An investigation of weed seed banks reveals similar potential weed community diversity among three different farmland types in Anhui Province, China

Article *in* Journal of Integrative Agriculture · April 2019

DOI: 10.1016/S2095-3119(18)62073-8

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Journal of Integrative Agriculture 2019, 18(4): 927–937

Available online at www.sciencedirect.com

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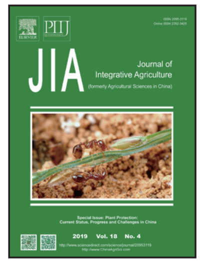

RESEARCH ARTICLE

An investigation of weed seed banks reveals similar potential weed community diversity among three different farmland types in Anhui Province, China

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Abstract

Crop type is one of main factors influencing weed community structure. However, the identity of weed communities associated with the cultivation of different crops in farmlands remains largely unclear. A field survey of weed seed banks was conducted in 2 280 fields at 228 sites of 62 locations representing three different types of farmland (95 paddy, 73 summer-ripe, and 60 autumn-ripe farmlands) along the bank of the Yangtze River in Anhui Province, China. A total of 43 families and 174 species of weeds were found in these weed seed banks. A comparison of the composition of weed groups in the seed banks showed that the species number and density percentage of grass, sedge and broadleaf weed groups were similar among the different types of farmland. The seed banks of all three farmland types shared 71 common weed species, accounting for 40.80% of the total number of species. These common weeds, which were both associated and not associated with crops, accounted for 91.71% of the total dominance degree among all farmland types. The crop-associated weed species were distributed in all soil layers of each farmland type. The Shannon-Wiener index H' (description of species diversity which is more sensitive to dense species) and Pielou's evenness index J (description of species evenness) in summer-ripe farmland were similar to those in autumn-ripe farmland but differed from those in paddy farmland. However, the Simpson's index D (description of species diversity which is more sensitive to sparse species) was similar among all three farmland types. The results of similarity comparison indicated that although the aboveground weed community differed among the different cropping patterns, the weed species composition in the soil seed bank was still similar. Consequently, our results demonstrate that after the implementation of long-term monoculture patterns, weed species compositions in the soil seed bank in different farmlands become homogenized regardless of the crop type.

Keywords: species composition, dominance degree, community similarity, community variation, Anhui Province

Received 30 May, 2018 Accepted 13 August, 2018
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doi: 10.1016/S2095-3119(18)62073-8

1. Introduction

There is a general standing viewpoint that different farmland types contain different weed seed banks because cultivating various crop types cause different weed communities to occur (Liebman and Dyck 1993; Buhler *et al*. 2001; Bellinder *et al*. 2004). Most field weeds are annual species that regenerate from seed (Manley *et al*. 2002). The weed community associated with a particular crop type produces seeds and feeds back to the soil, forming a corresponding weed seed bank (Shrestha *et al*. 2002; Hosseini *et al*. 2014). Hence, the conventional viewpoint is that as long as different crops are grown, different weed communities associated with the crops will occur. Therefore, changing the cropping system will alter the environmental conditions, which may adversely impact weed growth and consequently mitigate weed occurrence and infestation (Anderson 2005). However, this notion may not be universal to all agroecosystems. There may not always be a corresponding weed seed bank in different crop fields, and, in some cases, the potential weed communities within the seed bank may be complex. This causes challenges to integrated weed control strategies *via* the alteration of cropping systems or crop cultivation.

Agricultural sustainability is a basic approach to agricultural development in China, and integrated weed management is regarded as one of the key elements of sustainable agriculture. However, in recent years, changing tillage and cultivation methods have accelerated the succession of weed communities (Ball 1992; Zhang and Huang 1999). The long-term intense use of chemical herbicides produces pesticide residues, increases weed resistance, aggravates agro-product pollution, and threatens farmland biodiversity and ecological environments (Donald *et al*. 2001; Strek 2014). Weed seed banks in the soil function as the source of weed communities, determining their occurrence, dynamics, and succession (Ball 1992; Bàrberi and Cascio 2001). Therefore, knowledge of weed seed bank structure will contribute to the prediction of weed community structure and dynamic patterns and the adoption of appropriate control measurements. The species composition, dominance and diversity of weed seed banks in the soil should be studied to provide a theoretical basis for the sustainable management of weeds in agricultural production (Zhang *et al*. 1998). However, investigations of the short- and long-term dynamics of weed seed bank size, structure and composition in various types of crop farmlands have not been widely conducted in China (Zhang *et al*. 2004; Wei *et al*. 2005). Before 2000, research on weed seed banks in farmlands along the Yangtze River of Anhui Province were rarely conducted. Only one case study was conducted on the soil weed seed banks of rice-wheat rotation fields at Baihu Farm, Anhui (Wang *et al*. 2005). More than six different weed communities have been found in the different farmland types of this region (Qiang 1988). The weed community is dominated by *Echinochloa* spp., *Monochoria vaginalis*, *Rotala indica* and *Najas minor* in early rice fields and by *R. indica*, *Eleocharis yokoscensis*, *M. vaginalis* and *Sagittaria pygmaea* in late rice fields (Qiang and Li 1994). The weed community of summer-ripe farmland is closely correlated with the fore-rotating crops. The dominant weed species in wheat (rape)-rice rotation fields is *Alopecurus aequalis*, while *Galium aparine* var. *tenerum* and *Avena fatua* are dominant in wheat (rape)-sweet potato (soybean or cotton) rotation fields, and *Digitaria sanguinalis* is dominant in autumn-ripe crop fields (Qiang and Li 1990; He and Qiang 2014). Hence, it may be hypothesized that the different intensive cropping systems in the region harbour different and complex weed seed banks. The present study was conducted mainly to reveal the diversity of the weed seed banks in three predominant farmland types in this region.

2. Materials and methods

2.1. Study site

The farmland sites used in this study occur along the Yangtze River in Anhui Province. These sites stretch across 400 km and occur in the low hills and mountains between the Yangtze and Huaihe rivers and southern Anhui. The area is bordered by the Jiangxi Poyang Lake Plain to the west and is linked to the Yangtze River Delta of Jiangsu and Zhejiang provinces in the east (including Anqing, Chaohu, Tongling, Wuhu, Xuancheng, and Maanshan cities and more than 20 counties and 700 towns). The investigated area ranged from 29°54´54.4´´ to 31°46´46.1´´N and from 116°08´26.6´´ to 119°23´49.0´´E, with a total area of 1.52×10^6 ha (Fig. 1). The farmland soils are paddy soils that consist of grey moist soils and yellow, red, and brown soils. This area is in the north subtropic zone and has a monsoon climate with an average temperature of 16°C, an effective accumulated temperature of 5770°C, a frost-free period of 240 d, and a yearly rainfall of 1000–1300 mm. This region is an important agricultural region in Anhui Province. The main crops grown include rice, rapeseed, cotton, wheat, sweet potato, peanut, bean, and tobacco. The majority of the cropping systems include two types: continuous annual cropping of paddy rice and summer-ripe crops (rapeseed and wheat), and continuous annual cropping of autumn-ripe upland crops (corn, sweet potato, cotton, soybean, etc.) and summer-ripe crops, resulting in three different farmland types in the region.

2.2. Aboveground weed survey and seed bank sampling

Seed identification, composition, and diversity and the relationships between the weed seed bank and the aboveground weed community were investigated through sampling from 2004 to 2006. The survey of the aboveground weed communities and sampling of the soil

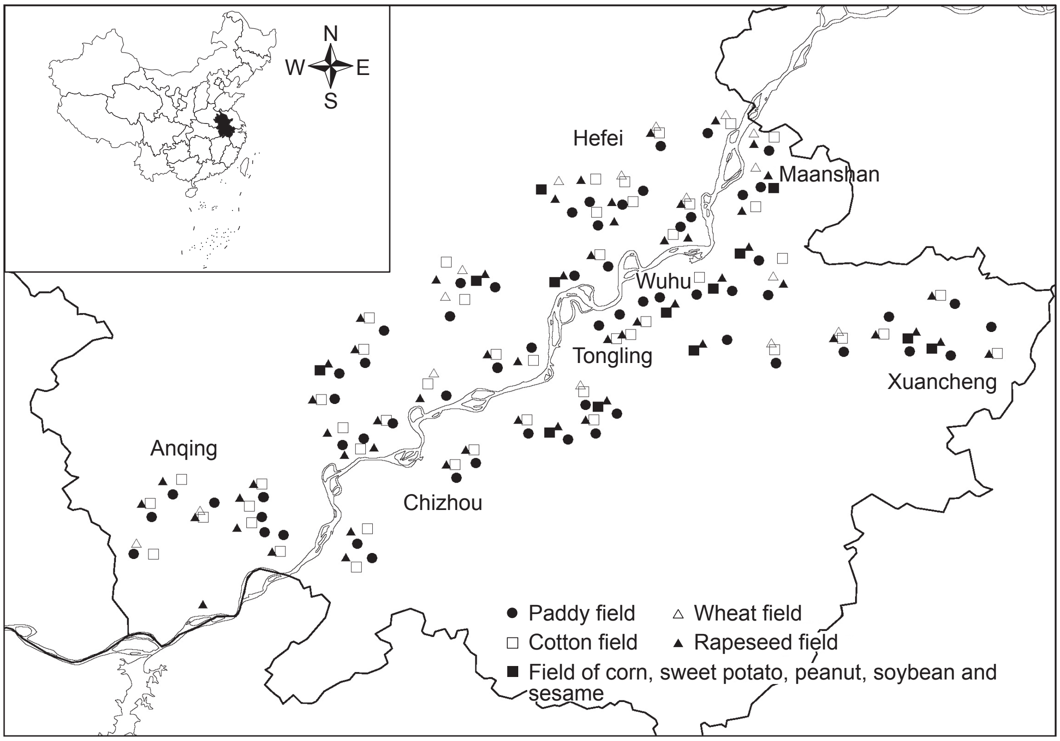

Fig. 1 Study sites in Anqing, Hefei, Tongling, Wuhu, Xuancheng, and Maanshan cities of Anhui Province, China.

seed bank were conducted at the crop mature period and after crop harvesting respectively in each cropping pattern. We randomly selected 10 quadrats (a piece of field) of approximately 667 m^2 in size at all sites in each type of farmland and recorded the weed species, dominance degree, and frequency. An aboveground weed survey was conducted using a seven-grade visualization assessment method (the grade values were 0, 0.5, 1, 2, 3, 4, and 5, as defined by the relative degree of cover, relative height and relative abundance) (Qiang 2001). The farmlands were divided into three different types: paddy, summer-ripe and autumn-ripe farmlands (according to the crop maturation phase). The paddy farmlands were further divided into early-season paddy farmlands, middle-season paddy farmlands, single-season late paddy farmlands, and double-season late paddy farmlands. The summer-ripe farmlands were divided into rape farmlands and wheat farmlands, and the autumn-ripe farmlands were divided into cotton farmlands and other autumn-ripe farmlands. The weeds were divided into paddy farmland weeds, summer-ripe farmland weeds and autumn-ripe farmland weeds in each farmland. A total of 2 280 fields at 228 sites (10 fields in each site) of 62 locations, including 95 sites of paddy farmlands, 73 sites of summer-ripe farmlands, and 60 sites of autumn-ripe farmlands, were assessed.

Five quincunx sampling points were used to sample each block. The total number of samples in each quadrat was 50. A cylindrical soil sampler with a diameter of 5 cm was used to sample the upper (0–5 cm), middle (5–10 cm), and lower (10–15 cm) soil layers. These samples were divided into three sections and placed into three different bags before they were transported to the laboratory for storage. In addition, the location, topography, land-use type, soil type, crop type, cultivation method, and environmental factors were recorded during sampling. The samples were collected for two successive years when the crops were mature. The first 1/3 of the sample was used for seed identification, and the remaining 2/3 of each sample was used for soil analysis. Seeds in the soil samples that had been divided into three portions were detected under a microscope with a 150× objective aperture using the elutriation method and were then placed in gauze. These samples were washed with water to remove the soil, passed through a 20–120 mesh sieve (mesh diameter of 830–120 μm), and identified and counted using an anatomical microscope. Seed identification was performed based on the available seed specimens in our laboratory and the book edited by Yin and Yan (1997). The seeds that were not identified using these methods were identified using the direct germination methods (Gross 1990). Those undiscerned seeds were transferred to flat seedling trays into which a thin layer mixture of vermiculite and peaty soil (1:1). After transferring, the seedling trays were immediately placed in a temperature-controlled (max. 30°C; min. 20°C) glasshouse under natural light and watered once or twice daily to keep the soil surface moist until weed seedlings had become identifiable, then the number of individuals of each species was recorded.

2.3. Data processing and analysis

Weed importance values and species diversity and community similarity indices were computed using the following formulas:

Frequency (%)=Number of quadrats in which a species occurs/Total number of quadrats×100

Relative frequency (%)=Frequency of a weed species/Total frequency of all weed species×100

Seed density=Number of seeds per m^2

Species richness (S)=Number of species

Dominance degree=Σ(Number of quadrats in which a species occurs per grade×Grade value)

Relative dominance degree (%)=Dominance degree of a weed species/Total dominance degree of all weed species×100

Importance value (aboveground weed)=(Relative frequency+Relative dominance degree)×100/2

Importance value (seed bank)=(Relative frequency+Relative density)×100/2

Simpson's index (D)=$1-\Sigma P_i^2$

Shannon-Wiener index (H')=$-\Sigma P_i \ln P_i$

Pielou's evenness index (J)=$H'/\ln S$

Sørenson community similarity index (Cs)=$2j/(a+b)$

In these formulas, P_i is the relative importance value of species i, $P_i=N_i/N$, N_i is the importance value of species i, N is the total importance value of every species in all quadrats, j is the number of a particular species in communities A and B, and a and b are the total number of species in communities A and B (Gross 1990; Tang *et al*. 1999).

To compare the composition of weed groups and community structure features in the weed seed banks, one-way ANOVA analyses were conducted to determine the difference of species number and density percentage (data of per site) among different weed groups and species diversity (S, D, H' and J index of per site) in the weed seed banks among different farmland types. Multiple comparisons were also performed using a Tukey's test at a significance level of 5%. All data were tested before being subjected to the ANOVA analyses to ensure compliance with the assumptions of normality (Shapiro-Wilkinson's W-test) and homoscedasticity (Levene's test). These analyses were performed using SPSS 20 Software (SPSS Inc., Chicago, IL, USA), and graphs were generated using Origin 9.0 (OriginLab, Hampton, MA, USA).

3. Results

3.1. Composition of families and species in the weed seed banks

A total of 43 families in the weed seed banks of farmlands along the Yangtze River in Anhui Province were found, although most weed species were members of 12 families. These dominant families, which had more than five species, were Gramineae (28), Cyperaceae (20), Compositae (14), Labiatae (10), Polygonaceae (9), Scrophulariaceae (9), Leguminosae (8), Cruciferae (7), Caryophyllaceae (6), Euphorbiaceae (5), Convolvulaceae (5), and Rosaceae (5) (Table 1). The results showed that the paddy, summer-ripe and autumn-ripe farmlands shared 30 common families and similar numbers of families, with 35, 34 and 39 families, respectively. The family composition was also similar among the three farmland types. The family similarity indices (Cs) between paddy, summer-ripe and autumn-ripe farmland were 0.87, 0.88 and 0.89, respectively.

There were 174 weeds in the weed seed banks, with 38, 78, and 58 weeds belonging to paddy, summer-ripe, and autumn-ripe farmland weeds, respectively, and the number of weed species gradually decreased with increasing soil depth in the different farmland types. There were 107, 129 and 124 weed species which infests paddy, summer-ripe, and autumn-ripe farmland, respectively in the soil weed seed banks (Table 2). Seeds of the weed species which infests paddy, summer-ripe, and autumn-ripe farmland were distributed in all soil layers of each farmland type, but more species were found in the upper soil layers (0–5 or 5–10 cm). In total, there were 43, 34 and 28 weed species which infests summer-ripe, autumn-ripe and paddy farmland, respectively, in the weed seed bank of paddy farmland, 67, 35 and 27 weed species which infests summer-ripe, autumn-ripe and paddy farmland in the weed seed bank of summer-ripe farmland and 56, 45 and 23 weed species which infests summer-ripe, autumn-ripe and paddy farmland in the weed seed bank of autumn-ripe farmland.

3.2. Composition of weed groups in the weed seed banks

Comparison of the composition of weed groups in the weed seed banks from the different farmland types (Fig. 2) showed that the species percentage in the different weed groups were similar among different types of farmland. The highest number of species occurred in broadleaf weeds, followed by grass weeds and sedge weeds, and the species percentage in the same weed groups were similar among the different farmland types. In addition, the density percentages of the different weed groups were

Table 1 The number of species in different families in three farmland types (by number of species)

Family	All three farmland types	Paddy farmland	Summer-ripe farmland	Autumn-ripe farmland
Gramineae	28	20	21	19
Cyperaceae	20	16	14	14
Compositae	14	5	11	11
Labiatae	10	6	4	5
Scrophulariaceae	9	4	7	8
Polygonaceae	9	4	9	4
Leguminosae	8	4	5	6
Cruciferae	7	6	7	4
Caryophyllaceae	6	3	6	5
Euphorbiaceae	5	3	4	5
Convolvulaceae	5	2	5	4
Rosaceae	5	4	2	3
Ranunculaceae	4	2	3	2
Boraginaceae	3	2	3	3
Amaranthaceae	3	1	2	3
Chenopodiaceae	3	1	3	2
Commelinaceae	3	2	1	2
Umbelliferae	3	0	3	1
Lythraceae	2	2	2	2
Juncaceae	2	2	2	1
Plantaginaceae	2	1	2	1
Primulaceae	2	0	0	2
Rubiaceae	1	1	1	1
Onagraceae	1	1	1	1
Najadaceae	1	1	1	1
Portulacaceae	1	1	1	1
Pontederiaceae	1	1	1	1
Geraniaceae	1	1	1	1
Aizoaceae	1	0	1	1
Oxalidaceae	1	1	1	1
Moraceae	1	1	1	1
Verbenaceae	1	1	0	1
Solanaceae	1	1	1	1
Sterculiaceae	1	1	0	1
Cucurbitaceae	1	1	1	1
Nyctaginaceae	1	1	0	1
Valerianaceae	1	0	0	1
Asclepiadaceae	1	0	1	0
Liliaceae	1	0	0	1
Saxifragaceae	1	1	0	0
Violaceae	1	1	0	0
Malvaceae	1	0	0	1
Alismataceae	1	0	1	0

similar among the different farmland types. The highest weed density occurred in broadleaf weeds, followed by grass weeds and sedge weeds; however, the density percentage of the same weed groups differed among the different types of farmland.

3.3. Dominant weed species in the weed seed banks

Among all the weed species, 71 species were commonly found in the seed banks of all three farmland types, accounting for 40.80% of the total number of species and composing 91.71% of the total dominance degree. Among all species, the total dominance degree of 28 weed species was greater than 1.0, indicating that these weed species were the most important species in the seed banks of all three farmland types. These species were *Cyperus iria*, *A. aequalis*, *Leptochloa chinensis*, *Myosoton aquaticum*, *Mazus japonicus*, *Lapsanastrum apogonoides*, *Beckmannia syzigachne*, *Cyperus difformis*, *R. indica*, *G. aparine* var. *tenerum*, *Eleusine indica*, *Cerastium glomeratum*, *Stellaria uliginosa*, *Digitaria ciliaris*, *Lindernia procumbens*, *Capsella bursa-pastoris*, *Fimbristylis miliacea*, *Ludwigia epilobioides*, *N. minor*, *Portulaca oleracea*, *M. vaginalis*, *Echinochloa crusgalli* var. *mitis*, *Alopecurus japonicus*, *Ammannia baccifera*, *Polygonum lapathifolium*, *Juncus effusus*, *Hemistepta lyrata* and *Conyza canadensis*. According to the dominance degrees of different weed species in the seed banks of the different farmland types (Table 3; Appendix A), the dominant weed community in the seed bank of paddy farmland was composed of summer-ripe farmland weeds, followed by paddy farmland weeds and autumn-ripe farmland weeds. Summer-ripe farmland weeds was the dominant weed community in the seed bank of summer-ripe farmland, followed by autumn-ripe farmland weeds and paddy farmland weeds; however, *C. iria* (a weed species of autumn-ripe farmlands) was the most dominant species. In the seed bank of autumn-ripe farmland, the dominant weed communities were autumn-ripe farmland weeds and summer-ripe farmland weeds, followed by paddy farmland weeds.

Table 2 Species composition of the weed seed banks in the different farmland types

Farmland type	Weed type[1)]	Soil layer (cm)			
		0–5	5–10	10–15	All layers
Paddy farmland	PW	23	26	21	28
	SW	31	37	32	43
	AW	30	17	20	34
	TW	84	80	73	105
Summer-ripe farmland	PW	23	23	23	27
	SW	57	50	47	67
	AW	26	29	25	35
	TW	106	102	95	129
Autumn-ripe farmland	PW	20	17	17	23
	SW	47	43	40	54
	AW	37	38	33	47
	TW	104	98	90	124

[1)] PW, SW and AW represent weed species which infests paddy, summer-ripe and autumn-ripe farmland, respectively; TW represents all weed species in the seed bank of each farmland type.

In paddy farmland, 105 weed species were found in the soil seed bank (Table 3; Appendix A); among these species, the dominance degrees of 27 species were greater

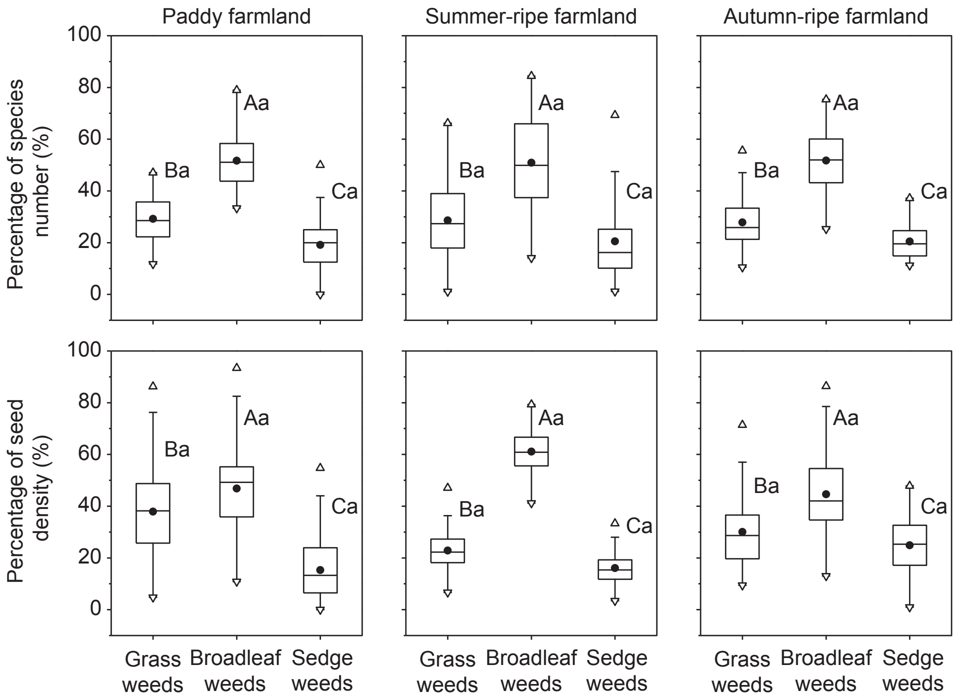

Fig. 2 Species number and density percentage for different weed groups in the weed seed banks of the different farmland types. Here, different uppercase letters represent significant differences among the different weed groups within a farmland type, and different lowercase letters represent significant differences among the different farmland types for a particular weed group. The points, horizontal lines, and upper and lower triangles in the boxplots represent means, medians, and maximum and minimum values, respectively.

Table 3 Dominance degrees (>0.1) of weeds in the different farmland types

Weeds[1)]	Total dominance degree	Paddy farmland	Summer-ripe farmland	Autumn-ripe farmland
Cyperus difformis L.[a)]	2.96	3.03	2.94	2.89
Rotala indica (Willd.) Koehne[a)]	2.49	4.48	2.01	0.93
Lindernia procumbens (Krock.) Borbas[a)]	1.84	1.45	3.25	0.09
Fimbristylis littoralis Grandich.[a)]	1.81	2.39	1.62	1.45
Ludwigia epilobioides Maxim[a)]	1.70	2.41	1.22	1.59
Najas minor All.[a)]	1.64	2.93	1.21	0.82
Monochoria vaginalis (N. L. Burman) C. Presl ex Kunth[a)]	1.61	3.09	1.35	0.34
Echinochloa crusgalli var. *mitis* (Pursh) Peterm.[a)]	1.44	2.77	1.37	0.00
Ammannia baccifera L.[a)]	1.10	1.98	1.00	0.24
Juncus effusus L.[a)]	1.10	2.08	0.73	0.50
Cyperus serotinus Rottb.[a)]	0.90	1.52	0.91	0.19
Schoenoplectus juncoides Roxb.[a)]	0.54	1.38	0.19	0.04
Fimbristylis dichotoma (L.) Vahl[a)]	0.47	0.59	0.45	0.36
Schoenoplectus mucronatus subsp. *Robustus* (Miq.) T. Koyama[a)]	0.45	0.36	0.52	0.46
Pycreus flavidus (Retz.) T. Koyama[a)]	0.36	0.27	0.11	0.84
Murdannia triquetra (Wall. ex Clarke) Bruckn.[a)]	0.33	0.76	0.11	0.14
Cardamine lyrata Bunge[a)]	0.31	0.11	0.67	0.00
Eleocharis yokoscensis (Franch. et Savat.) Tang et Wang[a)]	0.23	0.51	0.07	0.14
Paspalum thunbergii Kunth ex Steud.[a)]	0.15	0.17	0.03	0.28
Paspalum distichum L.[a)]	0.14	0.39	0.03	0.00
Juncus gracillimus (Buchenau) V. I. Krecz. et Gontsch.[a)]	0.13	0.09	0.25	0.00
Hemarthria altissima (Poir.) Stapf et C. E. Hubb.[a)]	0.11	0.00	0.26	0.00
Alopecurus aequalis Sobol.[b)]	6.54	10.68	5.98	2.82
Myosoton aquaticum (L.) Moench[b)]	4.89	3.80	7.71	1.34

(Continued on next page)

Table 3 (Continued from preceding page)

Weeds[1)]	Total dominance degree	Paddy farmland	Summer-ripe farmland	Autumn-ripe farmland
Mazus pumilus (N. L. Burman) Steenis[b)]	4.52	6.69	3.07	4.37
Lapsanastrum apogonoides (Maxim.) Pak et Bremer[b)]	3.87	5.59	4.01	1.65
Beckmannia syzigachne (Steud.) Fern.[b)]	3.82	4.23	5.03	1.41
Galium spurium L.[b)]	2.30	0.86	3.04	2.86
Cerastium glomeratum Thuill.[b)]	2.14	0.00	2.83	3.52
Stellaria alsine Grimm[b)]	1.99	1.61	2.96	0.78
Capsella bursa-pastoris (L.) Medic.[b)]	1.83	0.74	2.75	1.70
Alopecurus japonicus Steud.[b)]	1.20	1.60	1.56	0.22
Polygonum lapathifolium L.[b)]	1.10	1.04	0.95	1.42
Hemisteptia lyrata (Bunge) Fischer et Meyer[b)]	1.07	1.09	1.32	0.71
Erigeron canadensis L.[b)]	1.04	0.75	0.88	1.60
Geranium carolinianum L.[b)]	0.88	0.90	0.77	1.06
Roegneria kamoji Ohwi[b)]	0.81	2.33	0.14	0.18
Polygonum aviculare L.[b)]	0.75	1.24	0.32	0.82
Veronica persica Poir.[bc)]	0.73	0.07	1.21	0.80
Cardamine hirsuta L.[b)]	0.70	1.44	0.25	0.52
Polygonum hydropiper L.[b)]	0.67	0.71	0.73	0.53
Poa annua L.[b)]	0.54	0.70	0.26	0.83
Rumex dentatus L.[b)]	0.47	0.52	0.59	0.25
Trigonotis peduncularis (Trev.) Benth. ex Baker et Moore[b)]	0.45	0.07	0.54	0.79
Veronica anagallis-aquatica L.[b)]	0.45	0.32	0.49	0.57
Bothriospermum zeylanicum (Jacquin) Druce[b)]	0.42	0.20	0.60	0.43
Veronica polita Fries[b)]	0.40	0.00	0.47	0.74
Euphorbia helioscopia L.[b)]	0.37	0.08	0.34	0.75
Coronopus didymus (L.) Smith[b)]	0.29	0.18	0.17	0.59
Medicago polymorpha L.[b)]	0.27	0.47	0.03	0.39
Polypogon fugax Nees ex Steud.[b)]	0.24	0.26	0.40	0.00
Vicia sativa L.[b)]	0.24	0.09	0.35	0.28
Stellaria media (L.) Villars[b)]	0.22	0.00	0.17	0.54
Avena fatua L.[b)]	0.20	0.04	0.46	0.00
Kochia scoparia (L.) Schrad.[b)]	0.15	0.00	0.23	0.23
Ranunculus sieboldii Miq.[b)]	0.13	0.04	0.26	0.05
Erigeron annuus (L.) Pers.[b)]	0.11	0.00	0.23	0.05
Plantago virginica L.[b)]	0.10	0.09	0.13	0.07
Cyperus iria L.[ac)]	9.52	5.45	8.87	15.06
Leptochloa chinensis (L.) Nees[ac)]	5.73	4.83	4.79	8.19
Eleusine indica (L.) Gaertn.[c)]	2.24	0.92	2.43	3.42
Digitaria ciliaris (Retz.) Koel.[c)]	1.99	2.16	1.15	3.06
Portulaca oleracea L.[c)]	1.62	0.16	1.50	3.56
Eclipta prostrata (L.) L.[ac)]	0.89	0.55	0.74	1.51
Acalypha australis L.[c)]	0.88	0.12	0.97	1.69
Setaria viridis (L.) Beauv.[c)]	0.79	0.74	0.41	1.40
Echinochloa crusgalli (L.) var. *austrojaponensis* Ohwi[ac)]	0.54	0.00	0.27	1.60
Digitaria sanguinalis (L.) Scopoli[c)]	0.52	0.36	0.53	0.72
Echinochloa colona (L.) Link[ac)]	0.45	0.12	0.00	1.50
Cyperus rotundus L.[bc)]	0.42	0.04	0.63	0.57
Setaria pumila (Poir.) Roemer et Schultes[c)]	0.39	0.43	0.28	0.49
Mollugo stricta L.[c)]	0.38	0.00	0.03	1.37
Chenopodium album L.[bc)]	0.37	0.25	0.30	0.59
Amaranthus viridis L.[c)]	0.35	0.00	0.66	0.31
Oxalis corniculata L.[c)]	0.34	0.04	0.43	0.59
Euphorbia maculate L.[c)]	0.29	0.07	0.18	0.72
Celosia argentea L.[c)]	0.25	0.00	0.28	0.50
Artemisia lavandulifolia Candolle[c)]	0.24	0.00	0.04	0.82
Digitaria violascens Link[c)]	0.22	0.49	0.10	0.09
Amaranthus retroflexus L.[c)]	0.21	0.15	0.00	0.59

(Continued on next page)

Table 3 (Continued from preceding page)

Weeds[1)]	Total dominance degree	Paddy farmland	Summer-ripe farmland	Autumn-ripe farmland
Cirsium arvense var. *integrifolium* Wimmer et Grabowski[c)]	0.17	0.00	0.38	0.09
Ipomoea nil (L.) Roth[c)]	0.13	0.00	0.17	0.24
Cyperus orthostachyus Franch. et Savat.[c)]	0.13	0.06	0.25	0.04
Euphorbia humifusa Willd.[c)]	0.12	0.00	0.21	0.13
Leptochloa panicea (Retz.) Ohwi[c)]	0.12	0.00	0.00	0.44
Potentilla discolor Bunge[c)]	0.11	0.18	0.00	0.18
Perilla frutescens (L.) Britt.[c)]	0.11	0.00	0.00	0.39

[1)] Weed species with superscript letter a, b and c represents weed species which infests paddy, summer-ripe, autumn-ripe farmland, respectively. In addition, weed species with two superscript letters represents weed species which infests both types of farmland but the fisrt letter indicate that this species belongs to type of farmland.

than 1.0. *A. aequalis*, *M. japonicus*, *L. apogonoides*, *C. iria*, *L. chinensis*, *R. indica*, *B. syzigachne*, *M. aquaticum*, *M. vaginalis*, and *C. difformis* were the dominant species, accounting for 63.09% of the total number of seeds. Sixteen species were found only in the seed banks of paddy farmland.

In the seed bank of summer-ripe farmland, 129 weed species were recorded, and among these species, the dominance degrees of 26 species were greater than 1.0. *C. iria*, *M. aquaticum*, *A. aequalis*, *B. syzigachne*, *L. chinensis*, *L. apogonoides*, *L. procumbens*, *M. japonicus*, *G. aparine* var. *tenerum*, and *S. uliginosa* were the dominant species, accounting for 66.03% of the total number of seeds. Twenty-five species were unique to the seed banks of summer-ripe farmland.

There were 124 weed species in the seed bank of autumn-ripe farmland, and the dominant species were *C. iria*, *L. chinensis*, *M. japonicus*, *P. oleracea*, *C. glomeratum*, *E. indica*, *D. ciliaris*, *C. difformis*, *G. aparine* var. *tenerum*, and *A. aequalis*, which composed 67.23% of the total number of seeds. The dominance degrees of 25 species were greater than 1.0, and only 19 species were unique to autumn-ripe farmland.

3.4. Community structure features and similarity among weed seed banks and aboveground weed communities

The species richness (*S*) of the weed seed banks differed among the different farmland types. The species richness was the highest in summer-ripe farmland, followed by the autumn-ripe farmland and paddy farmland. The weed species diversity index *H´* and evenness index *J* in summer-ripe farmland were similar to those of autumn-ripe farmland but different from those of paddy farmland, while the weed species diversity index (*D*) was similar among the three types of farmland (Table 4). According to Magurran (1988), the Shannon-Wiener index (*H´*) is more sensitive to dense species, while Simpson's index (*D*) is more sensitive to sparse species. Therefore, the difference of weed species diversity index *H´* and evenness index *J* among the three types of farmland was due to the relative higher density of hygrophilous species in the seed bank of paddy farmland, such as *M. vaginalis*, *N. minor*, *J. effusus*, *A. baccifera* and *E. crusgalli* var. *mitis*.

The similarity between the weed seed banks of paddy farmland and summer-ripe farmland was 0.68, and that between paddy farmland and autumn-ripe farmland was 0.69; these values were higher than the similarity (0.35) between the seed bank of paddy farmland and its aboveground weed community. The similarity between the weed seed banks of summer-ripe farmland and autumn-ripe farmland was 0.75, while the similarity between the seed bank of summer-ripe farmland and its aboveground community was 0.59, and that between autumn-ripe farmland and its aboveground community was 0.53. Consequently, the similarities in the weed seed banks among the different types of farmland were higher than those between the seed bank and the aboveground weed community in each farmland type (Table 5).

4. Discussion

Our results showed that most of the weed species identified

Table 4 Community structure features of the weed seed banks in different types of farmland

Farmland type	*S*	*H´*	*D*	*J*
Paddy farmland	16.40±0.42 C	2.40±0.02 B	0.95±0.00 A	0.87±0.00 A
Summer-ripe farmland	23.15±0.59 A	2.62±0.03 A	0.95±0.00 A	0.84±0.00 B
Autumn-ripe farmland	21.23±0.95 B	2.53±0.04 A	0.94±0.00 A	0.85±0.01 B

Data are mean value±standard deviation (n=228). Values with different uppercase letters within a column are significantly different at P<0.05.

in this study from the seed banks belong to only 12 families and that the number of species within each family was similar among across the three farmland types. Moreover, the species number and relative (percent) density percentage of grasses, sedges and broadleaf weeds were also similar among the different farmland types. These results indicate that long-term monoculture practices will not increase the simplification of weed families and groups. The seed banks exhibit regenerative potential for establishment in most plant communities (Dessaint *et al*. 1997). In our study, the crop-associated weed species of paddy, summer-ripe, and autumn-ripe farmland were distributed among all soil layers within farmland type but the number of non-crop-associated species (the weed species unable to infest a particular type of farmland) was even higher than that of crop-associated weeds. In a particular cropping pattern, weed species adapted to the management practices — such as planting time, crop competition, fertility, and herbicide choice to infest and survive (Mahajan *et al*. 2014; Jabran *et al*. 2017). In contrast, when the typical cropping pattern as well as the management practices change, the seeds of non-crop-associated species existing in the seed banks will most likely have the opportunity to germinate and become problematic.

The density distributions of seeds in the weed seed banks of the three different types of farmland were highly positively skewed since the majority of the weed species seeds were low in density and only a few species had contributed a large number of seeds. Similar positively skewed distributions of weed species have been found in the seed banks of most arable fields (Bàrberi and Cascio 2001; Anderson and Beck 2007; Holland *et al*. 2008). Many farming practices influence the composition, density and diversity of weed communities (Buhler *et al*. 1997), including fertilization, irrigation and tillage practices (Yin *et al*. 2005; Franke *et al*. 2007) and rotation, continuous cropping and weeding methods (Haas and Streibig 1982; Chamanabad *et al*. 2009). Crop rotation has traditionally been regarded as an important strategy for weed control (Leighty 1938; Froud-Williams 1988). However, it has also been documented that long-term crop rotation did not influence the weed seed bank size or seedling distribution among soil layers and only had a small influence on the abundance of dominant species (Bàrberi and Cascio 2001). The failure of non-crop-associated weed species to become established is due to their being controlled under current cropping pattern (Chauhan and Gill 2014). However, our results demonstrate that even a 20 years' unsuitable cropping pattern was conducted, non-crop-associated weed species still had a relatively higher degree of dominance (compare with that of crop-associated weed species) in the soil seed bank of each farmland type. Therefore, crop rotation may not substantially contribute to non-crop-associated weed control in the considered region.

In fact, the summer-ripe farmland, autumn-ripe farmland and paddy farmland are separated by both time and space. The autumn-ripe and paddy farmlands differ in space, and the flooding in paddy farmland causes differences in the ecological environments of crops in these two farmland types, which affects the weed communities, while the summer-ripe crops overlap with the rice and autumn-ripe crops in space. The flooded environment of paddy farmland causes seeds with weak waterlogging resistance to rot and die out (Qiang 2005) but stimulated the emergence and growth of hygrophilous species and increased their seed density (Kent and Johnson 2001; Singh 2010), therefore led to a decrease in species richness and an increase in species evenness of soil seed bank in the surveyed paddy farmland. However, comparison the similarity of the weed seed banks among different farmland types and the seed banks with their associated aboveground weed community indicates that although the aboveground weed community differed among the different cropping patterns, the weed species composition in the soil seed bank was still similar. In the past decades, the implementation of a light cultivation system, such as changing a double-rice cropping system to a single-rice cropping system and changing rice transplantation to direct seedling, the flooding frequency is significantly decreased and the water storage period is shortened, which causes the weed species associated with autumn-ripe crops, such as *E. indica* and *Digitaria sanguinalis*, to appear in paddy fields and the convergence of the weed communities with that in the subsequent summer-ripe farmland (Li *et al*. 2012). Furthermore, high rainfall in lowlands with a subtropical humid climate, where this study was conducted, reduces the difference in soil water content between autumn-ripe farmland and paddy fields. This consequently causes the homogenization of weed communities among the three farmland types.

Table 5 Similarities between the weed seed banks of the different types of farmland and the similarity between weed seed banks and the associated aboveground weed communities

Farmland type	Weed seed bank			Aboveground weed community
	Paddy farmland	Summer-ripe farmland	Autumn-ripe farmland	
Paddy farmland	1	0.68	0.69	0.35
Summer-ripe farmland	0.68	1	0.75	0.59
Autumn-ripe farmland	0.75	0.69	1	0.53

5. Conclusion

The existence of a weed seed bank in the soil is the main factor leading to the continuous infestation of weeds in farmland. Currently, weed management measures normally focus on the aboveground vegetation and are only aimed toward controlling the associated weeds and obtaining a high yield of a single crop, but outbreaks of weeds in subsequent years caused by the weed seed bank are not considered. Therefore, in terms of long-term interests, sustainable weed management should be conducted considering both the aboveground weed vegetation and the potential weed community (weed seed bank). Based on the soil weed seed bank, weed management with the goal of halting the continuity of weeds will gradually replace traditional weed control measures and become the main approach for sustainable weed management (Qiang 2001). For example, a sustainable weed management measure based on seed bank depletion which was conducted by filtering irrigation water, fishing float weed seeds during field flooding of paddy and combining with herbicide application effectively reduced weed seed bank and controlled weeds in rice-wheat rotation field (Zhang 2013).

Acknowledgements

We acknowledge the assistance and support provided by Mr. Ji Mengcheng, Mr. Zhou Bin, and Ms. Wu Hairong from the Weed Research Laboratory, Nanjing Agricultural University, China. This study was financially supported by the National Natural Science Foundation of China (31500350) and the National Key Research and Development Program of China (2016YFD0200805).

Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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