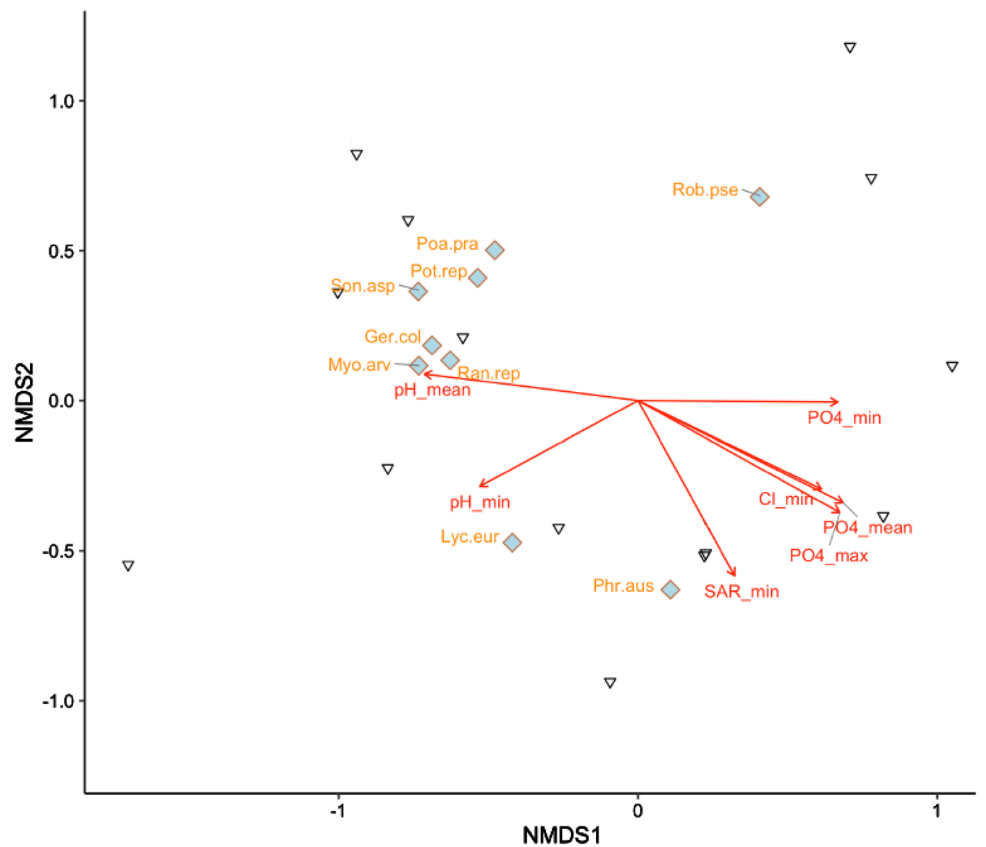


Fig. 5 Non-metric multidimensional scaling plot in which each point represents a H₂O transect (stress = 0.13); presence/absence data were used applying the Jaccard method. The arrows represent the water quality parameters whose correlation with the plant composition of the transects is statistically significant ($P \leq 0.05$): Cl_min: chlorines (minimum), pH_min/mean: minimum and mean pH, PO₄_min/mean/max: orthophosphates (minimum, mean and maximum), SAR_min: minimum sodium absorption ratio. The plant species that most characterise the groups of transects are also shown ($P \leq 0.05$): Ger.col: *Geranium columbinum*, Lyc.eur: *Lycopus europaeus*, Myo.arv: *Myosotis arvensis*, Phr.aus: *Phragmites australis*, Poa.pra: *Poa pratensis*, Pot.rep: *Potentilla reptans*, Ran.rep: *Ranunculus repens*, Rob.pse: *Robinia pseudoacacia*, Son.asp: *Sonchus asper*



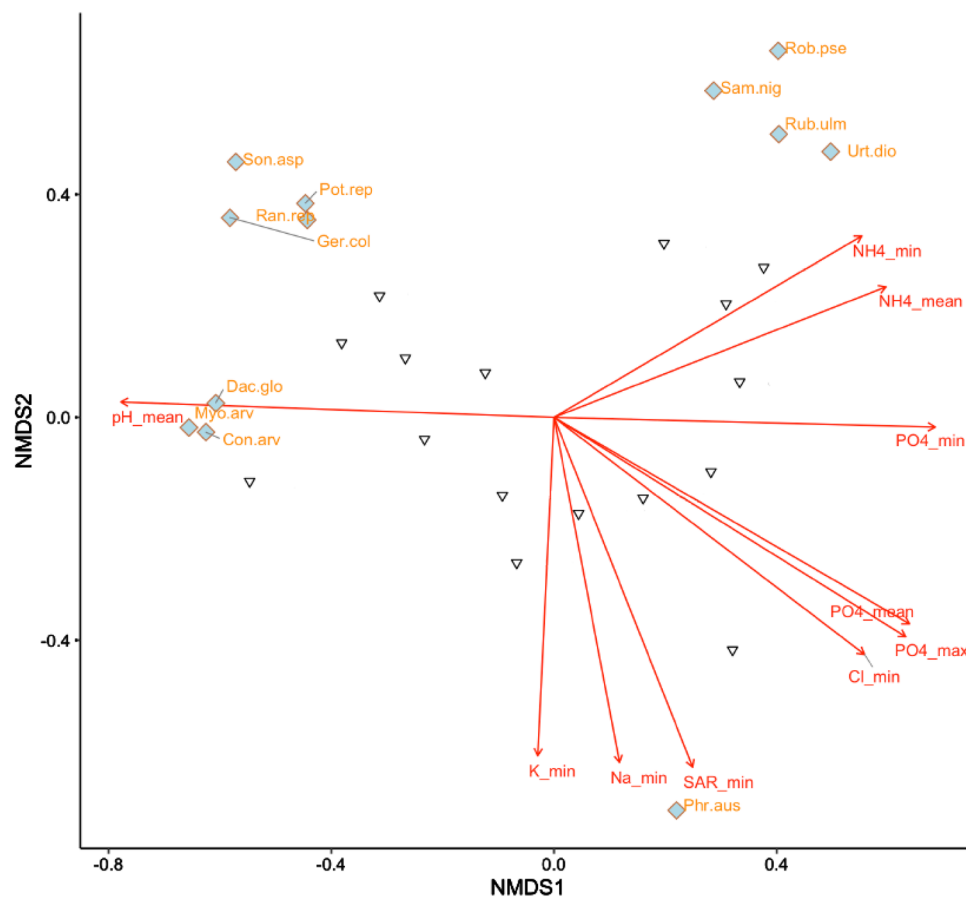


Fig. 6 Non-metric multidimensional scaling plot in which each point represents a H₂O transect (stress=0.134); occurrence data were used applying the Bray–Curtis method. The arrows represent the water quality parameters whose correlation with the plant composition of the transects is statistically significant ($P \leq 0.05$): Cl_min: chlorines (minimum), K_min: potash (minimum), Na_min: sodium (minimum), NH₄_min/mean: ammonia (minimum and mean), pH_mean: mean pH, PO₄_min/mean/max: orthophosphates (minimum, mean and

maximum), SAR_min: minimum sodium absorption ratio. The plant species that most characterise the groups of transects are also shown ($P \leq 0.05$): Con.arv: *Convolvulus arvensis*, Dac.glo: *Dactylis glomerata*, Ger.col: *Geranium columbinum*, Myo.arv: *Myosotis arvensis*, Phr.aus: *Phragmites australis*, Pot.rep: *Potentilla reptans*, Ran.rep: *Ranunculus repens*, Rob.pse: *Robinia pseudoacacia*, Rub.ulm: *Rubus ulmifolius*, Sam.nig: *Sambucus nigra*, Son.asp: *Sonchus asper*, Urt.dio: *Urtica dioica*

bank plant biodiversity not considered in this investigation. Nevertheless, the present data contribute to reinforce the idea of the presence of complex regulatory mechanisms underlying the plant richness and abundance along the banks of HMWBs, with clearly differentiated responses by functional group (e.g., rare or threatened taxa, alien and invasive taxa).

This is a general relevant outcome considering that, as remarked by Bolpagni et al. (2019) and Cantonati et al. (2020), freshwater environments are key ecosystem service providers. Therefore, reclamation consortia, farmers, environmental managers and politicians must know the biological, ecological and conservation importance of drainage canals as one of the last aquatic habitats and refuge available in agricultural areas and, wherever appropriate, protect the most valuable sites (Buldrini et al. 2013c; Hill et al. 2016; Bolpagni 2020).

Regarding the initial hypotheses, the present findings suggest the existence of differentiated behaviours of plant spatial patterns along the explored HMWB network. Contrary to our expectations, a reduction of species richness along with the increase of average slope of canals was not verified, given the absence of significant slope gradients between all the sites analysed (H1 rejected). Otherwise, no changes in the plant composition of the transects in relation to their aspect were confirmed, demonstrating that the factor «aspect» turns out to be not (or only weakly) influent on the bank plant composition (H2 accepted). The hypothesis that there is a reduction in endangered species richness as the distance from protected areas increases has to be discarded, since threatened species increase as the distance from protected areas increases (H3 rejected). In addition, the same behaviour was fully confirmed for alien and invasive species (H4 accepted). Finally, the key role of water quality of canals

in driving flora and plant communities is also confirmed, with an increase of community simplification as canal waters worsened (H5 accepted).

Structural, geographical and hydrochemical drivers

In our study area, we verified that both structural and geographical features characterizing the transects (slope, aspect, proximity to protected areas) and land use behave as weak drivers of the plant composition of the transects (apart from the proximity to protected areas). It emerged that a significant proportion of variability among transects is not explained by the drivers considered. Probably, the forces acting at the local scale, e.g. multiple and random events such as floods, sudden drought events, variations in management practices, crop changes in upstream basins and so on, can deeply modify the spatial patterns of species along canals. At the same time, the level of pressure exerted on the system under study is so intense as to homogenise the distribution patterns of the characteristic flora of canal banks, reducing the expected differences among canal types, as already observed by Montanari et al. (2020) exactly on the same area and canal system here studied. This is confirmed by the significant role attributable to the quality of water. Some of the monitored parameters (pH, orthophosphate, ammonia and sodium absorption ratio) were significant with respect to the HMWB plant richness, but limited to particular groups of species (e.g., nitrophilous ones). Nitrogen availability confirms its high predictivity value, being one of the key elements controlling plant composition, especially in riparian ecosystems due to its high mobility across ecosystem boundaries (Bornette and Puijalon 2011).

Our results agree with the study of Baláži and Hrivnák (2016), who reported significant correlations between macrophyte communities and the water parameters within the Pannonian Lowland (South Slovakia), especially in terms of chemical oxygen demand (COD), electrical conductivity, ammonia and pH. In the present case, the almost complete absence of submerged macrophytes along the studied canals can be explained by the low levels of oxygenation of the canals (Sukhodolova et al. 2017) in line with the COD and biochemical oxygen demand results. A possible explanation may be the large use of pesticides in the area, and the presence of point civil and industrial discharges along the canal network, all possible causes of relevant, local organic pollution (Baláži and Hrivnák 2016). However, in the present study area, a key role in shaping the biodiversity of the banks can be attributable to the current canals management strategies, which foresee, during autumn and winter, the partial emptying of the canals themselves to prevent flood events due to strong and prolonged rainfall. These aspects must necessarily be investigated to try to maximise the ecological contribution of canals.

Final remarks

Over centuries, extensive artificial hydrological networks have been created and maintained to reclaim floodplains and offer spaces for agriculture and livestock and, subsequently, to irrigate crops and protect the inhabitants from floods. The preeminent uses of HMWBs imply the frequent remodeling of sections and embankments, and a direct exposure to physical and chemical perturbations due to their role of drainage of agricultural landscapes and urban settlements, with important consequences on canal bank biodiversity. Only recently, the awareness that artificial hydrological networks could act as a refuge for species of conservation interest and may improve the environmental quality of agroecosystems has become increasingly widespread.

These functions would be even more relevant if the management of the canals—and HMWBs more generally—paid more attention to sustain their natural features and services (Soana et al. 2019; Pinardi et al. 2020). In view, therefore, of the huge susceptibility of overexploited floodplains to external perturbations, it will be necessary to rethink the role of irrigation canals soon. They have to be considered not only as an irreplaceable infrastructure for the hydraulic management of catchments, but also as the ecological cornerstone of agroecosystems to enhance the environmental quality of crossed areas. HMWBs have to be transformed into a powerful green infrastructure able to mitigate the impacts of human action and climate change and to connect the residual wetlands of the Po Valley.

This work reinforces the belief that long-term sampling plans and greater knowledge about canal biodiversity and management practices are needed. In fact, it is important to act now to reduce the biodiversity loss before critical levels difficult to restore are reached. In this regard, Tickner et al. (2020) identified the following priority actions: accelerating implementation of environmental flows, improving water quality, protecting and restoring critical habitats, managing the exploitation of freshwater ecosystem resources (especially species and riverine aggregates), preventing and controlling alien species invasions, and safeguarding and restoring river connectivity. The present data warn about the presence of complex driving mechanisms difficult to explore, suggesting the need to adopt innovative approaches such as the functional ones to grasp the complexity of biological interactions in highly disturbed ecosystems, such as HMWBs.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11355-022-00504-y>.

Acknowledgements We gratefully thank Dr. Giuseppe Bortone, Dr. Franco Zinoni, Ing. Paolo Cagnoli (Arpa Emilia-Romagna), Dr. Paolo Pini, Dr. Michele Solmi, Dr. Davide Rondini (Consorzio della Bonifica Renana) for their technical and logistic support during this research,

and Dr. Marco Baldo for the support on the field activities. The Consorzio della Bonifica Renana should also be thanked for making the hydrochemical data available.

Author contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by IM, SL, FB, NDB, GG, LC, IC, LS; analyses were performed by NDB, GG, IM and RB. The first draft of the manuscript was written by FB, IM and RB. AC directed and supervised the entire study and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Alma Mater Studiorum - Università di Bologna within the CRUI-CARE Agreement. I. Montanari was supported by institutional funds of an industrial doctorate planned by Arpa Emilia-Romagna and Università di Bologna, financed by Arpa Emilia-Romagna. S. Landi received funds from Fondazione Cassa di Risparmio di Bologna for her technical and scientific support during field work. The other authors declare they have no financial interests.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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