Weed seed-bank responses to long-term fertilization in a rice-wheat rotation system

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ABSTRACT

We studied the heterogeneity of soil weed seed-bank in a rice-wheat rotation system after long-term application of different organic or non-organic fertilizers, and the effects of major nutrients on the characteristics of the weed seed-bank. The soil was sampled in the Taihu area after a 31-year long-term fertilization experiment. Weed seeds were identified and counted in the surface soil of 12 differentially treated areas using microscopic examination, and analyzed by the Simpson, Shannon, Margalef, and Pielou indexes. The long-term application of organic fertilizers could significantly reduce the density of soil weed seed-bank; non-organic fertilizers and a combination of non-organic and organic fertilizers had a significant influence on the number of species and diversity of weeds. The application of organic fertilizers improved the Simpson, Shannon and Pielou indexes of soil weed seed-bank community and stabilized the community structure. In terms of the soil nutrient system itself, the soil organic materials and total nitrogen content are the main environmental factors affecting the distribution of soil weed seed-bank.

Keywords: soil weed seed-bank; nutrient management; weed community; Taihu area; biodiversity

Weeds are common components of the farmland ecosystem, the soil weed seed-bank is a demonstration of the existence of a weed community and a link of the growth phases of an ecosystem. Together with the above-ground weed community, the seed bank forms the weed community complex (Roberts 1981, Cavers 1995, Qiang 2002). Therefore, research of the characteristics of farmland soil weed seed-banks has a great significance for the conservation of farmland biodiversity and the stability of ecosystems. Fertilizer amendments can impact weed populations in a variety of ways, the present study shows that the application of fertilizers significantly changes the density of a soil weed seed-bank, the diversity index, and the community structure (Albrecht and Auerswald 2003, Davis et al. 2005). Nitrogen is the most important factor in plant growth that affects weed-crop competition and ultimately, seed rain into the soil (Hemmati et al. 2011). Both non-organic and organic fertilizers had significant effects on weed communities; organic fertilizers could reduce weed density and increase weed-community species diversity and evenness (Everaarts 1992, Major et al. 2005). These findings provide a basis for the study of soil weed seed-banks in different fertilizer-management conditions. The aim of this study was to answer following research questions: How does fertilization influence the development of the weed seed bank?; (2) Is there any correlation between soil nutrients and species composition of the soil weed-seed bank?

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MATERIAL AND METHODS

The long-term experimental field is located at the Suzhou Academy of Agricultural Sciences in Jiangsu province in the Taihu area (31°27'45''N, 120°25'57''E). Treatments were arranged in a two-factor block randomization design with three replicates (Table 1). Each plot, 5 × 4 m in size, is separated by cement plates, which are 15 cm above soil surface so as to avoid water mixing among the plots. Irrigation and drainage are separated by different ditches. Pig manure from 1980 to 1996 and oil rape cake (powder) are applied thereafter as manure at the rates calculated on the basis of total N input equal to pig manure. Manure and calcium superphosphate are all applied as basal fertilizer (Table 1). The tested cropping system was a rice-wheat crop rotation system. Soil samples were collected in June 2011 after the wheat harvest. Each block was divided into 15 cells of 1 m × 1 m without the marginal 5 m^2, and a 15-cm-deep soil column in the middle of each cell was collected using a sampler (3.30 cm in diameter). Soil samples from the same block were mixed together. In total, 36 soil samples from 12 treatments with 3 replicates were analyzed. Soil weed seed-bank species were identified based on a microscopic examination of washed soil. The soil samples were air-dried and divided equally.

The species diversity was determined using the Shannon index:

$$H' = \sum_{i=1}^{s} P_i \ln P_i$$

Where: S – number of species, the total number of weed types in a single treatment; P_i – species abundance of species i, calculated as follows:

$$P_i = \frac{n_i}{N}$$

Where: n_i – number of individuals of species i; N – total number of individuals of all of the species in the block.

The community dominance was determined based on the Simpson index:

$$D = 1 - \sum_{i=1}^{s} P_i^2$$

The community evenness was measured using the Pielou index:

$$J = \frac{H'}{\ln S}$$

The richness index was measured based on the Margalef index:

$$R = \frac{S-1}{\ln N}$$

RESULTS AND DISCUSSION

Variation of soil nutrients in the long-term fertilization experiments. The nutrient indexes of the differently treated soils varied significantly (Table 1). Compared with the initial soil nutrients, for the no-nitrogen treatments, the soil total nitrogen contents increased by 4.1% and 23.1% and 46.8% in the C0, CPK, and MPK treated soil, respectively. For the no-phosphorus fertilization treatments, the soil total phosphorus content was the same as the N- and NK-treated without any increase, but the soil total phosphorus increased by 600% in the MPK treatment. The available potassium contents in all of the treatments decreased to variable degrees compared with the initial values, with the most significant decrease in the no-potassium treatment.

The density of the soil weed seed-bank in the long-term fertilization experiments. The density of the soil weed seed-bank differed significantly among the tested soils, with the lowest density in the MNPK-treated soil, which had only 20.25% of the

Table 1. Description of nutrient inputs into different plots under rice-wheat rotations from 1980 to 2012

Treatment	Chemical fertilizer group	Treatment	Manure group
C0	control, no fertilizer	M0	manure at the averaged rate equivalent to 103.1 kg N/ha/year, 82.7 kg P/ha/year and 70.1 kg K/ha/year
CN	150–300 kg N/ha/year (depending years)	MN	manure + CN
CNP	150–300 kg N/ha/year + 55.8 kg P/ha/year	MNP	manure + CNP
CNK	150–300 kg N/ha/year + 137.5 kg K/ha/year	MNK	manure + CNK
CPK	55.8 kg P/ha/year + 137.5 kg K/ha/year	MPK	manure + CPK
CNPK	150–300 kg N/ha/year + 55.8 kg P/ha/year + 137.5 kg K/ha/year	MNPK	manure + CNPK

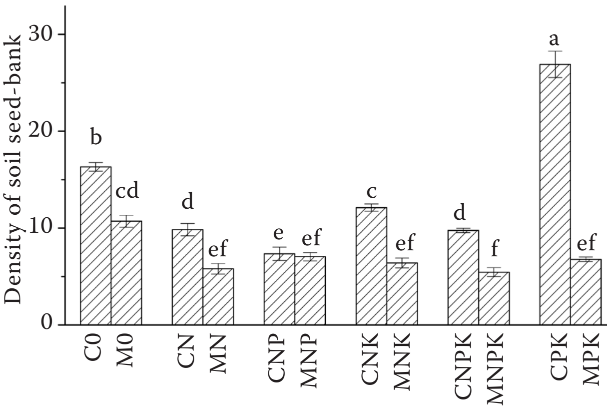

Figure 1. Density of soil seed-bank under long-term different fertilization treatments (10^4 individual/m^2). Different lowercases present significant differences at 0.05 level. Treatments are explained in Table 1

maximum density in the CPK-treated soil (Figure 1). The average seed density of the different organic fertilizer treatments was 48.71% lower than that in the soil treated with the chemical fertilizer ($F = 29.822$, $P < 0.001$). The application of the organic fertilizers significantly reduced the density of the soil weed seed-bank, and at the same time, organic fertilizers could minimize the effects that the chemical fertilizers exerted on the soil weed seed-bank density.

In a study of long-term localized experiments that were started in 1843 in Britain, they also found that the level of fertility affected the individual levels of weed seed-banks, and the application of fertilizers significantly decreased the soil weed seed density (Moss et al. 2004). Total weed seed-bank density was affected by mineral N fertilization but not by compost or animal slurry application. Weed seed-bank composition was related to compost amendment and mineral N fertilization (De Cauwer et al. 2010). The primary reason may be that poor soil limits crop growth; therefore, more water, heat, light, space, and other resources are available for weeds. However, dominant weed populations formed in nutritious soil together with crops restrict the growth of other weeds (Blackshaw et al. 2005).

Species composition of the soil weed seed-bank in the long-term fertilization experiments. Thirty species of weed seeds were detected in the soil samples, belonging to 15 families. The seed density of *Monochoria vaginalis*, *Lindernia procumbens* and *Ammannia baccifera* accounted for 20.78, 15.83 and 10.37% of the total density of the seed-bank, respectively (Table 2), and were therefore considered the dominant species. These weeds had high seed densities and were widely distributed in the various treatments. The results of this study showed that after the application of organic fertilizers, the number of seeds of *Eleocharis acicularis*, *Monochoriav aginalis*, *Polygonum lapathifolium*, *Ammannia baccifera*, *Cyperus difformis*, and *Ammannia arenarid* were reduced significantly. Suding et al. (2004) showed that a decrease of soil nitrogen could increase

Table 2. Soil nutrient under different fertilization treatments

Treatment	Total-N (g/kg)	Total-P	Available-N	Olsen-P	Available-K	SOM (g/kg)
		(mg/kg)				
C0	1.49^{e}	424.44^{f}	131.47^{d}	2.02^{f}	66.50^{cd}	28.84^{d}
CN	1.61^{de}	428.92^{f}	135.71^{cd}	1.48^{f}	53.94^{cde}	28.70^{d}
CNP	1.86^{bc}	1014.68^{d}	148.83^{abcd}	18.82^{d}	48.42^{de}	31.16^{abcd}
CNK	1.61^{de}	440.55^{f}	138.82^{bcd}	2.95^{f}	95.25^{b}	29.14^{cd}
CNPK	1.84^{bc}	965.45^{d}	157.08^{abc}	18.85^{d}	62.38^{cde}	30.86^{abcd}
CPK	1.76^{cd}	1296.84^{c}	151.37^{abcd}	36.64^{c}	119.51^{a}	30.23^{bcd}
M0	1.91^{abc}	956.84^{d}	162.74^{a}	18.80^{d}	47.52^{e}	30.16^{bcd}
MN	1.94^{abc}	733.39^{e}	159.66^{ab}	10.07^{e}	51.76^{cde}	32.42^{ab}
MNP	2.03^{ab}	2142.69^{b}	164.87^{a}	52.20^{b}	52.17^{cde}	33.61^{a}
MNK	1.97^{ab}	770.83^{e}	161.09^{ab}	9.61^{e}	67.79^{c}	29.62^{bcd}
MNPK	2.07^{a}	2123.65^{b}	164.84^{a}	53.55^{b}	67.47^{c}	33.65^{a}
MPK	2.10^{a}	2996.64^{a}	152.16^{abcd}	65.28^{a}	90.32^{b}	32.10^{abc}

Different letters in the same column present significant differences at 0.05 level. Treatments are explained in Table 1. SOM – soil organic matter

Table 3. Species composition and density of soil seed-bank under long-term different fertilization treatments individual/m^2

Family	Weed species	Chemical fertilizer treatment group						Manure treatment group					
		C0	CN	CNP	CNK	CNPK	CPK	M0	MN	MNP	MNK	MNPK	MPK
Gramineae	*Alopecurus aequalis Sobol*	0	312^{cd}	3118^{a}	779^{bcd}	390^{cd}	1637^{abc}	78^{d}	0	2182^{ab}	78^{d}	468^{cd}	0
	Beckmannia syzigachne	312^{cd}	0	6235^{a}	234^{cd}	624^{cd}	6937^{a}	390^{cd}	156^{d}	3819^{abc}	2260^{bcd}	1013^{bcd}	4521^{ab}
	Echinochloa crusgalli	78^{a}	0	234^{a}	0	156^{a}	0	156^{a}	0	0	0	312^{a}	0
	Leptochloa chinensis	0	1091^{bc}	0	0	0	2105^{ab}	3118^{a}	857^{bc}	0	0	156^{c}	0
Cyperaceae	*Cyperus difformis*	7093^{bc}	6781^{bc}	3741^{cde}	16 446^{a}	4287^{cde}	8964^{b}	6469^{bc}	1949de	4989^{bcde}	4599^{cde}	1091^{e}	5456^{bcd}
	Fimbristylis miliaceae	1481^{b}	857^{bc}	0	312^{bc}	1091^{bc}	3274^{a}	0	0	0	0	78^{c}	0
	Scirpus juncoides	12 783^{a}	390^{bc}	0	2182^{b}	78^{c}	546^{bc}	857^{bc}	390^{bc}	0	0	156^{c}	0
	Cyperus imbricatus	4053^{ab}	1793^{bc}	312^{c}	4989^{a}	234^{c}	156^{c}	468^{c}	0	0	0	312^{c}	0
	Eleocharis yokoscensis	10 288^{bc}	13 328^{b}	4521^{d}	17 538^{a}	2884^{d}	8574^{c}	36 634^{d}	3274^{d}	2650^{d}	2494^{d}	857^{d}	2416^{d}
Lythraceae	*Ammannia baccifera*	21 123^{b}	0	9977^{cd}	10 133^{cd}	6002^{def}	37 804^{a}	15 511^{bc}	8028de	8496^{d}	4755^{def}	5456^{def}	1793^{ef}
	Rotala indica	0	312^{b}	234^{b}	468^{b}	234^{b}	1247^{a}	546^{b}	0	0	0	312^{b}	390^{b}
	Ammannia arenara	32 114^{a}	0	0	12 315^{b}	0	0	8574^{cd}	390^{e}	95 097^{bc}	5378^{d}	779^{e}	0
Asteraceae	*Gnaphalium affine*	9509^{a}	5222^{abcd}	156^{e}	8496^{abc}	8028^{abcd}	9431^{ab}	4365^{cde}	3741de	6314^{abcd}	8418^{abc}	6236^{abcd}	5066^{bcd}
	Hemistepta lyrata	6859^{a}	7015^{a}	0	0	857^{cd}	0	4365^{b}	2416^{bc}	0	390^{cd}	0	0
	Eclipta prostrata	0	0	0	78c	0	0	0	0	0	0	7327a	2728^{b}
Scrophulariaceae	*Lindernia procumbens*	26 891^{a}	16 368^{bcd}	10 756^{def}	15 121^{def}	14 186^{def}	22 214^{ab}	21 201^{abc}	21 591^{abc}	10 133^{ef}	13 095^{def}	16 057^{cde}	9509^{f}
	Mazus japonicus	6781^{bc}	7795^{b}	6158^{bc}	3430^{cde}	935^{e}	16 213^{a}	3352^{cde}	2494de	0	0	1169^{e}	4677^{bcd}
Pontederiaceae	*Monochoriav aginalis*	5924^{d}	10 523^{d}	19 408^{c}	8808^{d}	40 298^{b}	99 614^{a}	19 798^{c}	10 601^{d}	10 133^{d}	9198^{d}	4833^{d}	19 642^{c}
Onagraceae	*Ludwigia prostrata*	4365^{a}	1793^{cd}	0	0	702de	2884^{abc}	2182^{cd}	0	4131^{ab}	0	2416^{bcd}	2260^{cd}
Caryophyllaceae	*Malachium aquaticum*	0	0	2105^{a}	78^{c}	1403^{ab}	0	2027^{a}	0	779^{bc}	0	0	0
	Stellaria media	1247^{b}	312^{b}	0	312^{b}	156^{b}	5612^{a}	0	78^{b}	0	0	0	78^{b}
Alismataceae	*Sagittaria pygmaea*	0	12 861^{a}	0	10 133^{a}	1403^{b}	0	0	0	0	0	0	0
Polygonaceae	*Polygonum lapathifolium*	10 601^{b}	10 834^{b}	6392^{bc}	8652^{bc}	10 834^{b}	30 555^{a}	7950^{bc}	0^{d}	6002^{bc}	9665^{b}	4443^{cd}	6625^{bc}
	Polygonum viscosum	0^{a}	0^{a}	0^{a}	78^{a}	0^{a}	0^{a}	0	0	0	0	0	78^{a}
Leguminosae	*Vicia cracca*	1247^{bc}	0^{d}	0^{d}	390^{cd}	390^{cd}	2338^{a}	0^{d}	2105^{ab}	0^{d}	1793^{ab}	312^{cd}	2338^{a}
	Vicia sativa	390^{ab}	0^{b}	0^{b}	0^{b}	468^{ab}	1481^{a}	156^{ab}	0^{b}	0^{b}	624^{ab}	702^{ab}	156^{ab}
Eriocaulaceae	*Eriocaulon buergerianum*	0^{b}	156^{b}	0^{b}	0^{b}	0^{b}	0^{b}	234^{b}	0^{b}	1091^{a}	0^{b}	0^{b}	0^{b}
Geraniaceae	*Geranium carolinianum*	234^{b}	0^{b}	0^{b}	0^{b}	78^{b}	234^{b}	78^{b}	0^{b}	0^{b}	779^{a}	0^{b}	0^{b}
Umbelliferae	*Herba glechomae*	0^{c}	624^{bc}	78^{c}	156^{c}	1793^{a}	156^{c}	1559^{ab}	0^{c}	312^{c}	0^{c}	0^{c}	78^{c}
Plumbaginaceae	*Limonium bicolor*	0^{b}	0^{b}	0^{b}	78^{b}	0^{b}	7093^{a}	0^{b}	0^{b}	0^{b}	779^{b}	0^{b}	0^{b}

Different letters in the same row present significant differences at 0.05 level. Treatments are explained in Table 1

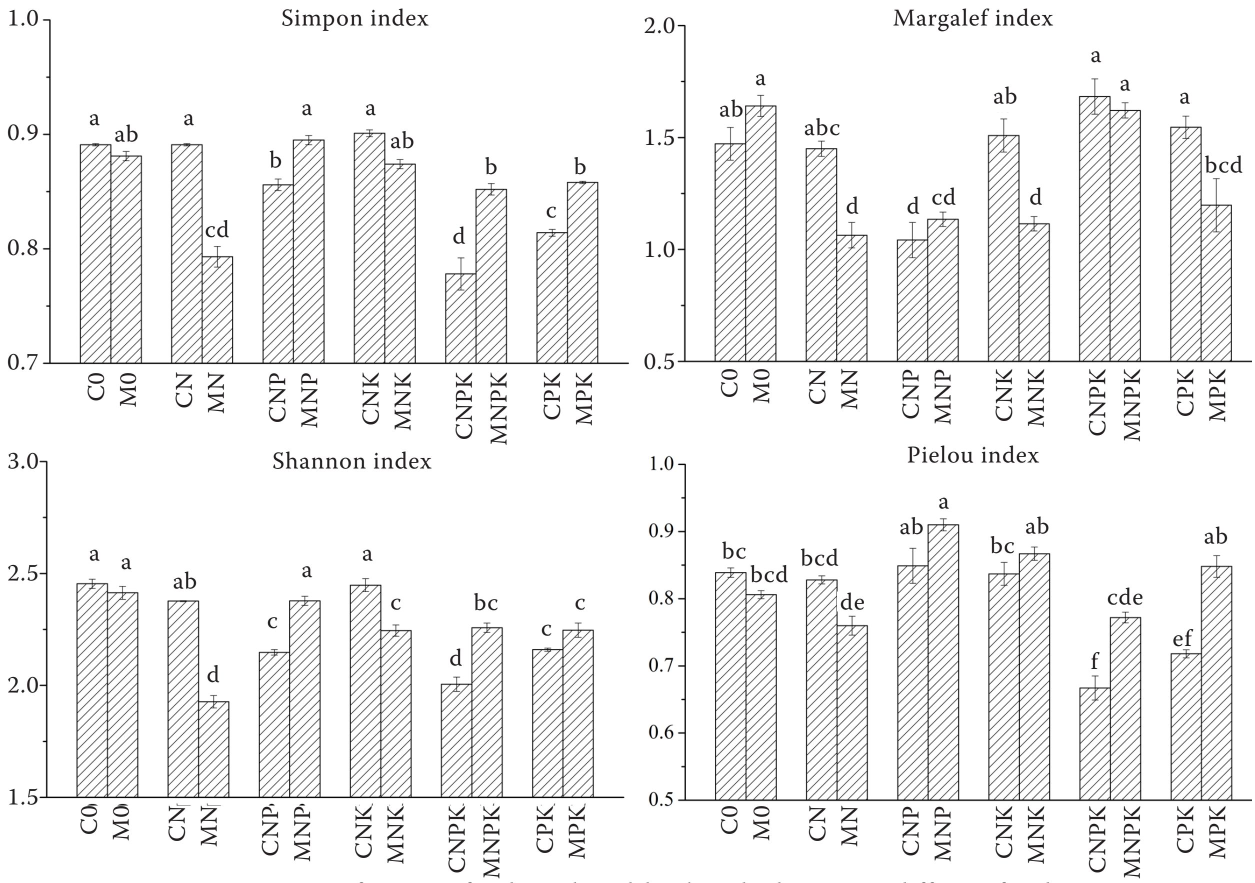

Figure 2. Community structure features of soil weed seed-bank under long-term different fertilization treatment. Different lowercases present significant differences at 0.05 level. Treatments are explained in Table 1

the intra-species competition of weeds, while phosphorus had a stronger effect on inter-species competition (Suding et al. 2004).

Community diversity characteristics of the soil weed seed-bank under long-term fertilizer experiments. Among all of the treatments, MNPK treatment not only maintained higher diversity and evenness indexes but also had a significantly higher species number and Margalef index than the other treatments (Figure 2), suggesting that balanced fertilization with organic and non-organic fertilizers can maintain the stability of a farmland ecosystem. Fertilization can change the composition and species diversity of farmland weeds (Gough et al. 1994, Conn 2006). Loreau et al. (2001) proposed that the diversity of plant species was a part of the productivity function and was positively associated with primary productivity, and both of these factors were associated with soil fertility (Loreau et al. 2001). The functions of an ecological system are determined by the type and number of species in the system. Greater differences in the requirements of different species for different nutrients result in higher chances of the preservation of such nutrients in the system (Tilman et al. 1997, Huston et al. 2000, Estes et al. 2011). The application of organic fertilizers reduced the species number and richness index of the soil weed seed-bank in the experimental area and improved the diversity index and evenness index of the community, thereby stabilizing the community structure, better preserving nutrients in the system, and forming a system with high productivity and a stable population structure. Wardle et al. (2011) found that biological diversity played a buffering role in environmental fluctuation, suggesting that systems with high diversity can better respond to environmental changes (Wardle 1994, Wardle et al. 2011). In the absence of application of exogenous substances (synthetic agents) as well as under the use of only organic fertilizers (traditional agriculture), the biodiversity of the farmland ecosystem in this experimental study was maintained at a high level. Under the condition of balanced fertilization with non-organic or organic fertilizers (modern agriculture), the farmland biodiversity

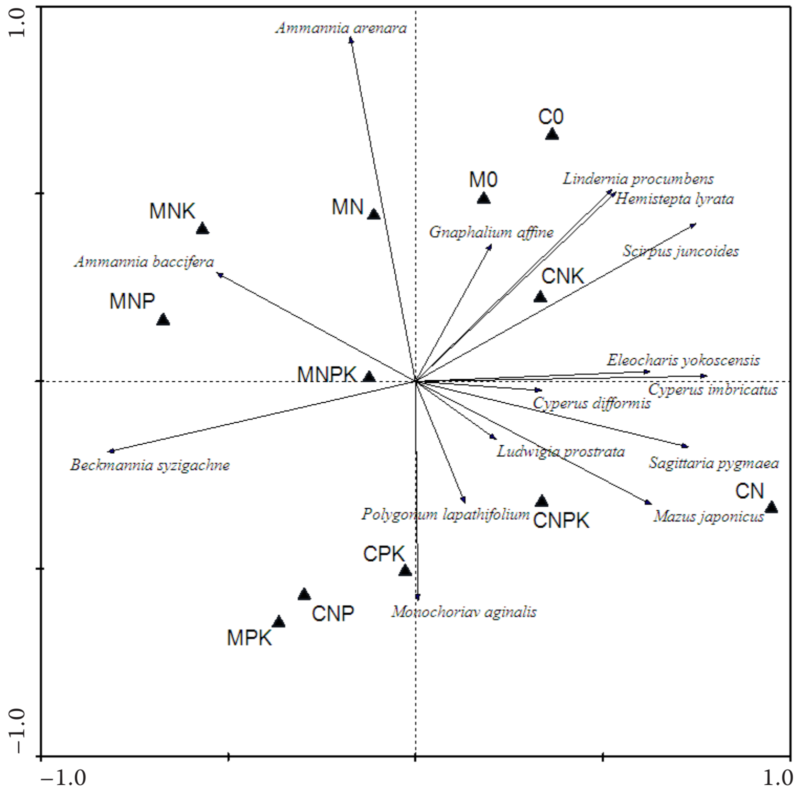

Figure 3. Principle component analysis (PCA) ordination diagram of weed species and weed community in different fertilization treatments. Treatments are explained in Table 1

was maintained at a proper level, while under the unbalanced fertilization condition, the farmland ecosystem biodiversity was reduced.

The correlation between the soil weed seedbank and soil environmental factors. The characteristic values of the principal components 1 and 2 were 0.310 and 0.221 (Figure 3), respectively. The PCA ordination diagram also demonstrated some weed species associations. In particular, *Monochoriav aginalis* was associated with CPK, *Ammannia baccifera* with MN, *Scirpus juncoides* and *Hemistepta lyrata* with CNK treatment.

The characteristic values of the RDA axis 1 and 2 were 0.214 and 0.156, respectively (Figure 4). The correlation coefficients of the soil total nitrogen, total phosphorus, available-N and Olsen-P with the first axis were –0.7949, –0.7588, –0.6106 and –0.7547, respectively. The levels of soil nitrogen and phosphorus content were the main environmental factors affecting the distribution of the weeds.

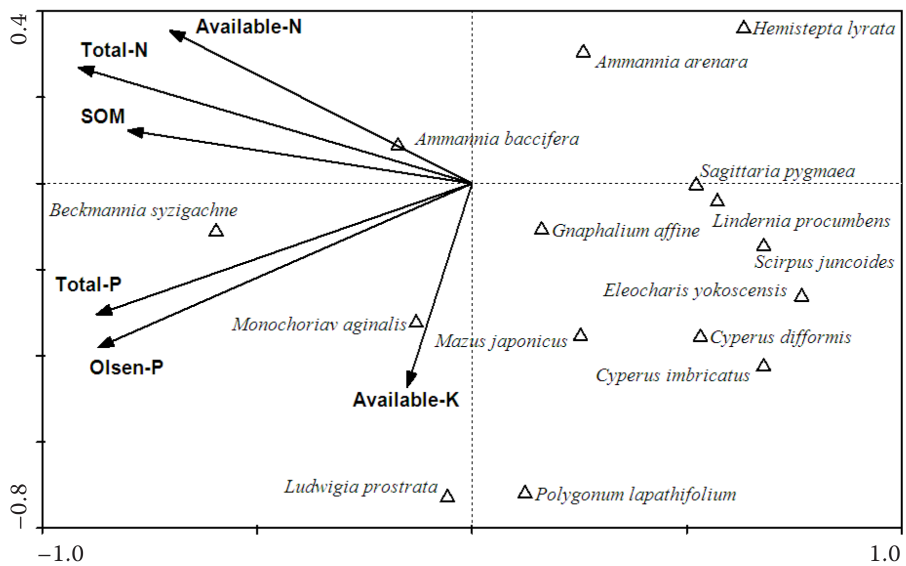

Figure 4. A two-dimensional graph of RDA ordination for soil seed bank and environment factors. SOM – soil organic matter

Suitable nutrient management can improve the competitive relationship between crops and weeds, reducing the effects of weeds on crop yield while maintaining a controllable biodiversity of weeds. The formation of a soil weed seed-bank community is the result of interactions of various environmental factors. In this study, the results of the PCA and RDA showed that soil nitrogen and phosphorus content were the main environmental factors affecting the distribution of weeds. The formation of the soil weed seed-bank was not affected by any single soil fertility factor; its formation was rather a long process of competition between crops and weeds as well as among weeds. The no-fertilizer treatment was adequate to meet the growing needs of most of the weeds. The main effects of organic fertilizers are to reduce the density of soil weed seed-banks and to improve such banks' diversity through increasing the advantage of crops and inhibiting the growth of dominant weeds, to balance the differences between treatments, and to improve and stabilize the productivity of the rice and wheat system.

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