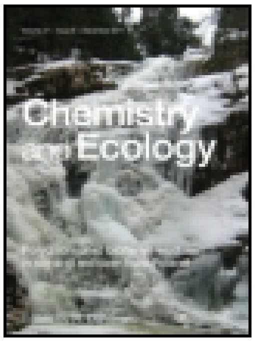

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Effects of drainage water on plant diversity and distribution of agricultural drainage ditch beds in an arid irrigated area of Northwestern China

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Agricultural drainage ditches are essential to sustaining food production in arid irrigation regions, with various sizes and drainage characteristics as important buffer ecotones in agricultural areas. Bed vegetation and water properties were investigated in 39 agricultural drainage ditches in the Lingwu District of Ningxia Yellow River Irrigation Area in Northwestern China. The results showed that water depth, width, and velocity generally increased with larger ditch size. Water salinity was higher in drainage ditches (> 1 g/L) than in croplands, canals, and the Yellow River. Total nitrogen and total phosphorus were at high levels: ∼1.6 and ∼0.1 mg/L, respectively. Forty plant species belonging to 19 families and 31 genera were identified, with higher plant richness and diversity found in smaller sized drainage ditches. Macrophytes dominated the bed vegetation with a mean vegetative coverage of > 30% in all-sized ditches, and *Phragmites australis* occurred with the most frequency. Water depth and salinity were considered as the primary factors affecting the distribution of vegetation in drainage ditch beds. The study suggests that practical conservation of smaller sized drainage ditches is conducive to increasing the plant diversity of agricultural landscapes.

Keywords: water salinity; drainage ditch vegetation; macrophytes; CCA; arid region

1. Introduction

Agricultural drainage ditches constructed for farmland drainage are essential infrastructure improvements for food production in arid and semi-arid regions. Regular irrigation satisfies the water consumption of crops, and frequently a wet status results in drainage ditch beds.[1] Drainage ditch beds are seldom disturbed by cultivation, except due to casual dredging and fire,[2,3] and provide semi-natural habitats for various hygrophilous plants (e.g. perennial reed and cattail) and animals (e.g. birds and butterflies), thus increasing the biodiversity in agricultural landscapes.[4–8] In Europe and North America, agricultural drainage ditches sustain significant diversity, so agri-environmental managers and researchers have called for their protection due to potential ecological benefits.[9–11]

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Nonetheless, the plant communities structure is fragile in drainage ditch beds and is primarily affected by the hydrological environments of drainage systems, especially in arid regions.[6,11] Massive drainage greatly increases the water velocity and depth during irrigation periods, especially in large drainage ditches, which likely limits the development of aquatic vegetation types, such as floating and emerging plants, and causes growth restrictions on root systems.[12] Smaller drainage ditches have smaller water quantity, velocity, and depth, which is more appropriate for the growth of bed vegetation. Deeper water frequently results in less emergent plant cover as well as terrestrial plants due to less available shallow waters for proliferation. However, during non-irrigation periods, water deficiency may be the main reason for falling plant diversity and biomass.[11]

In addition, agricultural runoff transports abundant nutrients (phosphorus (P) and nitrogen (N)) from ambient fields,[13] further affecting aquatic vegetation structure and productivity of plants in the drainage ditch beds.[14–16] High nutrient levels ($>$ 0.05–0.1 mg total P/L or $>$ 1.2–2.0 mg total N/L) resulting from extensive fertiliser loss may limit the growth of hydrophytes such as submerged plants and negatively impact plant diversity and productivity.[17] Moreover, soil salinisation is widespread in arid agricultural areas because of low long-term rainfall and high evaporation, resulting in high drainage water salinity [17,18] that greatly restricts the development of non-halophytes.[19] Therefore, high nutrients and salt characterise the agriculture drainage water in arid regions and illustrate the decline of plant diversity in drainage ditch beds at a regional scale.[11]

Northwestern China is typically arid to semi-arid with saline soil conditions, and large-scale open-ditch constructions are applied for field drainage schemes.[18] During the growing season, a large amount of drainage water from croplands flows into drainage ditches. However, the properties of drainage water are largely unexplored in this region, and effects of drainage on the vegetation community structure have not been well understood. We therefore investigated the plant species composition and structure of drainage ditch beds in an area representative of arid irrigation conditions found in Northwestern China, and analysed the relationship between vegetative characteristics and drainage water features. Suggestions for conservation of drainage ditch habitats at the regional scale were also proposed.

2. Materials and methods

2.1. *Site location*

The study area was located in the Lingwu District in the Ningxia Yellow River Irrigation Area of Northwest China (106°10′–106°30′E, 37°45′–38°20′N) at an average elevation of 1250 m (Figure 1). Lingwu District is a representative of typical arid agri-irrigation area with approximately 240 km^2 of cropland producing $> 2 \times 10^6$ kg/a of food since 2010.[13] The quantity of average yearly irrigated water is 2.9×10^8 m^3, approximately 54% of which is discharged into drainage ditches, from mainly June to October. The main soil types are zonal steppe and desert soil. Annual average temperature is 8.8°C, and the effective accumulative temperature $\geq$ 10°C is 3350°C. The annual frost-free period is 157 days. Average annual precipitation is 213 mm, 70% of which falls from July to September, with an annual potential evapotranspiration up to 2000 mm.

Three trunk drainage ditches (East Ditch, West Ditch, and Kushui Ditch) and 36 associated branch drainage ditches were investigated in Lingwu District in August 2011. Drainage ditches collectively exceeded 60 km, accounting for 62% of the total length of trunk drainage ditches, and received $>$ 70% of local agricultural discharge. Most ditch banks were steep and covered by cement in case of landslide due to surface incompact soil. The drainage conveyance system

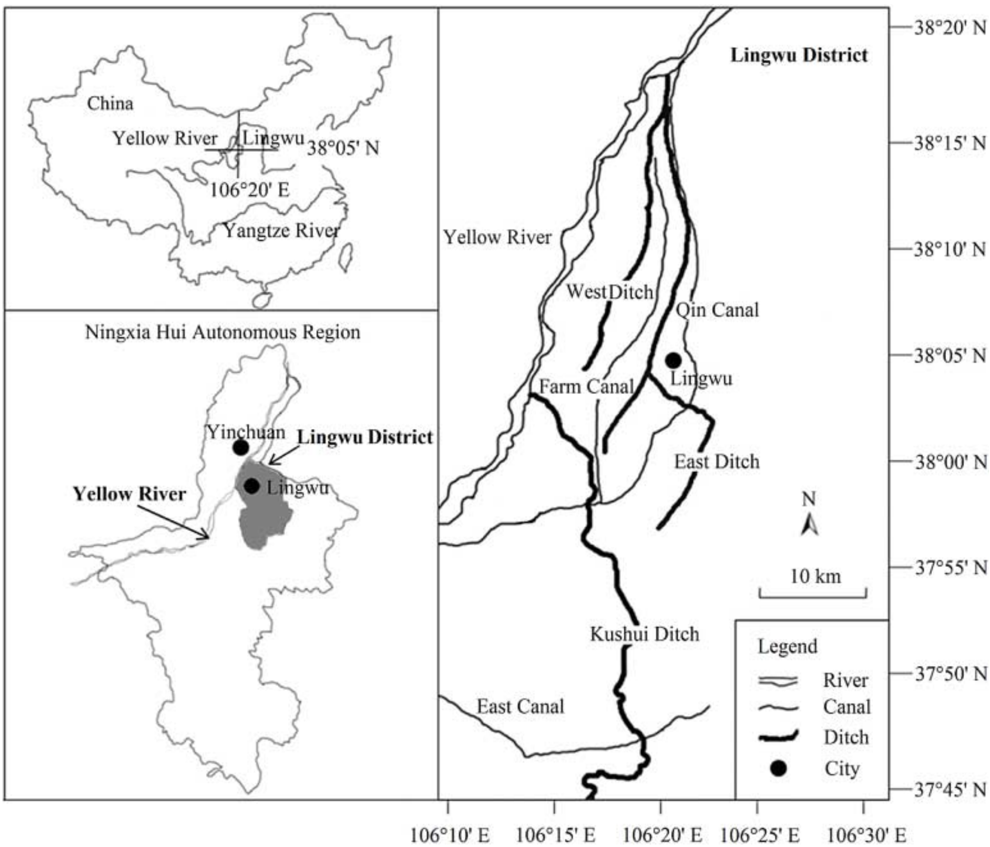

Figure 1. Agricultural drainage ditches investigated in the Lingwu District of Ningxia Hui autonomous region, Northwest China.

was categorised into three classes (D1, D2, and D3) based on the hydraulic transport capacity and measured by ditch width. Trunk drainage ditches were classified as first grade (D1) and identified as main water channels, receiving runoff with confluences from feeder drainage ditches and adjacent agricultural fields. Maximum width was two to three times that of feeder drainage ditches, and tail water drained directly into the Yellow River. Feeder drainage ditches were classified as second grade (D2) with intermediate sizes generally averaging ≤ 10 m, receiving drainage from lateral drainage ditches. Lateral and small drainage ditches were classified as third grade (D3) with width ≤ 5 m, usually receiving primary agricultural drainage water.

Three feeder ditches were randomly selected for each trunk ditch from upstream to downstream, and three lateral drainage ditches were randomly chosen on both sides of each feeder ditch. Special irrigation canals that pumped water from upstream of the Yellow River accompanied each trunk ditch (i.e. Qin Canal to East Ditch, Farm Canal to West Ditch, and East Canal to Kuishui Ditch). The East Ditch also received domestic sewage in the midstream as it passed through a farm.

2.2. *Field measurements and sampling*

Six sections were uniformly established in each D1 ditch from upstream to downstream, while three sections were used for each D2 and D3 ditch. A 1.0×1.0 m quadrat was selected and randomly placed at the drainage ditch bed for each section.

Total vegetation coverage and separate coverage of each species were visually estimated and recorded in each quadrat. All aquatic plants within the quadrat were harvested with a special plant sampling device (similar to a garden rake). Plants were identified according to Han et al. [20] López-Pujol et al. [21] and Du et al. [22]

Physical and hydraulic parameters of drainage ditches were determined at each section. Drainage ditch width was determined by using the minimum distance between the top of each banks. Slope length was from the boundary line of water to the top of the bank, and slope angle was documented. Width and depth of ditch water were measured thrice with a metre ruler. The velocity of water flow was assessed by a FP311 (Xylem Inc., White Plains, NY, USA) water flow meter.

Drainage ditch water and surrounding surface waters were sampled with an acid-washed polyethylene bottle (500 mL) at each section. Cropland ($>90\%$ cover was paddy fields, followed by wheat and corn lands) waters near the studied drainage ditches were also sampled. Some water samples were not collected due to drought status in ditches or croplands. Irrigation canal water was sampled at sites closest to the studied sections of trunk ditches. In addition, three water samples were taken from upstream to downstream on the Yellow River. Ambient land use and habitats with anthropogenic impacts were also recorded.

Physical and chemical features of sampled water were measured. Temperature, electric conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and pH were determined instantly using a YSI 556 multi-probe system (YSI Incorporated, Yellow Springs, OH, USA) at the study sites. Water samples were then stored in sealed plastic bags containing ice blocks and delivered to a local chemical laboratory for measurement. Total nitrogen (TN) was analysed by spectrophotometry after digestion with alkaline potassium persulphate ($K_2S_2O_8 + NaOH$) at 210 nm, and total phosphorus (TP) was analysed at 700 nm after digestion following the molybdenum blue method.[23] Water samples were filtered through a Whatman GF/F glass membrane (Whatman International Ltd., Maidstone, UK) for dissolved nutrients determination; ammonium nitrogen ($NH_4^+{-}N$) and nitrate nitrogen ($NO_3^-{-}N$) concentrations were determined using a flow injection (Skalar SAN^{++}, and Delft in the Netherlands) analyser. Chemical oxygen demand (COD) determination followed the potassium dichromate method with a 5 mg/L detection limit.

2.3. *Statistical analysis*

Vegetation species frequency was calculated as the ratio of the number of existing quadrats for species to the number of total quadrats. To assess the plant community structure, richness (R), the Shannon–Wiener index (H),[24] and Simpson's index (D) [25] were introduced as an estimate of plant diversity. The mathematical equations used were as follows:

$$\text{Richness index } R = S, \tag{1}$$

$$\text{Shannon} - \text{Wiener index H} = -\sum_{i=1}^{S} P_i \ln P_i, \tag{2}$$

$$\text{Simpson's index } D = 1 - \sum_{i=1}^{S} P_i^2, \tag{3}$$

where S stands for the number of species and P_i ($i = 1, \ldots, S$) denotes the (theoretical) probability of an individual belonging to the ith species.

Differences in plant diversity indexes in various ditches were analysed by one-way Analysis of Variance (ANOVA), and comparative analyses of chemical characteristics of different regional water samples were processed using a multivariate test of a general linear model with SPSS 13.0 software (Chicago, IL, USA). Canonical correspondence analysis (CCA) was conducted to assess the relationships between plant species and drainage water features with Canoco for Windows 4.5 (Biometrics-Plant Research International, Wageningen, the Netherlands) with a focus on interspecies distances and biplot scaling. All species were added in CCA with variables quantified to be Important Values (I).[26] I are parameterised as

$$I_{j,k} = (R_{j,k} + C_{j,k})/2, \tag{4}$$

where $I_{j,k}$ ($j = 1, \ldots, S_k$) is an important value of the jth species in quadrat k; S_k is the number of species in quadrat k; $R_{j,k}$ is the reciprocal of S_k; and $C_{j,k}$ is the ratio of coverage of the jth species to the total coverage. In particular, $I_{j,k} = 0$ if the jth species in quadrat k is absent.

Ten environmental factors were considered: WW (water width), WD (water depth), WV (water velocity), pH, TDS, TN, NH_4^+–N, NO_3^-–N, TP, and COD. Environmental variables were represented by arrows with the maximum value located at the arrow head. Only the distribution of species with a minimum weight of 1% was presented in plots.

3. Results

3.1. *Physical and chemical characteristics of drainage water*

Larger sized drainage ditches generally presented stronger hydraulic conveyance capacity with higher water width, depth, and velocity in drainage systems. Water widths at D1 sites were almost three times those found at D2 sites (mean = 10.8 and 3.3 m, respectively) and four to five times those found at D3 sites (mean = 2.2 m) (Table 1). Water levels were deepest at D1 sites with an average water depth of 0.63 m, while D2 sites and D3 sites had an average water depth of 0.36 m. Moreover, D1 sites presented the highest flow velocity with a mean value of 0.20 m/s, whereas the speed was $\leq$0.1 m/s in smaller sized ditches, which was also probably related to higher vegetative coverage on small ditch beds.

Water temperatures ranged from 20.0°C to 32.0°C due to various weather conditions. The pH ranged from 7.0 to 8.0, and DO ranged from 1.0 to 23.0 mg/L at all sites. The oxidation–reduction potential varied greatly, ranging from -200.0 to 150.0 mV. EC was highest at a D3 site (10.2 mS/cm), with a mean value of 2.27 mS/cm for all sites.

Table 1. Measured physicochemical parameters of water in drainage ditches of different classes, croplands, canals, and the Yellow River in August 2011.

	Ditch classes					
Parameters	D1	D2	D3	Cropland	Canal	River
Width (m)	10.8 ± 9.6	3.3 ± 3.2	2.2 ± 0.9	–[a]	–	–
Depth (m)	0.63 ± 0.43	0.36 ± 0.23	0.36 ± 0.27	–	–	–
Velocity (m/s)	0.20 ± 0.08	0.08 ± 0.03	0.04 ± 0.03	–	1.02 ± 0.54	1.34 ± 0.67
Temperature (°C)	26.2 ± 3.1	23.3 ± 2.9	23.1 ± 2.9	24.0 ± 2.9	23.7 ± 3.0	25.6 ± 3.0
pH	8.04 ± 0.48	7.85 ± 0.60	7.99 ± 0.40	7.80 ± 0.20	7.67 ± 0.12	8.17 ± 0.15
DO (mg/L)	11.4 ± 5.1	9.2 ± 5.4	9.3 ± 4.8	9.4 ± 4.7	9.5 ± 4.8	10.8 ± 6.9
Oxidation–reduction potential (mV)	46.8 ± 73.4	33.8 ± 61.2	45.5 ± 48.9	38.3 ± 57.4	44.4 ± 55.7	41.6 ± 70.4
EC (mS/cm)	2.30 ± 1.10	1.76 ± 0.81	2.27 ± 1.55	1.74 ± 1.27	1.98 ± 1.31	1.02 ± 0.68

[a]No data.

Mean TDS concentrations ranged from 403.8 mg/L in canals to 1625.5 mg/L in D1 ditches, and concentrations found in canals and the Yellow River were significantly lower than that in drainage ditches and croplands ($n = 88$, $p < .001$) (Figure 2). Moreover, drainage ditches and croplands had higher COD concentrations than canals and the Yellow River ($n = 88$, $p = .001$), which was likely due to high organic matter resulting from fertilisation. The highest TP levels were in cropland sites (mean = 0.23 mg/L), while mean TP concentrations of $\leq$ 0.15 mg/L were measured in drainage ditches, canals, and the Yellow River; D3 sites also presented the lowest mean TP value (0.03 mg/L). For nitrogen nutrient, the TN and NO_3^-−N concentrations were significantly higher in croplands and drainage ditches than those found in canals and the Yellow River ($n = 88$, $p < .05$). Mean TN concentration reached a maximum at D1 sites (1.59 mg/L) and minimum in the Yellow River (0.34 mg/L). Mean NO_3^-−N and NH_4^+−N values were lower than 1.0 mg/L for all sites. Nevertheless, canal and river water had

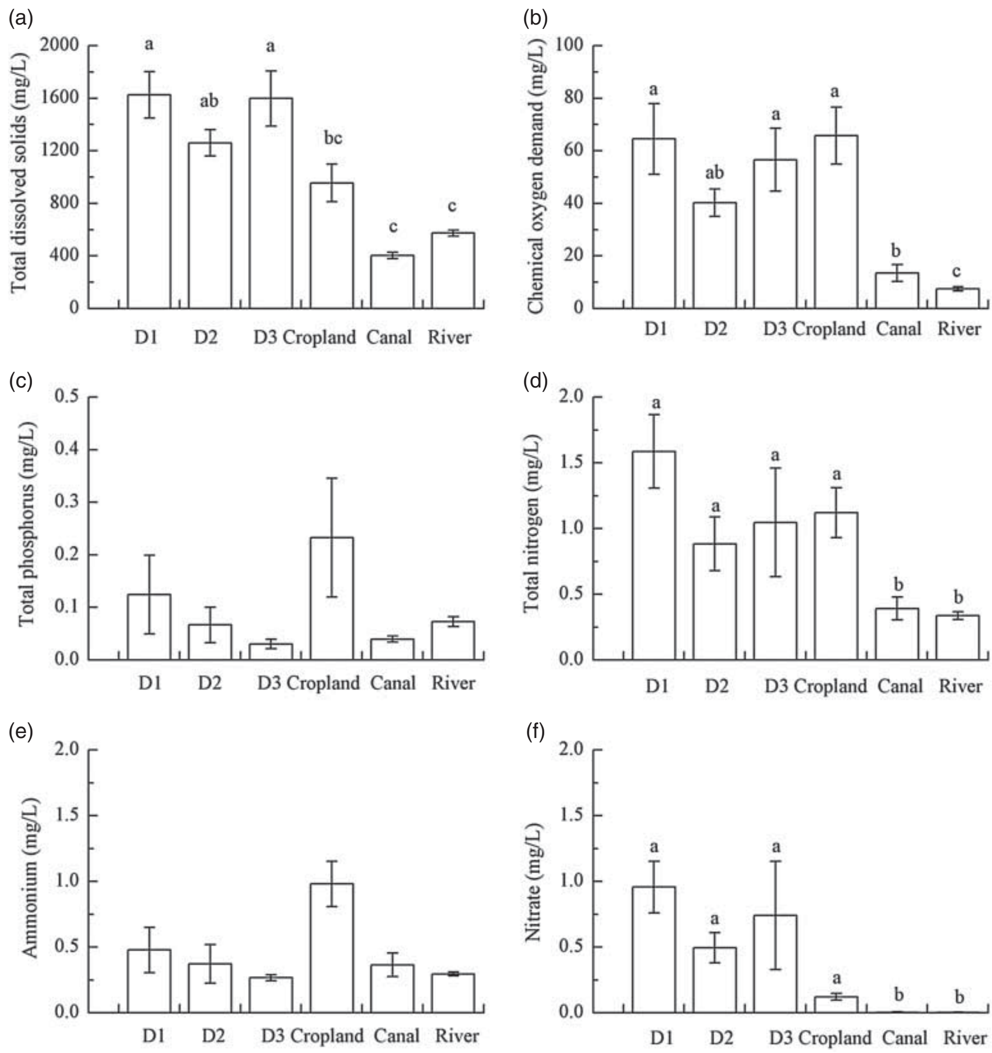

Figure 2. Measured TDS (a), COD (b), TP (c), TN (d), ammonium (e), and nitrate (f) concentrations of water in agricultural drainage ditches, croplands, canals, and the Yellow River, August 2011. Different lowercase letters indicate significant differences ($p < .05$). D1, D2, and D3 represent ditch classes 1–3.

relatively high natural NH_4^+-N background values (mean > 0.3 mg/L) compared with NO_3^--N (mean < 0.01 mg/L).

3.2. *Plant species*

A total of 19 families, 31 genera, and 40 plant species ranging from aquatic to terrestrial plants for all drainage ditches ($n = 39$) were recorded as shown in the appendix (Appendix 1). The Compositae family presented the highest number of species among all plants with six types, followed by Poaceae (types) and Chenopodiaceae (four types). Plant species increased from 11 in D1 ditches to 12 in D2 ditches and 39 in D3 ditches, of which nine aquatic species were found in all ditches. All plant species were present in D3 sites except for *Lemana minor*, which was a floating-leaved macrophyte occurring in D1 and D2 ditches. Plant species frequency and mean cover ranged from 0.8% to 76.2% and 0.06% to 11.0%, respectively. *Phragmites australis* had the highest frequency and mean cover, followed by *Typha angustifolia* (36.5% frequency and 5.2% mean cover), *Potamogeton natans* (13.5% frequency and 4.0% mean cover), and *Scirpus triqueter* (19.8% frequency and 2.0% mean cover). In addition, mean cover of bed vegetation increased from 31.8% in D1 ditches to 37.9% in D2 ditches and 38.3% in D3 ditches.

However, the characteristics of specific plant distribution varied with drainage ditch sizes. Frequency and cover of emergent plants including *P. australis*, *T. angustifolia*, *S. triqueter*, and *Sagittaria triflora* increased in smaller sized ditches, whereas *Typha* sp. presented greater variation in coverage than other species (Appendix 1). The submerged plants, especially *Ceratophyllum demersum* and *Potamogeton* sp., generally reduced in bed cover and frequency when ditch size declined. For instance, *C. demersum* significantly decreased from 50.0% frequency and 9.1% mean cover in D1 ditches to < 5.0% frequency and < 1.0% mean cover in D2 and D3 ditches. Moreover, all plants in D3 ditches presented low coverage (< 5% cover), except for the ubiquitous *P. australis*.

3.3. *Diversity of bed vegetation*

The richness of vegetation in D2 (mean = 2.48) and D3 sites (mean = 3.00) was large when compared to D1 sites (mean = 2.11) with a significant difference ($n = 125$, $p = 0.023$) (Table 2), indicating that smaller sized drainage ditches sustained more species, most of which were annual herbaceous plants. The mean Shannon–Wiener index increased with ditch size, 0.50 at D1 sites, 0.52 at D2 sites, and 0.58 at D3 sites ($n = 125$, $p = .698$). In addition, D3 ditches presented higher diversity with more species and quantity of hydrophytes in spite of similar Shannon–Wiener indexes among various drainage ditches. The mean Simpson's index was 0.70 at D1 sites, 0.69 at D2 sites, and 0.67 at D3 sites with little differentiation ($n = 125$, $p = .813$), revealing that the general distribution of vegetation including dominant macrophytes was statistically even on drainage ditch beds.

Table 2. Mean richness, Shannon–Wiener index, and Simpson's index of bed vegetation in agricultural drainage ditches in Lingwu District, August 2011 (number of quadrats in parentheses). Different lowercase letters indicate a significant difference ($p < .05$).

	Ditch class				
	D1($n = 17$)	D2($n = 27$)	D3($n = 81$)	All ditches ($n = 125$)	P
Richness	2.11 ± 1.23^b	2.48 ± 1.16^{ab}	3.00 ± 1.44^a	2.60 ± 1.45	0.023
Shannon–Wiener index	0.50 ± 0.48	0.52 ± 0.41	0.58 ± 0.42	0.56 ± 0.42	0.698
Simpson's index	0.70 ± 0.28	0.69 ± 0.24	0.67 ± 0.24	0.68 ± 0.24	0.813

3.4. *Ordination analysis*

The species–environment correlations for CCA axes 1 and 2 indicated a significant relationship between 10 environment variables and bed plant species (Table 3). The first axis was defined by TDS and the second axis by TP and TN. Canonical axes 1 and 2 explained the variance of 36.1% and 22.3%, respectively, in the species–environment relationship (Figure 3). Analysis suggested that most plants were usually located in aquatic environments with low TDS concentrations. TN and TP were significant factors for plant growth, and NO_3^-−N and NH_4^+−N sustained more

Table 3. Summary statistics (eigenvalues, species–environment correlations, cumulative percentage variance of species data, and cumulative percentage variance of species–environment relation) for axes 1–4 of CCA performed on the plant species distribution in drainage ditch beds.

CCA axes	1	2	3	4
Eigenvalues	0.327	0.202	0.154	0.116
Species–environment correlations	0.675	0.668	0.555	0.527
Cumulative percentage variance of species data	25.2	40.7	52.5	61.5
Cumulative percentage variance of species–environment relation	36.1	58.4	75.3	88.1

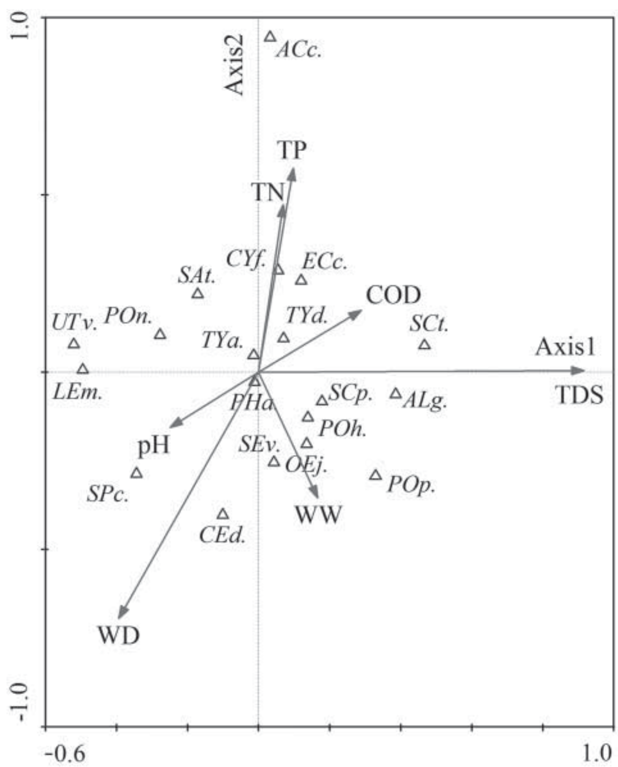

Figure 3. CCA ordination biplot showing drainage water features (arrows) and ditch bed vegetation (empty triangles), August 2011. Directions and lengths of the arrows indicate importance and correlation to the respective axes. WW = water width, WD = water depth, WV = water velocity, TDS = total dissolved solids, TN = total nitrogen, TP = total phosphorus, COD = chemical oxygen demand. *ACc.* = *Acorus calamus*, *ALg.* = *Alisma gramineum*, *CEd.* = *Ceratophyllum demersum*, *CYf.* = *Cyperus fuscus*, *ECc.* = *Echinochloa crusgalli*, *LEm.* = *Lemana minor*, *OEj.* = *Oenanthe javanica*, *PHa.* = *Phragmites australis*, *POh.* = *Polygonum hydropiper*, *POn.* = *Potamogeton natans*, *POp.* = *Potamogeton pectinatus*, *SAt.* = *Sagittaria triflora*, *SCp.* = *Scirpus planiculmis*, *SCt.* = *Scirpus triqueter*, *SEv.* = *Setaria viridis*, *SPc.* = *Spirogyra crassa*, *TYa.* = *Typha angustifolia*, *TYd.* = *Typha davidiana*, *UTv.* = *Utricularia vulgaris*.

macrophytes that were often associated with high biomass (e.g. *T. angustifolia* and *Typha davidiana*). Aquatic species were also greatly influenced by the physical features of water (water depth and width). *C. demersum* and *Spirogyra crassa* were most closely associated with deeper water, while other macrophytes such as *T. angustifolia*, *T. davidiana*, and *S. triflora* were rarely recorded. The impact of water velocity on emergent and submerged plants was limited, and most hydrophytes tended to present in relatively low velocity water.

4. Discussion

4.1. *Variation of drainage water in Lingwu District*

Various functions of water conveyance generally determined the hydrological conditions of the drainage system in arid agricultural areas. Rational classification of drainage ditches was an important and effective management policy for different quantities of agricultural discharge. It was evidenced that trunk drainage ditches presented stronger water conveyance capacity as main output channels. Moreover, the network density (total length/area) of drainage systems of Lingwu District was greater than that of other arid regions of North China, such as Shiyang River Basin [27] and Hetao Irrigation Region,[28] revealing a more hydraulic connection. However, compared with large-sized drainage ditches, ubiquitous smaller ditches received smaller quantity of agricultural runoff due to short distance from farmlands, presenting shallower water depth [28]; high coverage of bed vegetation also reduced water velocity.[5] Additionally, strong evaporation was another crucial factor declining the water depth in small-sized drainage ditches,[18] which was enhanced by longer transport path.

The high ionic level (including Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, and CO_3^{2-}) of irrigation water from the upper Yellow River ($\sim$0.5 g TDS/L) and saline croplands contributed to the increase in TDS content in drainage water.[29] Soil salination has existed in Lingwu District for more than 2000 years.[30] Although traditional irrigation and drainage have alleviated soil salinity and reduced water salinity in comparison with inland semi-arid agriculture regions of central China,[31] the TDS levels of drainage water in Lingwu District (0.3–4.3 g/L) were still higher than that of the Hetao Irrigation Region ($\sim$2.0 g/L) of the upper Yellow River basin.[28] Moreover, excessive irrigation resulted in rising groundwater level with high salinity, which aggravated the drainage salinity problems.[29] TDS content was concentrated with drainage water afflux from peripheral ditches in the main conveyance channels, which might cause long-term adverse effects in the aquatic environment.

The loss of fertiliser with outgoing water has been noted as the main source for nutrients gathering in drainage water.[1] The local annual amounts of phosphate and nitrogen fertiliser applied in the 2002–2007 time frame were 46.0 and 301.0 kg/ha, respectively, 1.6–2 times the national average in China.[13] Excessive fertilisation of crops with a finite nutrient-absorption capacity led to affluent P and N loss in soluble forms with drainage,[32] and the nutrients concentrations were enhanced in larger sized drainage ditches. Compared with the adjacent Hetao Irrigation Region and the agriculture regions of North America, the nutrient level of agricultural discharge in Lingwu District was lower [28,33,34]; nonetheless, the eutrophic states of drainage water would last for extended periods due to a lack of effective agricultural management.[13] Open vegetated drainage ditches provided optimum conditions for nutrient uptake and denitrification as constructed wetlands,[6] and the removal efficiency of P and N could reach 40–60%,[35] generating great variations in nutrient level across various sized ditches. Wang et al. also found that open drainage ditches with covered vegetation have higher nutrient-retention efficiency than subsurface drainage systems.[18] Organic matter (COD) was obviously reduced in drainage ditches because of the filtration effect caused by vegetation and absorption of substrates,[36] with greater removal efficiency in smaller sized ditches due to lower velocity and longer water residence time.

4.2. *Variation of ditch bed vegetation with drainage water*

In the upper Yellow River basin, the Lingwu District presented higher plant richness of agricultural drainage ditch beds than the Hetao Irrigation Region,[28] and more aquatic plants rather than halophytes responded to the adequate irrigation and drainage. Other inland humid regions, such as the Mississippi Delta,[5] have more upland species that occur in comparison with the plant composition of drainage systems in the Lingwu District.

In large drainage ditch systems, high water depth and velocity contribute to low plant diversity in bed vegetation. The occurrence of submerged aquatic macrophytes is primarily affected by irradiance related to water depth.[37] Submerged plants such as *C. demersum and Potamogeton* sp. tended to distribute in deeper water to obtain sufficient space for rooting and the growth of shoots in larger drainage ditches, as observed in the agricultural drainages in the Mississippi Delta.[5] Larger water depth ($>$ 70 cm) might limit the coverage of emergent macrophytes [38]; in the study, the dominant emergent species (*P. australis* and *T. angustifolia*) could not survive in water too deep for long-term persistence at D1 and D2 sites, and the frequency and coverage of which declined with the increasing depth gradient. Bouldin et al. also indicated that aquatic macrophytes rather than small-body hydrophytes were frequently recorded in deep and fast-moving waters.[5] Moreover, the most stochastic input of wild seeds difficultly rooted into the bed because of high flow velocity; in addition, regular maintenance (e.g. dredging) destroyed the original habitats and lowered the plant diversity in large drainage ditches.

Conversely, small-sized drainage ditches with shallow water depth and slow flow velocity frequently kept more species and higher diversity than large-sized drainage ditches. More emerging annual and perennial herb species (e.g. *Suaeda glauca*, *Chenopodium glaucum*, and *Oenanthe javanica*) colonised the area. Tarmi et al. found that the plant richness increased near the field margin in Finnish farmlands. Invasive opportunities for accidentally introduced weeds by wind or runoff generally increased due to the closer distance of croplands.[4] Feeder and lateral drainage sites were actually ungoverned, benefitting the development of bed plants. The species belonging to Compositae and Chenopodiaceae rapidly increased in small ditches. However, high species diversity brought more fierce interspecific competition in small drainage ditches, restricting the quantity and frequency of plants.[26]

In the Lingwu District, saline irrigation and lands greatly deteriorated the drainage water quality and threatened the survival of most glycophytes. Hart et al. noted that increases in salinity up to 1000 mg/L could have lethal and sublethal effects on aquatic plants.[39] Excessive uptake of ions, especially Na^+ and Cl^-, introduced toxicity and nutrient imbalance into plants (e.g. roots and shoots).[19] TDS concentrations of drainage water >1000 mg/L were observed in many conveyance structures, and most plants had stunted height and reduced coverage except for individual salt-tolerant species such as *P. australis*. In addition to North China, high TDS level elevated the risk of agricultural production as well as the maintenance of plant diversity of drainages in the arid and semi-arid agricultural areas of Southwest Asia and Australia.[40]

The transport of nutrients positively facilitated plant growth by improving metabolism, while the effects of nutrient levels on plant diversity remained uncertain.[41] Eutrophic drainage sustained the biomass accumulation of dominant species, that is, macrophytes. Although biomass data were unavailable during this investigation, a greater number of macrophytes presented in higher nutrient-rich drainage ditch sites. Nonetheless, high nutrient levels ($\sim$1.6 mg TN/L and $\sim$0.1 mg TP/L), approximating a borderline hypereutrophic state, could possibly reduce plant diversity and lead to declining coverage of submerged plants.[6,17,41] In the Hetao Irrigation Region, higher nutrient concentrations of drainage water ($\sim$3 mg TN/L and $\sim$0.16 mg TP/L) were negatively related to plant diversity.[28] Meanwhile, the P deficiency vs. N (TN:TP ratio > 120) might limit the biomass of aquatic plants rather than plant diversity,[11,17] whereas the effects of P deficiency on special species need more study.

Plant diversity was insensitive to pH and COD of drainage water. Alkalescent water with relatively stable pH had little effect on root cells, while alkali-affected soils would restrict the distribution of plants in agricultural landscapes.[18] Plant species were also rarely found in black waters with high COD and humic acid concentrations because of organic material decomposition.[36]

Agricultural activities generally promoted the trophic states of drainages as well as the surface receiving waters in Lingwu District.[13,18] Vegetation succession of drainage ditch beds was affected by periodic drainage (hydrologic variability) and long-term high nutrient loading. Though this investigation was a snapshot of the study area, the distribution of plants revealed both the visual vegetation structure and the species pool. The plant/water interaction in drainage systems brings about a beneficial insight for the management of agricultural landscape patterns.

4.3. *Applications of the study*

In arid and semi-arid climatic zones, salinity prior to nutrient is considered as the primary factor restricting crop production.[42] Saline drainage and fertiliser loss are co-products of agriculture, which could be retained in vegetated drainage ditches. For water-saving purposes, irrigation with light-salinity drainage recycling is suggested as an agricultural practice.

Drainage ditch habitats need practical protection in management because of their ecological function and high ecotone biodiversity in agricultural landscapes.[4–6,10,28] Smaller sized conveyance structures with higher plant diversity and more frequent disturbances deserve preferential conservation compared to larger ones. Although cultivated species may be sensitive to drainage habitat,[4] sown species could be an option for improving diversity. Drainage water in curved and shallower channels benefits the colonisation of more aquatic plants. These measures are also alternatives for various arid regions during hydroperiods.

Disclosure statement

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References

[1] Needelman BA, Kleinman PJA, Strock JS, Allen AL. Drainage ditches improved management of agricultural drainage ditches for water quality protection: an overview. J Soil Water Conserv. 2007;62:171–178.

[2] Heckman CW. Long-term effects of intensive pesticide applications on the aquatic community in orchard drainage ditches near Hamburg, Germany. Arch Environ Contamin Toxicol. 1981;10:393–426.

[3] Cooper CM, Moore MT, Bennett ER, Smith Jr S, Farris JL. Alternative environmental benefits of agricultural drainage ditches. Verh – Int Ver Theor Angew Limnol. 2003;28:1678–1682.

[4] Tarmi S, Tuuri H, Helenius J. Plant communities of field boundaries in Finnish farmland. Agric Food Sci Finland. 2002;11:121–135.

[5] Bouldin JL, Farris JL, Moore MT, Cooper CM. Vegetative and structural characteristics of agricultural drainages in the Mississippi Delta landscapes. Environ Pollut. 2004;132:403–411.

[6] Herzon I, Helenius J. Agricultural drainage ditches, their biological importance and functioning. Biol Conserv. 2008;141:1171–1183.
[7] Wu P, Chen YL, Zhao Y, Hu YG, Huang L, Zhang ZS. Plant species diversity in agricultural drainage ditches in Lingwu District of Ningxia, Northwest China (in Chinese). Chin J Ecol. 2011;30:2790–2796.
[8] Kang W, Hoffmeister M, Martin EA, Steffan-Dewenter I, Han D, Lee D. Effects of management and structural connectivity on the plant communities of organic vegetable field margins in South Korea. Ecol Res. 2013;28:991–1002.
[9] Marshall EJP, Moonen AC. Field margins in northern Europe: their functions and interactions with agriculture. Agric Ecosyst Environ. 2002;89:5–21.
[10] Williams P, Whitfield M, Biggs J, et al. Comparative biodiversity of rivers, streams, ditches and ponds in an agricultural landscape in Southern England. Biol Conserv. 2004;115:329–341.
[11] Blann KL, Anderson JL, Sands GR, Vondracek B. Effects of agricultural drainage on aquatic ecosystems: a review. Crit Rev Env Sci Technol. 2009;39:909–1001.
[12] Barrett SC, Eckert CG, Husband BC. Evolutionary processes in aquatic plant populations. Aquat Bot. 1993;44:105–145.
[13] Zhang AP, Yang SQ, Yi J, Yang ZL. Analysis on current situation of water pollution and pollutant sources in Ningxia Yellow River irrigation region (in Chinese). Chin J Eco-Agric. 2010;18:1295–1301.
[14] Barko JW, Adams MS, Clesceri NL. Environmental factors and their consideration in the management of submersed aquatic vegetation: a review. J Aquat Plant Manage. 1986;24:1–10.
[15] Serag MS, Khedr AHA. Vegetation-environment relationships along El-Salam Canal, Egypt. Environmetrics. 2001;12:219–232.
[16] Thiebaut G, Guérold F, Muller S. Are trophic and diversity indices based on macrophyte communities pertinent tools to monitor water quality? Water Res. 2002;36:3602–3610.
[17] Lacoul P, Freedman B. Environmental influences on aquatic plants in freshwater ecosystems. Environ Rev. 2006;14:89–136.
[18] Wang SL, Wang XG, Brown LC, Qu XY. Current status and prospects of agricultural drainage in China. Irrig Drain. 2007;56:S47–S58.
[19] Bernstein L. Effects of salinity and sodicity on plant growth. Ann Rev Phytopathol. 1975;13:295–312.
[20] Han W, Fang J, Guo D, Zhang Y. Leaf nitrogen and phosphorus stoichiometry across 753 terrestrial plant species in China. New Phytol. 2005;168:377–385.
[21] López-Pujol J, Zhang FM, Ge S. Plant biodiversity in China: richly varied, endangered, and in need of conservation. Biodivers Conserv. 2006;15:3983–4026.
[22] Du JX, Wang XF, Zhang GJ. Leaf shape based plant species recognition. Appl Math Comput. 2007;185:883–893.
[23] Murphy J, Riley JP. A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta. 1962;27:31–36.
[24] Izsák J, Papp L. A link between ecological diversity indices and measures of biodiversity. Ecol Modell. 2000;130:151–156.
[25] Magurran AE. Measuring biological diversity. Oxford: Balckwell Science; 2004.
[26] Barbour MG, Burk JH, Pitts WD. Terrestrial plant ecology. Menlo Park, CA: The Benjamin; 1980.
[27] Liu X, Wang S, Wang Y, Kang S, Hao X, Li F. Comprehensive evaluation of farmland infrastructure in the arid area of North-West China. Irrig Drain. 2014;63:561–572.
[28] Zhao Y, Li XR, Zhang ZS, Hu YG, Wu P. Species composition and species richness in the Hetao Irrigation Region drainage ditches, northern China. Arid Land Res Manage. 2013;27:167–177.
[29] Xu X, Huang G, Sun C, et al. Assessing the effects of water table depth on water use, soil salinity and wheat yield: searching for a target depth for irrigated areas in the upper Yellow River basin. Agric Water Manage. 2013;125:46–60.
[30] Xiong SY, Xiong ZX, Wang PW. Soil salinity in the irrigated area of the Yellow River in Ningxia, China. Arid Land Res Manage. 1996;10:95–101.
[31] Jia Z, Luo W, Xie J, et al. Salinity dynamics of wetland ditches receiving drainage from irrigated agricultural land in arid and semi-arid regions. Agric Water Manage. 2011;100:9–17.
[32] Vymazal J. Removal of nutrients in various types of constructed wetlands. Sci Total Environ. 2007;380:48–65.
[33] Bjorneberg DL, Leytem AB, Ippolito JA, Koehn AC. Phosphorus losses from an irrigated watershed in the Northwestern United States: case study of the Upper Snake Rock watershed. J Environ Qual. 2015;44:552–559.
[34] Williams MR, King KW, Fausey NR. Drainage water management effects on tile discharge and water quality. Agric Water Manage. 2015;148:43–51.
[35] Brix H, Schierup H-H. The use of aquatic macrophytes in water-pollution control. Ambio. 1989;18:100–107.
[36] Wauchope RD. The pesticide content of surface water draining from agricultural fields—a review. J Environ Qual. 1978;7:459–472.
[37] Chambers PA, Kaiff J. Depth distribution and biomass of submersed aquatic macrophyte communities in relation to Secchi depth. Can J Fish Aquat Sci. 1985;42:701–709.
[38] Squires L, van der Valk AG. Water-depth tolerances of the dominant emergent macrophytes of the Delta Marsh, Manitoba. Can J Bot. 1992;70:1860–1867.
[39] Hart BT, Bailey P, Edwards R, et al. A review of the salt sensitivity of the Australian freshwater biota. Hydrobiologia. 1991;210:105–144.

[40] Koyro HW, Lieth H, Gul B, et al. Importance of the diversity within the halophytes to agriculture and land management in arid and semiarid countries. In Khan MA, Böer B, Öztürk M, et al. editors. Sabkha ecosystems: volume IV: cash crop Halophyte and biodiversity conservation. Dordrecht, Netherlands: Springer; 2014.
[41] Güsewell S, Koerselman W. Variation in nitrogen and phosphorus concentrations of wetland plants. Perspect Plant Ecol Evol Syst. 2002;5:37–61.
[42] Pitman MG, Läuchli A. Global impact of salinity and agricultural ecosystems. In Läuchli A, Lüttge U, editors. Salinity: environment-plants-molecules. Dordrecht, Netherlands: Springer; 2002.

Appendix 1. Bed vegetative frequency and mean cover of agricultural drainage ditches in Lingwu District, August 2011.

		Ditch class					
		D1		D2		D3	
Abbreviation	Species	Frequency %	Mean cover %	Frequency %	Mean cover %	Frequency %	Mean cover %
ACc	*Acorus calamus*	5.6	2.2			6.2	1.3
AGc	*Agropyron cristatum*					3.7	0.8
ALg	*Alisma gramineum*					1.2	0.1
ARl	*Artemisia lavandulaefolia*					3.7	0.6
ARv	*A. vulgaris*					1.2	0.2
CAp	*Calamagrostis pseudophragmites*					3.7	0.3
CEd	*C. demersum*	50.0	9.1	3.7	0.2	3.7	0.9
CHa	*Chenopodium album*					1.2	0.1
CHg	*C. glaucum*					4.9	0.3
CHs	*C. serotinum*					1.2	0.1
CIs	*Cirsium setosum*					2.5	0.1
CYc	*Cynanchum chinense*					1.2	0.1
CYf	*Cyperus fuscus*			3.7	0.1	1.2	0.1
ECc	*Echinochloa crusgalli*			3.7	0.1	8.6	1.1
GLs	*Glycine soja*					1.2	0.1
HIt	*Hibiscus trionum*					2.5	0.2
HAc	*Halerpestes cymbalaria*					1.2	0.1
KOm	*Kobresia myosuroides*					1.2	0.1
LEm	*L. minor*	11.1	0.3	3.7	0.4		
MEo	*Melilotus officinalis*					4.9	0.5
OEj	*O. javanica*					2.5	0.1
PHa	*P. australis*	44.4	4.3	77.8	12.3	82.7	12.1
PLa	*Plantago asiatical*					1.2	0.1
POh	*Polygonum hydropiper*					2.5	0.1
POl	*P. lapathifolium*					4.9	0.2
POs	*P. sibiricum*					1.2	0.1
POn	*P. natans*	22.2	1.1	18.5	7.3	9.9	3.5
POp	*P. pectinatus*	16.7	3.9	22.2	2.9	2.5	1.1
SAt	*S. triflora*	5.6	1.4	18.5	2.5	13.6	1.4
SCp	*Scirpus planiculmis*					4.9	0.9
SCt	*S. triqueter*	11.1	1.6	22.2	1.9	21.0	2.1
SEv	*Setaria viridis*					4.9	0.6
SOb	*Sonchus brachyotus*					2.5	0.1
SOo	*S. oleraceus*					3.7	0.1
SPc	*S. crassa*	27.8	4.2	14.8	0.6	6.2	1.5
SUg	*S. glauca*					4.9	0.2
TYa	*T. angustifolia*	11.1	0.7	55.6	8.9	35.8	5.0
TYd	*T. davidiana*	5.6	3.1	3.7	0.7	11.1	1.6
UTv	*Utricularia vulgaris*					2.5	0.2
XAs	*Xanthium sibiricum*					1.2	0.2