长期不同施肥方式对稻油轮作制水稻田杂草群落的影响

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摘要：为揭示长期不同施肥方式下农田生态系统中杂草群落的变化规律，于 2006 年 10 月在太湖地区一个长期肥料试验定位监测田，运用群落生态学方法研究了 7 种长期不同施肥处理持续 20a 后对水稻-油菜轮作制水稻田杂草群落的影响。试验区共记录到杂草 11 种，隶属于 6 个科。其中，节节菜（*Rotala indica*）、陌上菜（*Lindernia procumbens*）、鸭舌草（*Monochoria vaginalis*）、异型莎草（*Cyperus difformis*）等 4 种杂草在所有施肥处理区发生密度较大。莎草科杂草牛毛毡（*Eleocharis yokoscensis*）只在不施肥区和纯氮肥区出现，而球穗扁莎（*Pycreus globosus*）和萤蔺（*Scirpus juncoides*）仅在不施肥区出现。长期不同施肥措施下，田间杂草群落的物种多样性有明显差异：全年秸秆区的物种丰富度（7.3 种）最小，不施肥区（10.7 种）最大；不施肥区、常规区、秋季秸秆区 Shannon-Wiener 指数显著大于其他处理区；不施肥区和常规区 Simpson 指数显著小于其他处理区；不施肥区和纯氮肥区 Pielou 均匀度指数显著小于其他处理区。田间杂草群落的优势种组成也发生了一定变化，Whittaker 指数表明，与不施肥处理相比，单施化肥、化肥配施猪粪对杂草群落结构及物种组成的影响最显著，化肥配施油菜秸秆和化肥配施油菜水稻秸秆次之，而纯施氮肥和化肥配施水稻秸秆的影响较小。Sørensen 群落相似性指数及聚类分析结果也得到相似的结论。结果表明，单施化肥（平衡施用 N、P、K 肥）、化肥配施猪粪、化肥配施夏季、秋季和全年秸秆处理均能显著改变田间杂草群落的组成，改变某些杂草在群落中的优势地位，从而抑制其发生危害程度。

关键词：长期施肥；杂草物种多样性；杂草群落；水稻-油菜轮作制
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Effects of long-term fertilization regimes on weed communities in paddy fields under rice-oilseed rape cropping system

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Abstract: The effects of long-term fertilization regimes on weed communities were evaluated in a rice-oilseed rape cropping system in Tai Lake region of Jiangsu Province. The fertilization treatments were: no fertilizer (NoF), N fertilizer (NF), chemical fertilizer (CF), chemical fertilizer plus pig manure (CFM), chemical fertilizer plus oilseed rape stalk (CFO), chemical fertilizer plus rice straw (CFR), and chemical fertilizer plus oilseed rape stalk and rice straw (CFOR). For each treatment there were three replicated plots and treatments were maintained for 20 years. The amount of fertilizer applied per year was 427.5 kg/hm^2 N as urea, 45 kg/hm^2 P_2O_5 as super phosphate, 54 kg/hm^2 K_2O, 2250 kg/hm^2 (fresh weight) oilseed rape stalk and/or rice straw, and 16800 kg/hm^2 pig manure (fresh weight) for the respective treatments. In October 2006, the number, coverage, and aboveground fresh weight of each weed species present in five 1-m^2 quadrats per plot were determined. A total of 11 weed species from 6 families were recorded. Of these, *Rotala indica*, *Lindernia procumbens*, *Monochoria vaginalis* and *Cyperus difformis* had high population densities under all fertilization treatments. The sedge weed *Eleocharis yokoscensis* was found only in the NoF and NF plots, while *Pycreus globosus* and *Scirpus juncoides* were found only in NoF plots. The weed species richness varied significantly among different fertilization treatments, ranging from 7.3 in CFOR to 10.7 in NoF. The composition and abundance of weed species also differed in different fertilization treatments. The Shannon-Wiener index for the NoF, CFM and CFR treatments was significantly higher than that of the other fertilization treatments. The Simpson dominance index in the NoF, CFM treatments was significantly lower than that of the other fertilization treatments. The Pielou evenness index in the NoF and NF treatments was significantly lower than that of the other fertilization treatments. Based on the Whittaker index, the CF and CFM treatments had the greatest, and the CFO and CFOR treatements the second greatest, effects on weed community composition. Whereas, the NF and CFR treatments had no significant effect on community composition as compared to the NoF treatment. The Sørensen similarity index and clustering analysis gave similar results as the Whittaker index. The results indicate that the application of a balanced N, P, K fertilizer with or without organic manure (pig manure and/or crop straw) allowed for all weed species present to thrive, thus maintaining weed species diversity as a result of no one species becoming dominant.

Key Words: long-term fertilization; weed species diversity; weed community; rice-oilseed rape cropping system

杂草是农业生态系统的重要组成部分[1]。农田杂草与作物竞争光照、土壤养分与水分等资源,是影响作物生长导致减产的重要因素之一[2]。因而,为保证作物良好生长,就必须对杂草进行合理控制。农田杂草群落组成直接受到农业栽培措施的影响,其中施肥是一项很重要的农业管理措施。通过施肥,不仅对作物的生长发育产生影响,同时也能影响田间各种杂草的生长,从而对农田杂草群落产生影响。

关于长期不同施肥方式对农田杂草群落的影响研究在国外已开展较多,发现长期不同施肥方式对田间杂草发生频率、群落组成、群落多样性等都有显著影响。在英国 Rothamsted 于 1843 年开始的冬小麦田肥料定位试验研究中发现,随着氮肥施用量的加大,杂草的发生频率变化各异:繁缕(*Stellaria media*)显著升高;天蓝苜蓿(*Medicago lupulina*)和问荆(*Equisetum arvense*)等显著降低;大巢菜(*Vicia sativa*)和野斗蓬草(*Aphanes arvensis*)等稍微降低;大穗看麦娘(*Alopecurus myosuroides*)和虞美人(*Papaver rhoeas*)等几乎没有变化[3]。Ciuberkis 等[4]在一项持续 53a 的施肥试验中发现,在酸性土壤中长期施用有机肥,喜酸性杂草种类明显减少,喜氮性杂草的密度增大;在不施有机肥的酸性土壤中,喜酸性杂草为优势种类。Davis 等[5]的研究表明,长期施全量氮肥的田间以洋野黍(*Panicum dichotomiflorum*)和马唐(*Digitaria sanguinalis*)等禾本科杂草为优势种,而施减量氮肥的田间以藜(*Chenopodium album*)为优势种。近年来,国内少量这方面的研究发现,玉米田中止血马唐(*Digitaria ischaemum*)能很好地适应长期低磷素养分条件,而香附子(*Cyperus rotundus*)能很好地适应长期低钾或氮素养分条件[6,7];随着土壤养分状况的改善,小麦田杂草群落的多样性指数逐渐减小[8],长期仅施氮、钾肥或不施肥处理的优势杂草为刺儿菜(*Cephalanoplos segetum*)和离子草(*Chorispora tenella*)[9]。这些研究均集中在旱地。在我国特殊的稻作区水稻—油菜轮作制农田中是否也存在类似的规律还缺乏可参考的

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资料,揭示其规律将能够为这类农田的杂草管理实践提供科学依据。

为此,选择长期不同施肥方式的水稻-油菜轮作制水稻田调查其杂草群落多样性,探讨不同施肥措施与田间杂草发生危害的关系,期望为通过合理施肥控制杂草的发生危害提供科学依据。

1 材料与方法

1.1 研究地区概况

试验田设在苏州市属吴江市金家坝镇前厅村(N 31°05′900″; E 120°46′924″),为太湖地区一个长期肥料试验定位监测田。该地地处北亚热带南部,年均温 15 ~16℃,降水量 1 000 ~1 100 mm,6 ~9 月份雨量占全年的 40% ~55%,稳定超过 3℃的年积温达 5300 ~5640℃,无霜期 220 ~240 d,常年平均日照达 2 000 ~2 200 h。本区农业生产历来以稻麦或稻油一年两熟为主。土壤类型为潴育性水稻土(黄泥土)。

1.2 试验设计及栽培管理

试验始于 1987 年,试验期间一直为水稻—油菜轮作。研究共设 7 种不同的施肥处理:不施肥(简称不施肥区,NoF),纯施氮肥(简称纯氮肥区,NF),单施化肥(简称化肥区,CF),化肥配施猪粪(简称常规区,CFM),化肥配施油菜秸秆(简称夏季秸秆区,CFO),化肥配施水稻秸秆(简称秋季秸秆区,CFR),化肥配施油菜水稻秸秆(简称全年秸秆区,CFOR)。在不施肥区不施任何肥料;纯氮肥区只施氮肥;其他施肥区的化肥施用量为 N 427.5 $kg\cdot hm^{-2}\cdot a^{-1}$,$P_2O_5$ 45 $kg\cdot hm^{-2}\cdot a^{-1}$和 K_2O 54 $kg\cdot hm^{-2}\cdot a^{-1}$;常规区加施 16,800 $kg\cdot hm^{-2}\cdot a^{-1}$(鲜重)的猪粪肥,在秋季水稻收割后施于土壤表面,夏(秋)季秸秆区分别加施 2250 $kg\cdot hm^{-2}\cdot a^{-1}$(鲜重)的油菜(水稻)秸秆,全年秸秆区加施 4500 $kg\cdot hm^{-2}\cdot a^{-1}$(鲜重)的秸秆,每季作物各占 50%,在作物收获后打碎翻入土壤。

每个处理设置 3 个重复,随机排列。每小区面积 25 m^2,小区之间筑水泥埂隔离。各处理除施肥不同外,其他各项栽培管理措施相同。

油菜品种 1987 ~2002 年为"秦油 2 号", 2003 年后为"苏油 1 号";9 月 30 日左右播种,11 月上旬在水稻收获后移栽,翌年 5 月 20 日前后收获。水稻品种 1987 ~2001 年为"武育粳",2002 年后为"武育粳 3 号";5 月中旬播种,6 月中旬移栽,11 月上旬收获。油菜季不除草;水稻季在 1987 ~1993 年人工除草,1994 ~2006 年化学除草,每 667 m^2使用 60% 丁草胺乳油 60 ml +10% 苄嘧磺隆可湿性粉剂 10 g,在水稻移栽后 7 d 施药,并且人工除草 1 次。

试验开始时,原表层(0 ~5 cm)土壤 pH 为 5.6,黏粒(<1 μm)含量为 249.30 $g\cdot kg^{-1}$,阳离子交换量 20.20 cmol(+)$\cdot kg^{-1}$,有机碳 16.40 $g\cdot kg^{-1}$,全氮 1.72 $g\cdot kg^{-1}$,全磷 0.42 $g\cdot kg^{-1}$。2006 年水稻收割后各施肥处理小区表层(0 ~5 cm)土壤基本性状如表 1 所示。

表 1 不同施肥处理持续 20a 后各施肥处理区表层(0 ~5 cm)土壤基本性状

Table 1 Basic properties of surface layer (0 −5 cm) soil in plots after different fertilization treatments were maintained for 20 years

施肥处理 Fertilization treatment	pH	有机碳 Organic C ($g\cdot kg^{-1}$)	全氮 Total N ($g\cdot kg^{-1}$)	全磷 Total P ($g\cdot kg^{-1}$)	速效钾 Available K ($mg\cdot kg^{-1}$)
不施肥 NoF	6.13 ± 0.032	16.11 ± 0.049	1.65 ± 0.041	0.23 ± 0.028	80 ± 4.1
纯施氮肥 NF	6.07 ± 0.033	16.40 ± 0.062	1.84 ± 0.043	0.25 ± 0.026	81 ± 2.6
单施化肥 CF	5.93 ± 0.032	16.64 ± 0.046	1.87 ± 0.038	0.39 ± 0.035	107 ± 3.2
化肥配施猪粪 CFM	5.75 ± 0.062	17.20 ± 0.058	2.03 ± 0.058	0.73 ± 0.058	98 ± 4.1
化肥配施油菜秸秆 CFO	5.87 ± 0.041	16.77 ± 0.035	1.93 ± 0.054	0.39 ± 0.029	85 ± 3.2
化肥配施水稻秸秆 CFR	5.91 ± 0.035	16.80 ± 0.052	1.95 ± 0.050	0.40 ± 0.046	87 ± 3.5
化肥配施油菜水稻秸秆 CFOR	5.88 ± 0.035	17.13 ± 0.056	2.02 ± 0.046	0.42 ± 0.042	91 ± 3.0

数据为平均值 ± SE The data are mean ± SE; NoF: No fertilizer; NF: N fertilizer; CF: Chemical fertilizer; CFM: Chemical fertilizer plus pig manure; CFO: Chemical fertilizer plus oilseed rape stalk; CFR: Chemical fertilizer plus rice straw; CFOR: Chemical fertilizer plus oilseed rape stalk and rice straw; 下同 the same below

1.3 调查方法及数据分析

水稻田小区杂草调查在 2006 年 10 月 13 日进行(杂草处于花果期,水稻处于乳熟期)。每小区按对角线

5 点取样法设 5 个样方,每样方面积 1 m^2,计数各样方内的杂草种类与数量,同时调查每种杂草的盖度,并称量地上部鲜重。

杂草密度为每 m^2的杂草株数;物种丰富度 S 即样方中包含的所有杂草种类数;综合优势度比 $SDR = (RD + RC + RF + RW)/4$,其中 RD 为相对密度(某杂草的密度占总密度的比例),RC 为相对盖度(某杂草的盖度占总盖度的比例),RF 为相对频度(某杂草的频度占所有杂草的总频度的比例),RW 为相对鲜重(某杂草的鲜重占总鲜重的比例)[10~12];物种多样性用 Shannon-Wiener 指数测度,$H' = -\sum P_i \ln P_i$,其中 $P_i = N_i/N$,N_i为样方中第 i 物种的个体数,N 为样方总个体数;群落优势度用 Simpson 指数测度,$D = \sum P_i^2$;群落均匀度用 Pielou 均匀度指数测度,$J = H'/\ln S$[13];群落结构组成的差异用 Whittaker 指数测定,$\beta = S/ma - 1$, ma 为各样方的平均物种数[14];群落相似性用 Sørensen 指数测度,定性测度 $C_s = 2j/(a+b)$,定量测度(又称 Bray-Curtis 指数)$C_N = 2jN/(aN + bN)$,其中 j 为群落 A 与 B 所共有的物种数,a、b 分别为群落 A、B 含有的全部物种数,aN、bN 分别为群落 A、B 所有物种的个体数目,jN 为群落 A(jNa)和 B(jNb)共有种中个体数目较小者之和[14]。

研究数据使用 Excel 和 MVSP 3.1 进行处理、绘图,并使用 SPSS 13.0 进行统计分析,测验各处理间的差异显著性。

2　结果

2.1　对杂草密度的影响

在试验区水稻田发生危害的杂草有 6 科 11 种,其中节节菜(*Rotala indica*)、陌上菜(*Lindernia procumbens*)、鸭舌草(*Monochoria vaginalis*)、异型莎草(*Cyperus difformis*)等 4 种杂草发生密度较大,群体数量占田间杂草的 90% 以上。但总体而言,试验区水稻田发生的杂草种类较少,密度较低。在不施肥区,莎草科杂草球穗扁莎(*Pycreus globosus*)、牛毛毡(*Eleocharis yokoscensis*)、水虱草(*Fimbristylis miliacea*)、异型莎草、萤蔺(*Scirpus juncoides*)的密度较大,大于 16 株·m^{-2},占据优势地位。在纯氮肥区,牛毛毡、异型莎草的密度较大,大于 10 株·m^{-2}。在其他小区,节节菜、陌上菜、鸭舌草为优势杂草,但密度均较低,小于 7 株·m^{-2}。从所有杂草的密度来看,不施肥区的杂草密度最大,为 141.9 株·m^{-2},显著大于其他施肥处理;纯氮肥区的杂草密度次之,为 48.3 株·m^{-2},显著大于化肥区、常规区、夏季秸秆区、秋季秸秆区和全年秸秆区(表 2)。

2.2　对杂草群落物种多样性的影响

在不施肥区、纯氮肥区发现的杂草种类较多,分别为 11 和 9 种;而在化肥区、常规区、夏季秸秆区、秋季秸秆区和全年秸秆区发现的杂草种类较少,均为 8 种。从各长期不同施肥处理区中杂草物种丰富度来看,不施肥区为 10.7 种,显著多于其他处理区;纯氮肥区为 9 种,显著多于化肥区(7.7)、常规区(7.7)、夏季秸秆区(8)、秋季秸秆区(8)和全年秸秆区(7.3),后 5 个处理区间差异不显著(表 3)。从 Shannon-Wiener 指数看,不施肥区、常规区、秋季秸秆区显著大于其他处理区,这 3 个处理区间差异不显著。说明不施肥、化肥配施猪粪和化肥配施水稻秸秆处理会显著提高水稻田杂草群落的物种多样性。从表征优势度的 Simpson 指数来看,各处理区的优势度均较低,其中不施肥区和常规区指数均为 0.18,显著小于其他处理区。从 Pielou 均匀度指数看,不施肥区和纯氮肥区指数分别为 0.80 和 0.79,它们之间差异不显著,均显著小于化肥区、常规区、夏季秸秆区、秋季秸秆区和全年秸秆区,表明与不施肥相比,单施化肥、化肥配施猪粪、化肥配施油菜秸秆、化肥配施水稻秸秆和化肥配施油菜水稻秸秆处理均显著提高了杂草群落的均匀度。

2.3　对杂草群落结构组成的影响

比较不同施肥处理小区中各杂草的综合优势度比(表 4),可以发现,长期不同施肥措施下,田间杂草群落的结构组成均发生了一定变化。(1)不施肥区杂草群落优势种组成为球穗扁莎 + 萤蔺 + 牛毛毡,它们的综合优势度比分别为 0.247、0.154 和 0.145。(2)纯氮肥区杂草群落优势种组成为牛毛毡 + 异型莎草 + 陌上菜,牛毛毡的综合优势度比显著上升为 0.266,在群落中的优势地位提高;异型莎草和陌上菜的综合优势度比显著上升为 0.2 和 0.153,由次要杂草变为主要杂草;在该区没有发现球穗扁莎和萤蔺。(3)化肥区、常规区、夏

表 2 长期不同施肥的水稻田间杂草物种组成和密度

Table 2 Species composition and density of weeds in paddy fields under long-term different fertilization treatments

杂草种类 Weed species	杂草密度 Weed density (ind.·m^{-2})						
	不施肥 NoF	纯施氮肥 NF	单施化肥 CF	化肥配施猪粪 CFM	化肥配施油菜秸秆 CFO	化肥配施水稻秸秆 CFR	化肥配施油菜水稻秸秆 CFOR
稗 *Echinochloa crus-galli*	1.6±0.12^{bc}	1.3±0.07^{c}	0.9±0.07^{d}	1.5±0.18^{bc}	1.5±0.13^{bc}	1.8±0.12^{b}	2.5±0.07^{a}
千金子 *Leptochloa chinensis*	0.5±0.13^{c}	1.0±0.12^{bc}	1.6±0.12^{a}	1.6±0.12^{a}	1.5±0.07^{ab}	0.7±0.33^{c}	1.0±0.23^{bc}
丁香蓼 *Ludwigia prostrata*	0.2±0.12^{e}	0.7±0.07^{cd}	0.5±0.07^{d}	0.6±0.00^{cd}	0.8±0.20^{c}	1.3±0.16^{b}	1.6±0.07^{a}
节节菜 *Rotala indica*	6.9±0.71^{a}	6.9±0.35^{a}	3.6±0.35^{b}	3.1±0.18^{b}	5.7±0.64^{a}	6.2±0.67^{a}	6.6±1.34^{a}
陌上菜 *Lindernia procumbens*	4.9±0.53^{b}	7.2±0.53^{a}	3.9±0.64^{b}	4.0±0.46^{b}	4.9±0.64^{b}	6.6±0.43^{a}	6.6±0.87^{a}
鸭舌草 *Monochoria vaginalis*	1.7±0.18^{d}	2.5±0.07^{c}	3.7±0.07^{a}	3.3±0.13^{ab}	3.0±0.20^{b}	3.2±0.12^{b}	3.4±0.12^{ab}
水虱草 *Fimbristylis miliacea*	24.1±0.87^{a}	1.2±0.12^{b}	0.1±0.13^{c}	0.9±0.27^{bc}	0.7±0.18^{bc}	1.2±0.20^{b}	0.2±0.20^{c}
球穗扁莎 *Pycreus globosus*	41.1±1.09^{a}	—	—	—	—	—	—
异型莎草 *Cyperus difformis*	18.4±0.46^{a}	10.6±0.60^{b}	0.8±0.12^{d}	0.7±0.33^{d}	0.8±0.31^{d}	3.4±0.20^{c}	1.4±0.46^{d}
萤蔺 *Scirpus juncoides*	16.5 ±0.33^{a}	—	—	—	—	—	—
牛毛毡 *Eleocharis yokoscensis*	26.0±0.76^{a}	16.9±0.70^{b}	—	—	—	—	—
所有杂草 Overall weeds	141.9 ±3.74^{a}	48.3±0.70^{b}	15.1±0.98^{e}	15.6±0.60^{e}	18.8±1.80^{de}	24.5±1.52^{c}	23.4±3.11^{cd}

同一行平均值(±SE)后上标字母相同表示在 0.05 水平上差异不显著 Means (±SE) within the same row with same superscript letters are not significantly different at 0.05 level; "—"表示杂草在处理区没有出现 The en dash indicates the weed species was not found in the plots; 下同 the same below

表 3 长期不同施肥方式对水稻田杂草群落物种多样性的影响

Table 3 Effect of long-term different fertilization treatments on the species diversity of weed communities in paddy fields

项目 Item	施肥处理 Fertilization treatment						
	不施肥 NoF	纯施氮肥 NF	单施化肥 CF	化肥配施猪粪 CFM	化肥配施油菜秸秆 CFO	化肥配施水稻秸秆 CFR	化肥配施油菜水稻秸秆 CFOR
物种丰富度 S	10.70±0.33^{a}	9.00±0.00^{b}	7.70±0.33^{c}	7.70±0.33^{c}	8.00±0.00^{c}	8.00±0.00^{c}	7.30±0.33^{c}
Shannon-Wiener 指数 H'	1.88±0.015^{a}	1.74±0.023^{c}	1.75±0.030^{c}	1.85±0.044^{a}	1.78±0.017^{bc}	1.83±0.018^{ab}	1.74±0.010^{c}
Simpson 指数 D	0.18±0.000^{c}	0.22±0.009^{a}	0.20±0.007^{ab}	0.18±0.010^{c}	0.20±0.003^{ab}	0.19±0.003^{bc}	0.21±0.003^{ab}
Pielou 均匀度指数 J	0.80±0.009^{c}	0.79±0.012^{c}	0.86±0.012^{b}	0.91±0.015^{a}	0.85±0.007^{b}	0.88±0.010^{ab}	0.88±0.013^{ab}
Whittaker 指数 β	0.320	0.421	1.069	1.000	0.765	0.481	0.765

S: Species richness; H': Shannon-Wiener index; D: Simpson index; J: Pielou evenness index; β: Whittaker index

季秸秆区、秋季秸秆区和全年秸秆区杂草群落优势种组成均为鸭舌草+陌上菜+节节菜,其中鸭舌草的综合优势度比分别为0.34、0.346、0.303、0.256 和0.279;陌上菜的综合优势度比分别为0.172、0.187、0.18、0.194 和0.204;节节菜的综合优势度比分别为0.159、0.138、0.21、0.185 和0.2;它们均由次要杂草变为主要杂草;在这些施肥区中没有发现球穗扁莎、萤蔺和牛毛毡。

表 4　长期不同施肥方式对水稻田杂草综合优势度比的影响

Table 4　Effect of long-term different fertilization treatments on the summed dominance ratio of weed species in paddy fields

杂草种类 Weed species	综合优势度比 Summed dominance ratio						
	不施肥 NoF	纯施氮肥 NF	单施化肥 CF	化肥配施猪粪 CFM	化肥配施油菜秸秆 CFO	化肥配施水稻秸秆 CFR	化肥配施油菜水稻秸秆 CFOR
球穗扁莎 PYCGL	0.247 ± 0.001^{a}	—	—	—	—	—	—
萤蔺 SCIJU	0.154 ± 0.006^{a}	—	—	—	—	—	—
牛毛毡 ELEYO	0.145 ± 0.003^{b}	0.266 ± 0.009^{a}	—	—	—	—	—
水虱草 FIMMI	0.143 ± 0.002^{a}	0.032 ± 0.001^{cd}	0.017 ± 0.009^{de}	0.048 ± 0.010^{bc}	0.034 ± 0.004^{bcd}	0.052 ± 0.004^{b}	0.009 ± 0.009^{e}
异型莎草 CYPDI	0.135 ± 0.001^{b}	0.200 ± 0.017^{a}	0.045 ± 0.005^{c}	0.030 ± 0.015^{c}	0.041 ± 0.009^{c}	0.124 ± 0.010^{b}	0.058 ± 0.012^{c}
节节菜 ROTIN	0.052 ± 0.004^{d}	0.123 ± 0.004^{c}	0.159 ± 0.009^{b}	0.138 ± 0.005^{bc}	0.210 ± 0.004^{a}	0.185 ± 0.012^{a}	0.200 ± 0.019^{a}
鸭舌草 MONVA	0.042 ± 0.001^{e}	0.121 ± 0.015^{d}	0.340 ± 0.016^{a}	0.346 ± 0.011^{a}	0.303 ± 0.015^{b}	0.256 ± 0.018^{c}	0.279 ± 0.018^{bc}
陌上菜 LINPR	0.039 ± 0.003^{b}	0.153 ± 0.031^{a}	0.172 ± 0.021^{a}	0.187 ± 0.020^{a}	0.180 ± 0.019^{a}	0.194 ± 0.005^{a}	0.204 ± 0.008^{a}
稗 ECHCR	0.026 ± 0.001^{c}	0.043 ± 0.007^{c}	0.107 ± 0.012^{ab}	0.103 ± 0.014^{ab}	0.089 ± 0.012^{b}	0.089 ± 0.010^{b}	0.125 ± 0.020^{a}
千金子 LEPCH	0.011 ± 0.002^{c}	0.028 ± 0.002^{bc}	0.083 ± 0.009^{a}	0.085 ± 0.008^{a}	0.071 ± 0.009^{a}	0.028 ± 0.006^{bc}	0.042 ± 0.007^{b}
丁香蓼 LUDPR	0.008 ± 0.004^{d}	0.035 ± 0.001^{c}	0.077 ± 0.007^{ab}	0.062 ± 0.003^{b}	0.073 ± 0.011^{ab}	0.072 ± 0.010^{ab}	0.083 ± 0.004^{a}

PYCGL: *Pycreus globosus*; SCIJU: *Scirpus juncoides*; ELEYO: *Eleocharis yokoscensis*; FIMMI: *Fimbristylis miliacea*; CYPDI: *Cyperus difformis*; ROTIN: *Rotala indica*; MONVA: *Monochoria vaginalis*; LINPR: *Lindernia procumbens*; ECHCR: *Echinochloa crus-galli*; LEPCH: *Leptochloa chinensis*; LUDPR: *Ludwigia prostrata*

Whittaker 指数可以反映杂草群落在不同环境选择压力下结构的变化,在一定程度上能够准确反映群落物种的演替程度[14]。不施肥区、纯氮肥区、化肥区、常规区、夏季秸秆区、秋季秸秆区、全年秸秆区杂草群落 Whittaker 指数分别为 0.32、0.421、1.069、1、0.765、0.481、0.765(表 3)。由此可见,与不施肥处理相比,单施化肥、化肥配施猪粪对杂草群落结构及物种组成的影响最显著,化肥配施油菜秸秆和化肥配施油菜水稻秸秆次之,而纯施氮肥和化肥配施水稻秸秆的影响较小。

2.4　不同施肥方式间水稻田杂草群落的相似性

从 Sørensen 群落相似性指数(定性测度)看,不施肥区(对照区)与纯氮肥区的相似性较高,与其他施肥处理区的相似性稍低,差异达显著水平($P<0.05$)。Sørensen 群落相似性指数的定量测度(Bray-Curtis 指数)结果却表明,不施肥区与纯氮肥区的相似性较高,与夏季秸秆区、秋季秸秆区、全年秸秆区的相似性稍低,与化肥区和常规区的相似性低,差异达显著水平($P<0.05$)(表 5)。根据 Bray-Curtis 指数采用最远距离法进行聚类分析,可得图 1 所示的树状图。由图 1 可以看出,化肥区与常规区聚在一起,夏季秸秆区、秋季秸秆区和全年秸秆区聚在一起,纯氮肥区、不施肥区各为一类。以上结果表明,与不施肥相比,单施化肥、化肥配施猪粪、化肥配施夏季、秋季和全年秸秆处理均能显著改变田间杂草群落的组成, 改变某些杂草在群落中的优势地位,从而抑制其发生危害程度。

表 5　长期不同施肥方式下水稻田杂草群落间的相似性指数(对角线上、下分别为定量和定性测度)

Table 5　Sørensen similarity index among weed communities in paddy fields under different long-term fertilization treatments (above diagonal: quantitative measure; below diagonal: qualitative measure)

施肥处理 Fertilization treatment	Sørensen 相似性指数 Sørensen similarity index						
	NoF	NF	CF	CFM	CFO	CFR	CFOR
不施肥 NoF		0.463^{a}	0.149^{d}	0.156^{d}	0.195^{c}	0.236^{b}	0.202^{bc}
纯施氮肥 NF	0.881^{a}		0.418^{c}	0.438^{c}	0.521^{b}	0.613^{a}	0.536^{b}
单施化肥 CF	0.775^{b}	0.897^{a}		0.848^{a}	0.826^{a}	0.689^{c}	0.737^{b}
化肥配施猪粪 CFM	0.797^{b}	0.919^{a}	0.930^{b}		0.836^{a}	0.726^{b}	0.728^{b}
化肥配施油菜秸秆 CFO	0.821^{b}	0.941^{a}	0.956^{ab}	0.978^{a}		0.827^{a}	0.846^{a}
化肥配施水稻秸秆 CFR	0.821^{b}	0.941^{a}	0.956^{ab}	0.978^{a}	1.000^{a}		0.873
化肥配施油菜水稻秸秆 CFOR	0.775^{b}	0.897^{a}	1.000^{a}	0.930^{a}	0.956^{a}	0.956	

对角线上(下)同一行(列)平均值(±SE)后上标字母相同表示在 0.05 水平上差异不显著　Above (below) diagonal, means (±SE) within the same row (column) with same superscript letters are not significantly different at 0.05 level

3 讨论

已有研究报道,玉米田中莎草科杂草香附子能很好地适应长期低钾或氮素养分条件[6,7]。本文研究发现,莎草科杂草水虱草和异型莎草在不施肥区的密度显著大于其他施肥区,牛毛毡只在不施肥区和纯氮肥区出现,而球穗扁莎和萤蔺仅在不施肥区出现(表2)。这是首次发现莎草科杂草在稻田生境中也能很好地适应长期低养分条件。分析原因可能是水虱草、异型莎草和牛毛毡能适应长期低磷、钾素土壤养分条件,球穗扁莎和萤蔺能适应长期低氮、磷、钾素土壤养分条件(表1),也可能这些莎草科杂草更适应在自然或半自然生境中生长,而长期不施肥区和纯施氮肥区类似于这种生境,这也说明经过长期自然选择它们有可能演化出对这些养分进行高效吸收利用的机制。对这些机制开展进一步的研究,并把它们应用到作物的遗传改良上,对于提高作物产量,降低肥料施用量具有较大的现实意义。

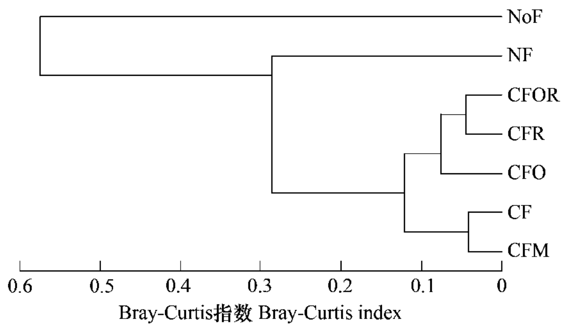

图1 长期不同施肥作用下水稻田杂草群落的聚类分析

Fig. 1 The dendrogram of the weed communities in paddy fields under different long-term fertilizations from clustering analysis based on Bray-Curtis index

不施肥 NoF: No fertilizer; 纯施氮肥 NF: N fertilizer; 单施化肥 CF: Chemical fertilizer; 化肥配施猪粪 CFM: Chemical fertilizer plus pig manure; 化肥配施油菜秸秆 CFO: Chemical fertilizer plus oilseed rape stalk; 化肥配施水稻秸秆 CFR: Chemical fertilizer plus rice straw; 化肥配施油菜水稻秸秆 CFOR: Chemical fertilizer plus oilseed rape stalk and rice straw

施肥直接或通过改变作物与杂草的竞争关系对农田杂草生物多样性产生影响。本文研究发现,不施肥区和纯氮肥区的杂草群落物种丰富度和 Shannon-Wiener 指数显著大于其他施肥处理区,这两个区的优势种类莎草科杂草在其他施肥处理区变为次要杂草或没有发生;莎草科杂草在这两个区的密度也显著大于其他施肥处理区。表明单施化肥、化肥配施猪粪和化肥配施秸秆处理显著降低了水稻田杂草群落的多样性,并降低了优势杂草的优势地位。这是杂草长期适应土壤养分条件及与作物竞争的结果[15~17]。本结果与已有的研究结果[3~9, 18~21]一致。但这些研究均集中在旱地,本研究是这一规律在我国特殊的稻作区水稻-油菜轮作制水稻田中的首次报道。

近年来,农业生态系统中杂草生物多样性的保护以及发挥其在维持生态平衡中的作用逐渐受到重视[1, 22~26],所以,对农业生态系统中的杂草进行有效控制的同时,也应对其生物多样性给予适当的保护。因此,平衡施用氮、磷、钾肥,并配合施用有机肥(猪粪和秸秆),不仅有利于促进作物的生长,保持农田生态系统中一定水平的杂草生物多样性,也有利于降低某些优势杂草在群落中的优势地位。本文的研究结果对指导我国稻作区水旱轮作制水稻田科学合理施肥,从而兼顾控制优势杂草的危害和保护杂草生物多样性具有重要意义。

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