

• 研究报告 •

不同施肥方式对稻麦轮作田土壤 杂草种子库的影响

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摘要: 为揭示不同施肥方式(纯施化肥、有机肥配施化肥、秸秆还田配施有机无机肥、有机无机复合肥)对稻麦两熟制地区农田土壤杂草种子库的影响, 在江苏常州金坛区进行了固定施肥试验。经过连续4年试验处理后, 对不同施肥处理下农田土壤杂草种子库杂草种子种类及密度进行了调查, 并对杂草种子多样性、数量、分布与施肥措施的关系进行了分析。结果表明, 与不施肥相比, 施肥有减少稻麦轮作田土壤杂草种子库杂草种子种类数、杂草种子群落均匀度指数和物种多样性指数的趋势, 并使稻麦轮作田土壤杂草种子库杂草种子总密度明显降低。施肥明显提高了土壤杂草种子库菵草(*Beckmannia syzigachne*)、日本看麦娘(*Alopecurus japonicus*)、看麦娘(*A. aequalis*)种子的密度, 施用猪粪堆肥配施化肥处理提高程度更为显著; 秸秆还田配施化肥、秸秆还田配施有机肥化肥、有机无机复合肥施用处理有减少菵草、日本看麦娘、看麦娘杂草种子密度的趋势。施肥明显降低了土壤杂草种子库阔叶杂草种子密度; 施用有机肥有增加土壤杂草种子库苦苣菜(*Veronica undulata*)、蛇床(*Cnidium monnieri*)种子密度的趋势; 施用猪粪堆肥有增加土壤杂草种子库鸭舌草(*Monochoria vaginalis*)种子密度的趋势。因此, 不同种类杂草对不同肥料存在偏好性差异, 不同施肥方式造成了土壤杂草种子库优势物种组成的差异。

关键词: 化肥; 有机无机肥配施; 秸秆还田; 有机无机复合肥; 土壤杂草种子库; 稻麦轮作田

Effects of fertilization regimes on weed seed banks in a rice–wheat crop system

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Abstract: To reveal the effects of different fertilization treatments on weed seed banks in a rice–wheat crop system, a field test using fixed fertilization was conducted in Jintan of Changzhou, Jiangsu Province. After the four-year experiment, the weed seed species and density of the soil seed bank were investigated and the relationships among weed seed diversity, density, distribution, and fertilization were analyzed. Results showed that: fertilization reduced the number of weed species and the evenness and diversity index of the weed seed bank in a rice–wheat crop system; fertilization significantly reduced the total density of the weed

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seed bank, but increased the seed density of *Beckmannia syzigachne*, *Alopecurus japonicus* and *A. aequalis*, especially with the application of pig manure plus chemical fertilizers. Straw returning plus chemical fertilizer, organic fertilizer plus chemical fertilizer, and organic-inorganic compound fertilizer treatments had the same tendency to reduce the seed density of *B. syzigachne*, *A. japonicus* and *A. aequalis*. Fertilization significantly decreased the seed bank densities of broadleaf weeds. Organic fertilizers had a tendency to increase the seed bank density of *Veronica undulate* and *Cnidium monnieri*. Application of pig manure compost increased the seed bank density of *Monochoria vaginalis*. Therefore, different weed species had different preferences to different fertilizers as the dominant species composition of the weed seed bank was influenced by different fertilization techniques.

Key words: chemical fertilizer; organic fertilizers plus chemical fertilizer; straw returning; organic and inorganic fertilizer; soil weed seed bank; rice-wheat cropping

杂草是农田生态系统的生物组分之一, 维持适当数量的杂草对保护农田生物多样性具有重要作用(Anderson et al, 1998; Fenn et al, 1998), 但杂草数量一旦增多, 会通过与作物竞争水、肥、光等自然资源而影响作物的生长与产量(李儒海等, 2008)。土壤杂草种子库是指存在于土壤及其上层凋落物中具有活力种子的总和(张玲等, 2004)。土壤杂草种子库是杂草存在的一种方式 and 生长过渡的纽带, 与地上杂草群落共同构成杂草群落综合体(Cavers, 1995; Qiang, 2002), 研究农田的土壤杂草种子库可为保护农田生物多样性提供依据。

农田杂草群落组成的变化源于农耕操作导致的杂草生境改变所带来的选择性压力(Hammerton, 1968; Hall et al, 2000)。化肥使用、轮作制度、栽培方式以及作物的密度都是影响杂草群落的关键因素(Dhima & Eleftherohorinos, 2001; Albrecht & Auerwald, 2003; Blackshaw et al, 2003; Dayis et al, 2005), 特别是长期不同施肥方式对土壤杂草种子库密度、多样性指数以及群落结构等都有显著影响。例如, 冯伟等(2006)在研究稻油轮作田土壤杂草种子库时发现, 在化肥配施秸秆的方式下, 农田生态系统表现出相对较高的生产力与杂草种子库生物多样性, 具有较好的农业生产实践意义; 万开元等(2010)在安徽蒙城地区研究旱地土壤杂草种子库时发现, 长期施用氮、磷、钾肥能显著改变旱地土壤杂草种子库的组成; Jiang等(2014)研究了太湖地区稻麦轮作田长期施肥方式对土壤杂草种子库的影响, 发现长期氮、磷、钾肥料单一或配合施用可显著影响稻麦两熟制农田杂草种子库的群落组成, 施氮显著降低农田杂草种子密度, 施磷使牛毛毡(*Heleocharis yokoscensis*)种子数量显著下降、鸭舌草(*Monochoria vaginalis*)种子数量显著增加。这些

研究均集中在农田杂草种子库与氮、磷、钾等作物所需营养元素的响应关系方面。Jiang等(2014)的研究虽已涉及有机肥, 但仅限菜籽饼肥配施化肥处理, 有机肥类型存在局限性。不同类型肥料的施用对稻麦轮作田土壤杂草种子库影响的研究尚不多见, 特别是针对中国典型的稻麦两熟制农田, 不同有机肥配施化肥、有机无机复合肥施用对土壤杂草种子库的影响缺乏研究。

为追求高产而过量施用化肥会导致面源污染。太湖地区为我国典型的稻麦轮作制高产田, 在稻、麦生产中, 当地农民长期有施用化肥并配施农家有机肥(猪粪、牛粪等)、秸秆还田等习惯。随着畜禽的规模化生产, 其粪便的无害化处理已成为商品有机肥、有机无机复合肥商品化生产的原料来源, 多元化肥料的生产, 结合肥料施用的科学化、简便化, 化肥配施有机肥、秸秆还田或直接施用商品有机无机复合肥已成为必然。本研究立足于南京农业大学在太湖地区的长期定位施肥试验点, 探讨纯施化肥、有机无机肥料配施、秸秆还田、商品有机肥施用等对农田土壤杂草种子库杂草种子种类、密度、多样性的影响, 拟为农田杂草的生态治理及杂草多样性的保护提供依据。

1 方法

1.1 试验地概况

试验点位于江苏省常州市金坛区指前镇建春村(31°39'41.8" N, 119°28'23.5" E)。该地海拔10 m, 属亚热带湿润季风性气候, 年均气温15.5℃, 年平均湿度78%, 年降水量1,084.7 mm。

1.2 试验设计

田间试验始于2010年11月小麦(*Triticum aestivum*)季, 为水稻(*Oryza sativa*)-小麦的水旱轮作体

系。实验小区共36个(9个处理 × 4次重复), 每小区40 m² (8 m × 5 m), 随机区组排列, 小区间以水泥埂隔离, 防止串水串肥。供试土壤为脱潜型水稻土(乌栅土); 小麦在播种后, 所有处理小区普用50%苄嘧磺隆·异丙隆可湿性粉剂除草1次, 用量2.1 kg/ha; 水稻在移栽后5-7天, 所有处理小区普用53%苄嘧磺隆·苯噻酰草胺可湿性粉剂除草1次, 用量0.9 kg/ha。

施肥处理: (1) CK, 完全不施肥; (2) F, 纯NPK (100%当地用量, 下同); (3) M1F1, 猪粪堆肥 (3,000 kg/ha) + 70% NPK; (4) M2F2, 猪粪堆肥 (6,000 kg/ha) + 50% NPK; (5) SF, 秸秆全量还田+100% NPK; (6) SM1F1, 秸秆全量还田+猪粪堆肥 (3,000 kg/ha) + 70% NPK; (7) SM2F1, 秸秆全量还田+猪粪堆肥 (6,000 kg/ha) + 70% NPK; (8) MOI1, 基肥猪粪有机无机复合肥+穗肥尿素; (9) MOI2, 猪粪有机无机复合肥作基肥, 全程一次施肥。

1.2.1 小麦季肥料运筹方案

F处理NPK化学肥料运筹方案: 基苗肥为配方肥(N-P₂O₅-K₂O = 16-18-8) 375 kg/ha + 尿素150 kg/ha, 拔节孕穗肥为配方肥(N-P₂O₅-K₂O = 18-7-10) 375 kg/ha + 尿素150 kg/ha, N、P₂O₅、K₂O用量分别为265.5、93.75、67.5 kg/ha。MOI1肥料运筹: 基肥猪粪有机无机复合肥(N-P₂O₅-K₂O = 12-4-4, 有机质 ≥ 16%) 1,500 kg/ha, 穗肥尿素130 kg/ha。MOI2肥料运筹: 猪粪有机无机复合肥(N-P₂O₅-K₂O = 12-4-4, 有机质 ≥ 16%) 2,250 kg/ha, 作基肥全程一次施肥。

1.2.2 水稻季肥料运筹方案

F处理NPK化学肥料运筹方案: 基肥为配方肥(N-P₂O₅-K₂O = 18-7-10) 375 kg/ha, 分蘖肥为尿素195 kg/ha, 拔节孕穗肥为配方肥(N-P₂O₅-K₂O = 15-5-15) 225 kg/ha + 尿素240 kg/ha, N、P₂O₅、K₂O用量分别为301.35、37.5、71.25 kg/ha; MOI1肥料运筹: 基肥猪粪有机无机复合肥(N-P₂O₅-K₂O = 9-3-3, 有机质 ≥ 20%) 2,370 kg/ha, 穗肥尿素90 kg/ha; MOI2肥料运筹: 猪粪有机无机复合肥(N-P₂O₅-K₂O = 9-3-3, 有机质 ≥ 20%) 3,330 kg/ha, 作基肥全程一次施肥。

稻麦两季施用猪粪堆肥养分含量: 有机质45.4%, N 2.3%, P₂O₅ 2.9%, K₂O 1.2%, 含水量29.1%。

1.3 取样和测定方法

在2014年10月30日水稻收获后进行土样采集, 每个处理小区用内径为30 mm的取样器平行网状取样, 钻取12个土芯, 分0-5 cm、5-10 cm、10-15 cm分别混装, 共108份土样。采集的土样自然风干, 稍加粉碎, 混匀后用水洗镜检法测定杂草种子种类及数量。将每份土样分别倒入孔径为0.125 mm (150目)的标准分样筛中, 筛去细土后用自来水冲洗, 除去淤泥。然后将分样筛中残留物自然风干, 用20、40、60、80、100、120、150目的标准分样筛进行分级筛选, 剩余物分装在培养皿中。在双目解剖镜(最大放大倍数10 × 4倍)下计数杂草种子的种类和数量(印丽萍和颜玉树, 1997; 马波等, 2004)。

1.4 数据分析

杂草种子库密度即每平方米土壤中的杂草种子数量。杂草种子相对多度: 每种杂草种子的相对多度=每种杂草种子库密度/杂草种子库总密度。

物种多样性指数计算公式如下:

Shannon-Wiener指数(Putman & Wratten, 1984):

$$H' = -\sum P_i \ln P_i;$$

Simpson优势度指数(Parish et al, 1994): $D = \sum P_i^2$;

Pielou均匀度指数(Hill, 1973): $J = H'/\ln S$

其中S为土壤杂草种子库物种总数, $P_i = N_i/N$, N为样方中总个体数, N_i 为样方中第i物种的个体数。

采用SPSS 18.0软件进行LSD检验, 利用CANOCO for Windows 4.5软件对不同施肥处理土壤杂草种子库种子的相对多度矩阵结合不同类型肥料因子进行典范对应分析(CCA)。。

2 结果

2.1 施肥处理对土壤杂草种子库种子密度的影响

调查结果显示(图1), 不施肥处理的土壤杂草种子库杂草种子密度为22,322.48粒/m², 施肥处理后其密度显著降低。与纯施化肥、猪粪堆肥配施化肥处理比较, 秸秆还田配施化肥(SF)、秸秆还田配施有机肥化肥(SM1F1、SM2F1)和有机无机复合肥处理(MOI1、MOI2)的土壤杂草种子库密度有降低趋势。

从表1可以看出, 4年的不同施肥方式主要是影响了土壤杂草种子库中主要杂草的种子密度。对于麦田杂草而言, 施肥有增加禾本科杂草种子库密度

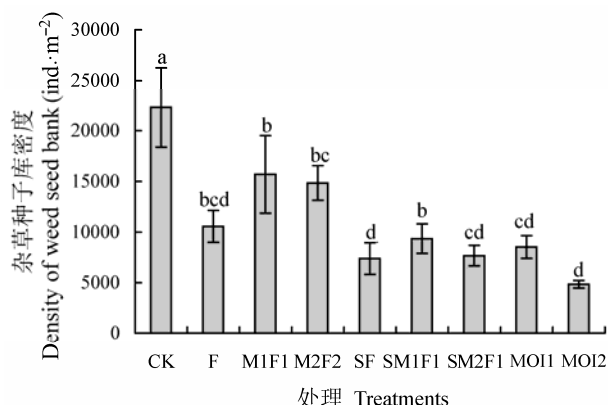


图1 不同施肥处理对土壤杂草种子库密度的影响(平均值±标准差)。不同小写字母表示不同处理间差异显著($P < 0.05$)。CK: 不施肥; F: 100%化肥; M1F1: 猪粪堆肥(3,000 kg/ha) + 70%化肥; M2F2: 猪粪堆肥(6,000 kg/ha) + 50%化肥; SF: 秸秆全量还田 + 100%化肥; SM1F1: 秸秆全量还田+猪粪堆肥(3,000 kg/ha) + 70%化肥; SM2F1: 秸秆全量还田+猪粪堆肥(6,000 kg/ha) + 70%化肥; MOI1: 猪粪商品有机无机复合肥+尿素; MOI2: 猪粪商品有机无机复合肥。下同。

Fig. 1 Effects of different fertilization treatments on the density of soil weed seed bank (mean ± SD). Different small letters meant significant difference among treatments at $P < 0.05$. CK: No fertilizer; F: 100% Chemical fertilizer; M1F1: Pig manure compost (3,000 kg/ha) + 70% chemical fertilizer; M2F2: Pig manure compost (6,000 kg/ha) + 50% chemical fertilizer; SF: Straw return + 100% chemical fertilizer; SM1F1: Straw return + pig manure compost (3,000 kg/ha) + 70% chemical fertilizer; SM2F1: Straw return + pig manure compost (6,000 kg/ha) + 70% chemical fertilizer; MOI1: Commercial fertilizer of pig manure mixed with chemical fertilizer + urea; MOI2: Commercial fertilizer of pig manure mixed with chemical fertilizer. The same below.

和降低阔叶杂草种子库密度的趋势,其中猪粪堆肥配施化肥(M1F1)处理对两者的影响均最显著。不同施肥对麦田杂草蒺藜(*Beckmannia syzigachne*)、通泉草(*Mazus japonicus*)、牛繁缕(*Malachium aquaticum*)、蛇床(*Cnidium monnieri*)、稻槎菜(*Lapsana apogonoides*)的种子密度影响较大。具体来看,连续4年不施肥处理小区土壤杂草种子库蒺藜种子平均密度为412.83粒/m²,施肥增加了其密度;其中猪粪堆肥配施化肥(M1F1、M2F2)处理下蒺藜种子的密度显著增加;与其他施肥处理相比,所有配合秸秆还田的施肥措施下,蒺藜种子密度均有降低的趋势;与猪粪堆肥配施化肥处理相比,有机无机复合肥处理(MOI1、MOI2)显著降低了蒺藜种子的密度。连续4年不施肥处理小区土壤杂草种子库中通泉草种子的平均密度为1,326.96粒/m²,施肥减少了其密

度;其中有机肥配施化肥处理、秸秆还田配施化肥处理、秸秆还田配施有机化肥处理明显减少了通泉草种子库的密度,但减少化肥用量、增加有机肥的施用量,通泉草种子库密度有增加的趋势。此外,施肥还有增加蛇床种子库密度、降低稻槎菜种子库密度的趋势。

对于稻田而言,施肥有降低其土壤杂草种子库杂草种子总密度和阔叶杂草种子密度的趋势,其中秸秆还田配施化肥(SF)、配施猪粪堆肥化肥(SM1F1、SM2F1)、有机无机复合肥(MOI1、MOI2)处理下,杂草种子库总密度和阔叶杂草种子密度显著降低;同时施肥处理显著降低了莎草科杂草种子库密度。具体地讲,不同施肥处理对稻田杂草鸭舌草、陌上菜(*Lindernia procumbens*)、节节菜(*Rotala indica*)、异型莎草(*Cyperus difformis*)、碎米莎草(*C. iria*)的种子库密度均有较大影响。不施肥处理小区鸭舌草种子平均密度为3,715.50粒/m²,而猪粪堆肥配施化肥有增加其种子密度的趋势,秸秆还田配施化肥、配施有机化肥处理有降低其种子密度的趋势,有机无机复合肥施用处理明显降低了其种子的密度;连续4年不施肥处理小区陌上菜种子平均密度为4,098.84粒/m²,施肥可降低其种子密度,施用有机肥处理、秸秆还田配施化肥、配施有机化肥处理可显著降低其种子密度;施肥可显著降低节节菜的种子密度;施肥可显著降低异型莎草的种子密度,与纯施化肥处理相比,施用有机肥、秸秆还田配施化肥、配施有机化肥处理有降低其种子密度的趋势;施肥可显著降低碎米莎草的种子密度。

2.2 施肥处理对土壤杂草种子库杂草种类与生物多样性的影响

从表2可以看出,与不施肥相比,施肥有降低土壤杂草种子库杂草种类数的趋势,秸秆还田配施化肥(SF)、有机无机复合肥处理(MOI1、MOI2)降低趋势更为明显。秸秆还田配施有机化肥处理(SM1F1)与不施肥(CK)相比,杂草种子种类与生物多样性差异显著。施肥有降低土壤杂草种子库物种丰富度(S)、物种多样性指数(H')、均匀度指数(J)的趋势。虽然在连续4年固定施肥处理下,土壤杂草种子库杂草种子密度已明显不同,但由于施肥对土壤种子库杂草种子种类的影响较小,导致不同施肥处理间生物多样性指数差异不显著。

表1 不同施肥处理对稻-麦田土壤种子库中杂草种子密度的影响(平均值±标准差)(粒/m²)

Table 1 Effects of different fertilization treatments on the weed seed density of weed seed bank under rice-wheat cropping system (mean ± SD) (ind./m ²)									
杂草种类 Weed species	CK	F	M1F1	M2F2	SF	SM1F1	SM2F1	MO11	MO12
麦田 Wheat fields									
禾本科杂草 Grassy weeds	442.32 ± 352.22 ^b	1,680.82 ± 1,474.40 ^b	6,074.55 ± 3,293.53 ^a	4,629.63 ± 3,239.40 ^a	1,032.08 ± 723.11 ^b	1,061.57 ± 714.24 ^b	619.25 ± 389.72 ^b	1,415.43 ± 788.31 ^b	1,150.04 ± 729.49 ^b
看麦娘 <i>Beckmannia syri-</i> <i>gachne</i>	412.83 ± 340.50 ^b	1,444.92 ± 1,286.26 ^b	5,101.44 ± 3,351.97 ^a	3,980.89 ± 2,375.45 ^a	914.13 ± 588.78 ^b	1,002.59 ± 642.45 ^b	589.76 ± 397.09 ^b	1,385.94 ± 790.52 ^b	1,120.55 ± 790.52 ^b
日本看麦娘 <i>Alopecurus japonicus</i>	29.49 ± 58.98 ^a	117.95 ± 96.31 ^a	206.42 ± 201.44 ^a	206.42 ± 412.83 ^a	29.49 ± 58.98 ^a	0 ^a	0 ^a	0 ^a	0 ^a
看麦娘 <i>A. aquatilis</i>	0 ^b	117.95 ± 235.90 ^b	766.69 ± 936.22 ^a	442.32 ± 807.92 ^{ab}	88.46 ± 176.93 ^b	58.98 ± 117.95 ^b	29.49 ± 58.98 ^b	29.49 ± 58.98 ^b	29.49 ± 58.98 ^b
阔叶杂草 Broadleaf weeds									
阔叶杂草	4,157.82 ± 1,784.62 ^a	2,830.86 ± 982.15 ^{ab}	1,739.80 ± 338.79 ^b	2,742.39 ± 503.89 ^{ab}	2,742.39 ± 1,699.43 ^{ab}	1,975.70 ± 1,307.71 ^b	2,653.93 ± 1,823.50 ^{ab}	3,479.59 ± 1,707.93 ^{ab}	2,182.12 ± 946.07 ^b
通泉草 <i>Mazus japonicus</i>	1,326.96 ± 1,260.77 ^a	943.62 ± 397.09 ^{ab}	501.30 ± 201.44 ^b	707.71 ± 333.62 ^{ab}	383.35 ± 310.21 ^b	412.83 ± 152.28 ^b	707.71 ± 481.54 ^{ab}	442.32 ± 112.93 ^b	589.76 ± 166.81 ^{ab}
水苦苣 <i>Veronica undulata</i>	206.42 ± 112.93 ^a	176.93 ± 152.28 ^a	58.98 ± 68.10 ^a	235.90 ± 166.81 ^a	58.98 ± 117.95 ^a	206.42 ± 201.44 ^a	324.37 ± 201.44 ^a	265.39 ± 294.88 ^a	176.93 ± 117.95 ^a
牛繁缕 <i>Malachium aquaticum</i>	1,562.87 ± 201.44 ^{ab}	1,120.55 ± 820.03 ^b	707.71 ± 215.35 ^b	973.11 ± 564.65 ^b	884.64 ± 59.57 ^b	1,032.08 ± 729.50 ^b	973.11 ± 884.64 ^b	2,300.07 ± 1,787.54 ^a	737.20 ± 572.81 ^b
泥胡菜 <i>Hemistepta lyrata</i>	501.30 ± 294.88 ^a	412.83 ± 280.78 ^a	353.86 ± 166.81 ^a	560.27 ± 445.26 ^a	501.30 ± 176.93 ^a	147.44 ± 223.28 ^a	471.81 ± 500.43 ^a	412.83 ± 225.86 ^a	442.32 ± 389.72 ^a
蛇床 <i>Cnidium monnieri</i>	29.49 ± 58.98 ^{ab}	0 ^b	58.98 ± 68.10 ^{ab}	88.46 ± 113.93 ^{ab}	29.49 ± 58.98 ^{ab}	147.44 ± 176.93 ^a	0 ^b	58.98 ± 68.10 ^{ab}	117.95 ± 96.31 ^{ab}
稻槎菜 <i>Lapsana apogonoides</i>	530.79 ± 225.86 ^a	176.93 ± 204.30 ^b	58.98 ± 117.95 ^b	88.46 ± 58.98 ^b	176.93 ± 117.95 ^b	29.49 ± 58.98 ^b	117.95 ± 96.31 ^b	0 ^b	88.46 ± 112.93 ^b
猪殃殃 <i>Gallium aparine</i> var. <i>tenerum</i>	0 ^b	0 ^b	0 ^a	88.46 ± 112.93 ^a	707.71 ± 1,415.43 ^a	0 ^a	58.98 ± 68.10 ^a	0 ^a	29.49 ± 58.98 ^a
总计 Total	4,600.14 ± 2,085.68 ^{bc}	4,511.68 ± 1,349.60 ^{bc}	7,814.34 ± 3,029.29 ^a	7,372.02 ± 3,370.08 ^{ab}	3,774.48 ± 2,131.86 ^c	3,037.27 ± 1,774.19 ^c	3,273.18 ± 1,696.70 ^c	4,895.02 ± 1,458.99 ^{bc}	3,332.15 ± 596.60 ^c
水稻田杂草 Rice fields									
禾本科杂草 Grassy weeds	117.95 ± 0.00 ^a	88.46 ± 112.93 ^a	58.98 ± 117.95 ^a	58.98 ± 117.95 ^a	29.49 ± 58.98 ^a	176.93 ± 280.78 ^a	206.42 ± 201.44 ^a	235.90 ± 166.81 ^a	117.95 ± 166.81 ^a
千金子 <i>Leptochloa chinensis</i>	58.98 ± 68.10 ^a	58.98 ± 68.10 ^a	29.49 ± 58.98 ^a	29.49 ± 58.98 ^a	29.49 ± 58.98 ^a	147.44 ± 294.88 ^a	88.46 ± 112.93 ^a	117.95 ± 96.31 ^a	117.95 ± 166.81 ^a
稗 <i>Echinochloa crusgalli</i>	58.98 ± 68.10 ^a	29.49 ± 58.98 ^a	29.49 ± 58.98 ^a	29.49 ± 58.98 ^a	0 ^a	29.49 ± 58.98 ^a	117.95 ± 96.31 ^a	117.95 ± 235.90 ^a	0 ^a
阔叶杂草 Broadleaf weeds									
鸭舌草 <i>Monochoria vaginalis</i>	8,905.40 ± 5,112.02 ^a	7,313.05 ± 6,327.06 ^{ab}	7,224.58 ± 4,949.67 ^{ab}	7,077.14 ± 2,957.45 ^{ab}	3,155.23 ± 2,018.73 ^{bc}	5,425.81 ± 2,756.15 ^{abc}	3,803.96 ± 1,825.72 ^{abc}	3,125.74 ± 1,026.03 ^{bc}	1,209.01 ± 564.65 ^c
陌上菜 <i>Lindernia procumbens</i>	3,715.50 ± 1,833.64 ^{abc}	1,25.73 ± 1,675.03 ^{abcd}	6,015.57 ± 4,441.65 ^a	4,718.09 ± 2,677.65 ^{ab}	2,594.95 ± 1,839.96 ^{bcd}	3,892.43 ± 2,874.75 ^{abc}	2,477.00 ± 788.31 ^{bd}	1,503.89 ± 465.63 ^{cd}	412.83 ± 312.07 ^d
节节菜 <i>Rotala indica</i>	4,098.84 ± 2,816.69 ^a	3,391.13 ± 3,944.36 ^{ab}	1,179.52 ± 1,050.59 ^{bc}	2,329.56 ± 2,110.82 ^{abc}	560.27 ± 352.22 ^c	1,533.38 ± 500.43 ^{abc}	1,238.50 ± 1,430.10 ^{bc}	1,592.36 ± 779.44 ^{abc}	796.18 ± 324.82 ^{bc}
丁香蓼 <i>Ludwigia prostrata</i>	1,032.08 ± 1,400.19 ^{ab}	766.69 ± 1,533.38 ^{ab}	29.49 ± 58.98 ^b	29.49 ± 58.98 ^b	0 ^b	0 ^b	29.49 ± 58.98 ^b	29.49 ± 58.98 ^b	0 ^b
齿果酸模 <i>Rumex dentatus</i>	29.49 ± 58.98 ^a	29.49 ± 58.98 ^a	0 ^a	0 ^a	0 ^a	0 ^a	58.98 ± 117.95 ^a	0 ^a	0 ^a
莎草科杂草 Cyperaceae weeds	8,669.50 ± 7,052.52 ^a	2,270.58 ± 3,371.28 ^b	648.74 ± 391.20 ^b	324.37 ± 201.44 ^b	412.83 ± 225.86 ^b	678.23 ± 261.54 ^b	383.35 ± 201.44 ^b	265.39 ± 261.54 ^b	206.42 ± 112.93 ^b
异型莎草 <i>Cyperus difformis</i>	8,168.20 ± 6,475.84 ^a	2,270.58 ± 3,371.28 ^b	648.74 ± 391.20 ^b	294.88 ± 152.28 ^b	383.35 ± 223.28 ^b	648.74 ± 280.78 ^b	383.35 ± 201.44 ^b	235.90 ± 215.35 ^b	206.42 ± 112.93 ^b
碎米莎草 <i>C. iria</i>	501.30 ± 723.11 ^a	0 ^b	0 ^b	29.49 ± 58.98 ^b	29.49 ± 58.98 ^b	29.49 ± 58.98 ^b	0 ^b	29.49 ± 58.98 ^b	0 ^b
总计 Total	17,692.85 ± 8,765.06 ^a	9,672.09 ± 9,244.03 ^b	7,932.30 ± 4,844.55 ^{bc}	7,460.49 ± 3,122.77 ^{bc}	3,597.55 ± 2,137.29 ^{bc}	6,280.96 ± 3,236.53 ^{bc}	4,393.72 ± 1,745.20 ^{bc}	3,627.03 ± 1,016.38 ^{bc}	1,533.38 ± 585.82 ^c

同行不同字母表示不同处理间差异显著($P < 0.05$)。施肥处理同图1。Different letters in the same row represent significant differences at $P < 0.05$. The fertilization treatments were same as in Fig. 1.

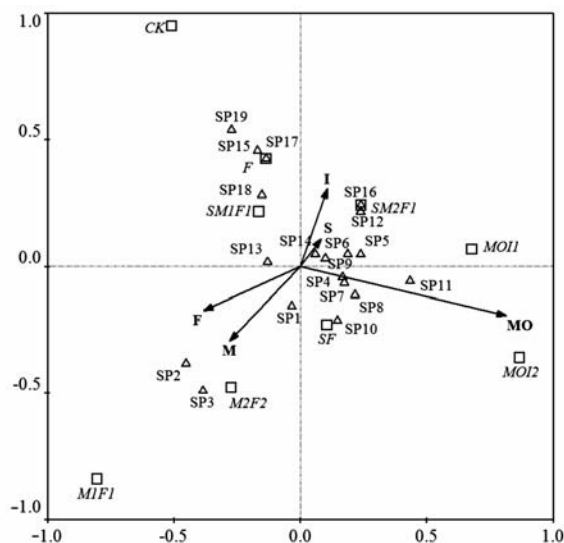


图2 不同施肥、秸秆还田处理与农田土壤杂草种子库杂草种子数量的典范对应分析。图中加粗字符F为化肥, I为无机肥, M为猪粪堆肥, MO为猪粪有机肥, S为秸秆; 斜体字符为不同施肥处理, 同图1; □为施肥处理, △为杂草种类。SP1, 蔺草; SP2, 日本看麦娘; SP3, 看麦娘; SP4, 通泉草; SP5, 水苦苣; SP6, 牛繁缕; SP7, 泥胡菜; SP8, 蛇床; SP9, 稻槎菜; SP10, 猪殃殃; SP11, 千金子; SP12, 稗; SP13, 鸭舌草; SP14, 陌上菜; SP15, 节节菜; SP16, 丁香蓼; SP17, 齿果酸模; SP18, 异型莎草; SP19, 碎米莎草。

Fig. 2 The canonical correspondence analysis (CCA) of different fertilization, straw returning and number of weed seeds. F, chemical fertilizer; I, inorganic fertilizer; M, pig manure; MO, pig manure organic fertilizer; S, straw. Italic characters represent different fertilizer treatments and the treatments are the same as in Fig. 1; □ are fertilizer measures; △ are weed species. SP1, *Beckmannia syzigachne*; SP2, *Alopecurus japonicus*; SP3, *A. aequalis*; SP4, *Mazus japonicus*; SP5, *Veronica undulata*; SP6, *Malachium aquaticum*; SP7, *Hemistepta lyrata*; SP8, *Cnidium monnieri*; SP9, *Lapsana apogonoides*; SP10, *Galium aparine* var. *tenerum*; SP11, *Leptochloa chinensis*; SP12, *Echinochloa crusgalli*; SP13, *Monochoria vaginalis*; SP14, *Lindernia procumbens*; SP15, *Rotala indica*; SP16, *Ludwigia prostrata*; SP17, *Rumex dentatus*; SP18, *Cyperus difformis*; SP19, *C. iria*.

2.3 土壤杂草种子库杂草种子数量与肥料因子的关系

肥料因子与土壤杂草种子库杂草种子的分布、数量的CCA分析结果显示(图2), 土壤杂草种子库中, 蔺草、鸭舌草、日本看麦娘(*Alopecurus japonicus*)、看麦娘(*A. aequalis*)的种子数量与施用猪粪堆肥(M)、化肥(F)呈正相关, 稻槎菜、陌上菜、丁香蓼(*Ludwigia prostrata*)、稗(*Echinochloa crus-*

galli)等杂草种子数量与施用无机肥(I)、秸秆还田(S)呈正相关, 通泉草、泥胡菜(*Hemistepta lyrata*)、千金子(*Leptochloa chinensis*)、蛇床、猪殃殃(*Galium aparine* var. *tenerum*)的种子数量与施用商品有机肥(MO)呈正相关; 而碎米莎草、异型莎草、节节菜和齿果酸模(*Rumex dentatus*)等杂草种子对肥料的偏好性较差。

3 讨论

本研究表明, 与不施肥相比, 在施用肥料的稻麦轮作农田中土壤杂草种子库的杂草种子种类数、种子群落均匀度指数和物种多样性指数均有下降趋势, 这与过去的研究基本一致(冯伟等, 2006)。这可能是由于试验处理的时间较短, 不施肥以及不同施肥处理对农田土壤杂草种子库杂草种子种类数、杂草种子群落均匀度指数和物种多样性指数的影响差异不显著。在杂草群落结构演变过程中, 杂草在数量上的变化比种类变化要快, 农艺措施会较为缓慢地影响土壤杂草种子库杂草种子种类、杂草种子群落均匀度指数和物种多样性指数(赵灿等, 2014)。

农田杂草的发生、消长、演替与土壤杂草种子库的关系密切, 一般情况下, 影响杂草种群动态的主要因素是土壤杂草种子库的动态(Martins & Engel, 2007; Riemsens et al, 2007; Ma et al, 2012)。本研究结果表明, 施肥明显改变了稻麦轮作田土壤杂草种子库杂草种子的密度, 但对不同杂草种类的影响不同。在施用肥料的农田中土壤杂草种子库禾本科杂草种子的密度增加, 这可能与作物和杂草同属禾本科植物, 其生物学特性相似相关, 施肥有利于提高作物产量, 也有利于增加禾本科杂草的生物量。对于土壤杂草种子库中多数阔叶杂草种来说, 施肥可明显影响其种子密度, 但影响趋势也不尽一致。施用有机肥有增加水苦苣、蛇床种子密度的趋势; 施用猪粪堆肥有增加鸭舌草种子密度的趋势。不同类型肥料的配施对麦田杂草群落生长的影响与对土壤杂草种子库不同杂草种子密度的影响一致(袁方等, 2016), 说明不同肥料种类、秸秆还田主要是对不同杂草的生长密度和生物量产生影响, 从而影响杂草结实, 通过杂草种子雨影响土壤杂草种子库不同杂草种子的密度。

表2 不同施肥处理对土壤种子库中杂草物种多样性的影响(平均值±标准差)
Table 2 Effects of different fertilization treatments on weed species diversity of soil seed bank (mean ± SD)

处理 Treatments	物种丰富度 Species richness (<i>S</i>)	Shannon-Wiener指数 Shannon-Wiener index (<i>H'</i>)	Pielou均匀度指数 Pielou evenness index (<i>J</i>)	Simpson指数 Simpson index (<i>D</i>)
CK	12.25 ± 0.96 ^a	0.60 ± 0.23 ^a	0.24 ± 0.10 ^a	0.24 ± 0.08 ^a
F	10.25 ± 2.50 ^{ab}	0.44 ± 0.34 ^a	0.19 ± 0.14 ^a	0.25 ± 0.08 ^a
M1F1	10.50 ± 0.58 ^{ab}	0.56 ± 0.17 ^a	0.25 ± 0.07 ^a	0.27 ± 0.11 ^a
M2F2	11.25 ± 2.06 ^{ab}	0.50 ± 0.06 ^a	0.21 ± 0.04 ^a	0.26 ± 0.04 ^a
SF	9.75 ± 0.50 ^{ab}	0.57 ± 0.30 ^a	0.26 ± 0.14 ^a	0.23 ± 0.07 ^a
SM1F1	9.25 ± 2.50 ^b	0.34 ± 0.21 ^a	0.15 ± 0.08 ^a	0.28 ± 0.15 ^a
SM2F1	10.50 ± 1.91 ^{ab}	0.44 ± 0.13 ^a	0.19 ± 0.06 ^a	0.23 ± 0.07 ^a
MO11	9.75 ± 1.26 ^{ab}	0.39 ± 0.07 ^a	0.18 ± 0.04 ^a	0.21 ± 0.05 ^a
MO12	9.75 ± 1.50 ^{ab}	0.40 ± 0.09 ^a	0.18 ± 0.04 ^a	0.18 ± 0.05 ^a

同列不同字母表示不同处理间差异显著($P < 0.05$)。施肥处理同图1。
Different letters in the same column represent significant differences at $P < 0.05$. The fertilization treatments were same as in Fig. 1.

已有研究表明, 施肥能够改变农田物种组成和群落多样性(Huenneke et al, 1990; Gough et al, 1994; Conn, 2006)。特别是大量秸秆还田后灌水泡田, 秸秆在微生物等的作用下发酵, 产生大量有机酸性物质如肉桂酸和丙酸等(Gotoh & Onikura, 1971; 单玉华等, 2006), 这些酚酸类物质能降低杂草对水分的吸收, 造成杂草叶面水势和膨压下降, 进一步抑制杂草ATP酶活性(丁永祯等, 2005), 进而破坏杂草种子在土壤中的休眠, 扰乱其生活周期, 导致其死亡, 这可能是影响部分杂草在秸秆还田处理区种子数量减少的主要原因。因此, 长期不同施肥处理造成了土壤杂草种子库杂草种子物种组成的差异。

土壤杂草种子库杂草种子的数量特征与肥料因子的典范对应分析表明, 不同杂草种子对不同肥料存在偏好性, 这也是导致不同施肥处理土壤种子库中杂草种子数量和组成出现差异的原因之一。已有研究证实, 不同肥料的施用对土壤结构、理化性状、土壤线虫、微生物都会产生明显影响(刘婷等, 2013; Zhao et al, 2014a, b), 进而改善农田生产和生态环境, 增加作物生物量, 提高作物竞争优势, 从而降低农田杂草的发生危害。

在农田生态系统中, 土壤种子库的产生与亲代杂草群落呈显著正相关, 每年从种子库中输出的种子能够萌发成幼苗的比例在3~7%之间, 这取决于杂草种子的种类及其所处的土壤环境条件(Roberts & Ricketts, 1979; Forcella, 1992; Cardina & Sparrow, 1996; Zhang et al, 1998)。地面杂草群落结实产生的种子雨是种子库输入的主要方式, 施肥有利于提高土壤杂草种子库禾本科杂草种子的密度, 对于以禾

本科杂草为主的农田, 采取秸秆还田配施有机肥化肥的施肥方式, 可以适度控制其危害; 对于以阔叶杂草和莎草科杂草为主的农田, 秸秆还田配施有机肥化肥或施用有机无机复合肥, 可提高农作物的生长竞争优势, 减少杂草发生危害。

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参考文献

Albrecht H, Auerswald K (2003) Arable weed seedbanks and their relation to soil properties. *Aspects of Applied Biology*, 69, 11–20.

Anderson RL, Tanaka DL, Black AL, Schweizer EE (1998) Weed community and species response to crop rotation, tillage, and nitrogen fertility. *Weed Technology*, 12, 531–536.

Blackshaw RE, Brandt RN, Janzen HH, EntzT, Grant CA, Derksen DA (2003) Differential response of weed species to added nitrogen. *Weed Science*, 51, 532–539.

Cardina J, Sparrow DH (1996) A comparison of methods to predict weed seedling populations from the soil seed bank. *Weed Science*, 44, 46–51.

Cavers PB (1995) Seed banks: memory in soil. *Canadian Journal of Soil Science*, 75, 11–13.

Conn JS (2006) Weed seed bank affected by tillage intensity for barley in Alaska. *Soil and Tillage Research*, 90, 156–161.

Dayis AS, Renner KA, Gross KL (2005) Weed seed bank and community shifts in a long-term cropping systems experiment. *Weed Science*, 53, 296–306.

Dhima KV, Eleftherohorinos IG (2001) Influence of nitrogen on competition between winter cereals and sterile oat. *Weed Science*, 49, 77–82.

- Ding YZ, Li ZA, Zou B (2005) Low-molecular-weight organic acids and their ecological roles in soil. *Soils*, 37, 243–250. (in Chinese with English abstract) [丁永祯, 李志安, 邹碧 (2005) 土壤低分子量有机酸及其生态功能. *土壤*, 37, 243–250.]
- Feng W, Pan GX, Qiang S, Li RH, Wei JG (2006) Influence of long-term fertilization on soil seed bank diversity of a paddy soil under rice/rape rotation. *Biodiversity Science*, 14, 461–469. (in Chinese with English abstract) [冯伟, 潘根兴, 强胜, 李儒海, 韦继光 (2006) 长期不同施肥方式对稻油轮作田土壤杂草种子库多样性的影响. *生物多样性*, 14, 461–469.]
- Fenn ME, Poth MA, Aber JD, Baron JS, Bormann BT, Johnson DW, Lemly AD, McNulty SG, Ryan DF, Stottlemeyer R (1998) Nitrogen excess in North American ecosystems: predisposing factors, ecosystem responses, and management strategies. *Ecological Applications*, 8, 706–733.
- Forcella F (1992) Prediction of weed seedling densities from buried seed reserves. *Weed Research*, 32, 29–38.
- Gotoh S, Onikura Y (1971) Organic acids in a flooded soil receiving added rice straw and their effect on the growth of rice. *Soil Science and Plant Nutrition*, 17, 1–8.
- Gough L, Grace JB, Taylor KL (1994) The relationship between species richness and community biomass: the importance of environmental variables. *Oikos*, 70, 271–279.
- Hall JC, Van Eerd LL, Miller SD, Owen MDK, Prather TS, Shaner DL, Singh M, Vaughn KC, Weller SC (2000) Future research directions for weed science. *Weed Technology*, 14, 647–658.
- Hammerton JL (1968) Past and future changes in weed species and weed floras. *Proceeding of the 9th British Weed Control Conference*.
- Hill MO (1973) Diversity and evenness: a unifying notation and its consequences. *Ecology*, 54, 427–432.
- Huenneke LF, Hamburg S, Koide R, Mooney H, Vitousek P (1990) Effects of soil resources on plant invasion and community structure in Californian serpentine grassland. *Ecology*, 71, 478–491.
- Jiang M, Shen XP, Gao W, Shen MX, Dai QG (2014) Weed seed-bank responses to long-term fertilization in a rice-wheat rotation system. *Plant, Soil and Environment*, 60, 344–350.
- Li RH, Qiang S, Qiu DS, Chu QH, Pan GX (2008) Effects of long-term fertilization regimes on weed communities in paddy fields under rice-oilseed rape cropping system. *Acta Ecologica Sinica*, 28, 3236–3243. (in Chinese with English abstract) [李儒海, 强胜, 邱多生, 储秋华, 潘根兴 (2008) 长期不同施肥方式对稻油轮作制水稻田杂草群落的影响. *生态学报*, 28, 3236–3243.]
- Liu T, Ye CL, Chen XY, Ran W, Shen QR, Hu F, Li HX (2013) Effects of different organic manure sources and their combinations with chemical fertilization on soil nematode community structure in a paddy field of East China. *Chinese Journal of Applied Ecology*, 24, 3508–3516. (in Chinese with English abstract) [刘婷, 叶成龙, 陈小云, 冉炜, 沈其荣, 胡锋, 李辉信 (2013) 不同有机肥源及其与化肥配施对稻田土壤线虫群落结构的影响. *应用生态学报*, 24, 3508–3516.]
- Ma B, Qiang S, Wei SH (2004) Farmland weed seed bank research methods. *Weed Science*, (2), 5–8. (in Chinese) [马波, 强胜, 魏守辉 (2004) 农田杂草种子库研究方法. *杂草科学*, (2), 5–8.]
- Ma MJ, Zhou XH, Ma Z, Du GZ (2012) Composition of the soil seed bank and vegetation changes after wetland drying and soil salinization on the Tibetan Plateau. *Ecological Engineering*, 44, 18–24.
- Martins AM, Engel VL (2007) Soil seed banks in tropical forest fragments with different disturbance histories in south-eastern Brazil. *Ecological Engineering*, 31, 165–174.
- Parish T, Lakhani KH, Sparks TH (1994) Modelling the relationship between bird population variables and hedgerow and other field margin attributes. I. Species richness of winter, summer and breeding birds. *Journal of Applied Ecology*, 31, 764–775.
- Putman RJ, Wratten SD (1984) *Principles of Ecology*. University of California Press, California.
- Qiang S (2002) Weed diversity of arable land in China. *Journal of Korean Weed Science*, 22, 187–198.
- Riemens MM, Groeneveld RMW, Lotz LAP, Kropff MJ (2007) Effects of three management strategies on the seed bank emergence and the need for hand weeding in an organic arable cropping system. *Weed Research*, 47, 442–451.
- Roberts HA, Ricketts ME (1979) Quantitative relationships between the weed flora after cultivation and the seed population in the soil. *Weed Research*, 19, 269–275.
- Shan YH, Cai ZC, Han Y, Johnson SE, Buresh RJ (2006) Accumulation of organic acids in relation to C : N ratios of straws and N application in flooded soil. *Acta Pedologica Sinica*, 43, 941–947. (in Chinese with English abstract) [单玉华, 蔡祖聪, 韩勇, Johnson SE, Buresh RJ (2006) 淹水土壤有机酸积累与秸秆碳氮比及氮供应的关系. *土壤学报*, 43, 941–947.]
- Wan KY, Pan JF, Li RH, Wang DZ, Tang LL, Chen F (2010) Influence of long-term different fertilization on soil weed seed bank diversity of a dry land under winter wheat-soybean rotation. *Ecology and Environmental Sciences*, 19, 836–842. (in Chinese with English abstract) [万开元, 潘俊峰, 李儒海, 王道中, 汤雷雷, 陈防 (2010) 长期施肥对旱地土壤杂草种子库生物多样性影响的研究. *生态环境学报*, 19, 836–842.]
- Yin LP, Yan YS (1997) *Identification of Weed Seeds with Colored Photos*. China Agricultural Science and Technology Press, Beijing. (in Chinese) [印丽萍, 颜玉树 (1997) 杂草种子图鉴. 中国农业科技出版社, 北京.]
- Yuan F, Li Y, Li FH, Sun GJ, Han M, Zhang HY, Ji Z, Wu CY (2016) Effects of different fertilization regimes on weed communities in wheat fields under rice-wheat cropping sys-

- tem. *Chinese Journal of Applied Ecology*, 27, 125–132. (in Chinese with English abstract) [袁方, 李勇, 李粉华, 孙国俊, 韩敏, 张海艳, 季忠, 吴晨钰 (2016) 不同施肥方式对稻麦两熟制小麦田杂草群落的影响. *应用生态学报*, 27, 125–132.]
- Zhang J, Hamill AS, Gardiner IO, Weaver SE (1998) Dependence of weed flora on the active soil seed bank. *Weed Research*, 38, 143–152.
- Zhang L, Li GH, Zhang X (2004) A review on soil seed banks study. *Chinese Journal of Ecology*, 23, 114–120. (in Chinese with English abstract) [张玲, 李广贺, 张旭 (2004) 土壤种子库研究综述. *生态学杂志*, 23, 114–120.]
- Zhao C, Dai WM, Li SX, Wei SH, Wei JG, Zhang CB, Qiang S (2014) Change in weed seed bank diversity over 13 consecutive years of rice–duck and straw returning farming system in the rice–wheat rotated wheat fields. *Biodiversity Science*, 22, 366–374. (in Chinese with English abstract) [赵灿, 戴伟民, 李淑顺, 魏守辉, 韦继光, 章超斌, 强胜 (2014) 连续13年稻鸭共作兼秸秆还田的稻麦连作麦田杂草种子库物种多样性变化. *生物多样性*, 22, 366–374.]
- Zhao J, Ni T, Li Y, Xiong W, Ran W, Shen B, Shen QR, Zhang RF (2014a) Responses of bacterial communities in arable soils in a rice–wheat cropping system to different fertilizer regimes and sampling times. *PLoS ONE*, 9, e85301.
- Zhao J, Zhang RF, Xue C, Xun WB, Sun L, Xu YC, Shen QR (2014b) Pyrosequencing reveals contrasting soil bacterial diversity and community structure of two main winter wheat cropping systems in China. *Microbial Ecology*, 67, 443–453.

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