生物多样性 2014, **22** (3): 366–374 Doi: 10.3724/SP.J.1003.2014.13264
Biodiversity Science http: //www.biodiversity-science.net

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

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摘要: 稻鸭共作能有效控制稻田杂草的危害, 但是它对后茬小麦田杂草的影响及其控制作用尚没有详细的报道。我们于2000–2012年对江苏丹阳稻鸭共作兼秸秆还田的有机稻麦连作田土壤杂草种子库进行了连续13年的观察实验。结果显示, 稻鸭共作兼秸秆还田的措施使看麦娘(*Alopecurus aequalis*)、通泉草(*Mazus japonicus*)、碎米荠(*Cardamine hirsuta*)等18种麦田主要杂草的种子库均有较大幅度的降低, 总体的降低幅度高达97%。除了Pielou指数处于小幅波动状态外, 麦田杂草群落多样性指数整体呈下降趋势。丰富度下降表明杂草种子库向种类少、多样性低的方向演变。从Bray-Curtis指数和Jaccard相似性指数也可以得到同样的结论。可见, 连续稻鸭共作兼秸秆还田能够降低下茬的麦田土壤里杂草种子密度及多样性, 控制杂草危害。

关键词: 稻鸭共作, 秸秆还田, 有机稻麦轮作, 种子库动态, 物种多样性, 杂草群落相似性, 杂草综合管理

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

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Abstract: Research has shown that rice-duck farming systems can effectively control weed infestations in rice paddy fields, but it remains elusive how this type of system influences the dynamics and density of weeds in wheat fields. In order to explore the diversity of weeds in wheat field seed banks, we conducted a long-term experiment (13 consecutive years) to observe changes in weed seed bank diversity in rice-wheat rotated wheat fields in Danyang, Jiangsu Province. Results showed that the density of weed seeds in wheat field seed banks decreased continuously. The seed density of 18 weed species, including *Alopecurus aequalis*, *Mazus japonicus*, and *Cardamine hirsuta*, all decreased gradually with some annual fluctuations, and the overall rate of decrease for seeds of all weed species was 97%. Furthermore, rice-duck and wheat rotation farming decreased the richness, diversity, and evenness of weed species in wheat fields. Ecological indices implied a gradual change, which included fewer species, lower density, and lower diversity after adopting rice-duck and wheat return farming. The same conclusions could be drawn from both Jaccard's similarity indices and Bray-Curtis coefficient of weed communities in wheat fields. Consecutive implementation of rice-duck and wheat rotation farming can significantly decrease both density and biodiversity of weeds in the seed bank of these ecosystems.

Key words: rice-duck farming, straw returning, organic rice-wheat cropping, weed seed bank dynamics, species diversity, weed community similarities, integrated weed management

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收稿日期: 2013-12-24; 接受日期: 2014-04-13
基金项目: 公益性行业(农业)科研专项经费(201303022)和国家科技支撑项目(2012BAD19B02)

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化学除草剂的长期大量使用带来了环境污染、农产品安全威胁、农田生物多样性破坏以及杂草抗药性的产生等问题(任康太和杨华铮, 1999)。稻鸭共作技术作为一种有机农业生产方式, 是以水田为基础, 优质稻为中心, 家鸭野养为特点, 通过种养相结合生产无公害或绿色稻、鸭产品的稻田立体种养模式(张孝安, 2007)。由于该技术既能有效控制水稻病虫草的危害, 又能减少化学农药的用量和次数, 达到绿色防控的目的(张银贵等, 2013), 近年来作为有机水稻生产中最主要的技术措施而被广泛采用, 应用面积迅速扩大(朱德峰等, 2007)。稻鸭共作技术最早起源于我国的明清时期, 而后被日本借鉴并迅速传播到越南、菲律宾等东南亚国家(卢跃红等, 2006)。前人对于稻鸭共作控制稻田杂草的效果已经做过一些研究, 魏守辉等(2006)研究表明, 随着稻鸭共作的进行, 田间杂草密度逐年降低, 4年后对于稻田主要杂草鸭舌草(*Monochoria vaginalis*)和丁香蓼(*Ludwigia prostrata*)等的防治效果均达到95%以上。Li等(2012)的研究认为稻鸭共作对于水田杂草的控制效果尤其突出, 鸭不仅采食杂草植株, 还采食其籽实、块茎与根茎。并且稻鸭共作的水环境, 使得缺氧土壤的N元素很难通过硝化作用变成N_2O, 这就减少了土壤中N元素的流失, 对于农业生产具有很高的经济价值(Yuan *et al.*, 2012)。此外, 鸭在稻田里的活动使水变浑, 影响透光, 可抑制大部分的杂草种子萌发(Van Nguyen & Ferrero, 2006)。有研究表明水稻收割后, 杂草在小麦田间的发生量随稻秸还田量的增加呈明显下降趋势(王国忠等, 2004)。因此, 此技术不但具有提高稻田土壤肥力(张帆等, 2011)、控虫除草等多方面作用(汪金平等, 2006; 李粉华等, 2007), 而且鸭子对水稻的机械刺激和扰动, 使水稻根系发达且抗倒伏, 在一定程度上降低了水稻植株的高度和水稻地上部秸秆的生物量, 从而提高了稻米品质(章家恩等, 2011)。但是, 有关稻鸭共作并秸秆还田措施对麦田杂草的影响还缺乏深入的研究。

稻麦连作是目前我国长江中下游地区主要的作物种植模式。麦田主要杂草包括看麦娘(*Alopecurus aequalis*)、菵草(*Beckmannia syzigachne*)、棒头草(*Polypogon fugax*)等(Qiang, 2002; 王开金和强胜, 2005), 这些杂草均喜湿, 能够适应下茬稻田水湿的土壤环境, 危害有逐年加重的趋势。由于小麦多撒播栽培, 所以杂草防除不得不依赖化学除草剂, 从而增加了下茬稻鸭共作生产环节的农药残留量(王小艺和黄炳球, 1997; 吴春华和陈欣, 2004), 导致有机水稻等产品的安全性得不到保证, 严重阻碍了有机农业的可持续发展(黄红, 2001; 刘玉凯, 2002)。关于稻鸭共作对水田杂草的控制效果和土壤种子库等的影响已有明确认识(强胜, 2000; 魏守辉等, 2005c; Van Nguyen *et al.*, 2006; Li *et al.*, 2012), 若能明确其对下茬麦田杂草的控制效果, 就可以不再使用化学除草剂, 真正在有机环境中开展稻鸭共作结合秸秆还田的有机轻简栽培方式。

为此, 作者连续13年研究了稻鸭共作兼秸秆还田措施对麦田杂草种子库物种多样性及其群落演替规律的影响, 以便为进一步推广这一复合农业生态体系提供科学依据。

1　材料和方法

1.1　研究区域概况

稻鸭共作技术在江苏省丹阳市延陵镇农技站农场进行示范推广。延陵地处亚热带季风气候区, 年均温15–16℃, 年降水量1,000–1,100 mm, 6–9月雨量占全年的40–55%, 无霜期约220–240 d, 全年日照2,000–2,200 h。本区水稻(*Oryza sativa*)、小麦(*Triticum aestivum*)以一年两熟为主。实验田为典型的稻麦连作田, 种植年限在15年以上。土壤类型为黄泥土, pH值为6.6, 耕层有机质含量为26.0 g/kg, 全氮为1.56 g/kg, 全磷为0.52 g/kg, 全钾为12.88 g/kg(江苏农业地理编写组, 1979)。

1.2　实验设计及稻鸭共作田间管理措施

从进行稻鸭共作的10块田中选择大小相似(面积2,667 m^2左右)的3块作为研究对象, 于2000–2012年连续13年进行稻鸭共作。田块四周筑埂高20 cm、宽80 cm, 以满足田间保水及鸭群栖息的需要。2000年6月4日麦收后, 小麦秸秆全部旋耕入土, 灌水沤泡10 d左右, 6月16日整平后手工插秧。水稻品种为‘香糯833’, 移栽规格为株距27.8 cm, 行距30.9 cm, 每穴5苗。为防止鸭子逃逸和天敌危害, 田块四周用尼龙网隔开, 辅以AC-40脉冲器及附属电流线路组成的电控防护栅栏。每块田边选择平地搭建一个6 m^2左右的鸭棚, 供鸭子遮阳、避雨和栖息。雏鸭品种选用‘镇鸭1号’, 鸭苗在水稻移栽后10 d左右放入稻田, 密度为每亩80只左右。稻田放鸭后2周, 每天

在鸭棚内定时投喂精饲料, 以后逐步减少投喂, 水稻齐穗前(9月6日)收鸭。放鸭初期田间保持3–5 cm水层, 随鸭体长大逐渐增至10–15 cm, 鸭收回后及时排水, 间歇灌溉并保持田间湿润状态。田间冬季种植小麦, 品种为‘扬麦15号’, 撒播用种量150 kg/ha。麦田1999年以前为化学除草, 1999年冬季起改为人工除草。

1.3 调查方法及数据分析

1.3.1 杂草种子库测定

于2000–2012年每年10月底在水稻收获后进行土样采集。用内径为25 mm的取样器在田间平行网状取样, 每块田50个土芯, 分0–5 cm、5–10 cm、10–15 cm三层分装, 同一层的土样混装在一起。然后将采集的土样自然风干, 稍加粉碎、混匀后分别称取总重的1/10(每份折合土表面积0.00245 m^2), 重复3次, 用水洗镜检法对样地的27份土样测定杂草种子数量(马波等, 2004)。把称好的土样放在200目的尼龙网中用自来水冲洗掉淤泥, 把尼龙网袋中剩余的残渣自然风干, 用20、40、60、80、100、120、150目的标准分级筛选, 剩余物分装在培养皿中, 在双目解剖镜下计数杂草种子的种类和数量(印丽萍和颜玉树, 1997)。

1.3.2 数据处理及统计分析

利用指数方程拟合不同年份麦田杂草种子库的变化趋势, 杂草种子库的密度即每平方米的杂草种子数量。

物种多样性指数计算公式如下:

Margalef丰富度指数(Margalef, 1958):

$$R = (S-1)/\ln N;$$

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

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

Simpson优势度指数(Parish *et al.*, 1994):

$$D = 1-\sum P_i^2;$$

Pielou均匀度指数(Hill, 1973):

$$E = H'/\ln S$$

其中S为物种总数, $P_i = N_i/N$, N为样方中总个体数, N_i为样方中第i物种的个体数。

群落相似性指数用Bray-Curtis指数(Bray & Curtis, 1957; Jiao *et al.*, 2012)及Jaccard相似指数(马克平和刘玉明, 1994; 马克平等, 1995; Milner *et al.*, 2008)。Bray-Curtis距离指数计算公式为:

$$D_{ij} = \sum_{k=1}^{p} \left| x_{ik} - x_{jk} \right| \Big/ \sum_{k=1}^{p} \left(x_{ik} + x_{jk} \right)$$

式中x_{ik}指第k个物种在年份i中的个体数目, x_{jk}含义与之类似, P是样方中的物种总数。

Jaccard相似性指数:

$$C_j = c \,/\, (a+b-c)$$

其中a为群落A含有的全部物种数, b为群落B含有的全部物种数, c为两群落共有的物种数。

研究数据使用Excel进行处理、绘图, 并使用软件SPSS、软件R进行统计分析并检验各处理间的差异显著性。

2 结果

2.1 麦田杂草总种子库的变化

连续13年的稻鸭共作措施下, 稻麦连作与秸秆还田使得麦田杂草种子库的密度整体呈下降趋势(图1)。2000年总密度高达144,831.00粒/m^2, 而到了2012年下降到4,074.37粒/m^2, 降低幅度高达97%。其曲线方程为$y = 28.425e^{-0.3x}$, $R^2 = 0.8966$($P<0.05$), 符合阻滞模型$y = k + a \cdot e^{bx}$, 其中b值越小, 群体数量的降低速度越快。表明稻麦连作的种植制度可以明显改变麦田杂草群落, 降低杂草的发生, 进而使得麦田杂草种子密度降低。但是个别年限有所反弹, 例如2004年麦田杂草种子在土壤中密度为130,171.48粒/m^2, 显著高于2001–2003年的值。

2.2 麦田主要杂草的种子库变化趋势

本实验主要研究了江苏麦田发生密度较高的看麦娘、通泉草(*Mazus japonicus*)、碎米荠(*Cardamine hirsuta*)、菵草、棒头草、牛繁缕(*Malachium aquaticum*)、蚊母草(*Veronica peregrina*)、鼠曲草(*Gnaphalium affine*)、泥胡菜(*Hemistepta lyrata*)、稻搓菜(*Lapsana apogonoides*)、野老鹳草(*Geranium carolinianum*)、北水苦荬(*Veronica anagallis-aquatica*)、酸模叶蓼(*Polygonum lapathifolium*)、荠菜(*Capsella bursa-pastoris*)、多头苦荬(*Ixeris polycephala*)、蛇床(*Cnidium monnieri*)、早熟禾(*Poa annua*)、珍珠菜(*Lysimachia clethroides*)等18种杂草。从图2和图3可以看出, 除个别年限有所升高外, 麦田阔叶、禾本科各种杂草均较大幅度地降低。到2012年, 禾本科杂草中的菵草和看麦娘在土壤种子库中还有少量存在, 而棒头草和早熟禾

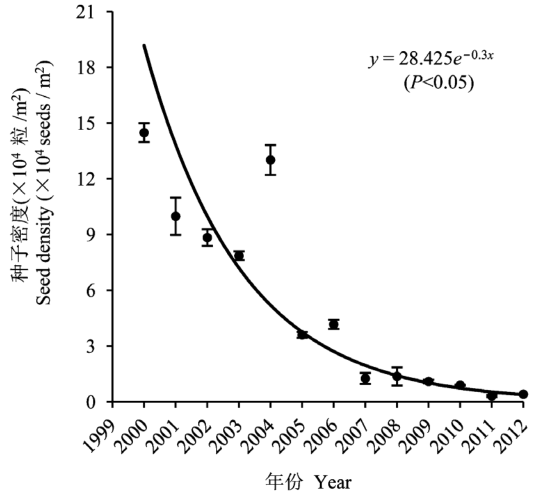


图1 稻鸭共作兼秸秆还田体系中麦田杂草种子密度动态回归模型

Fig. 1 Regression model of the dynamics of the weed seed density under rice-duck with straw returning system in wheat fields

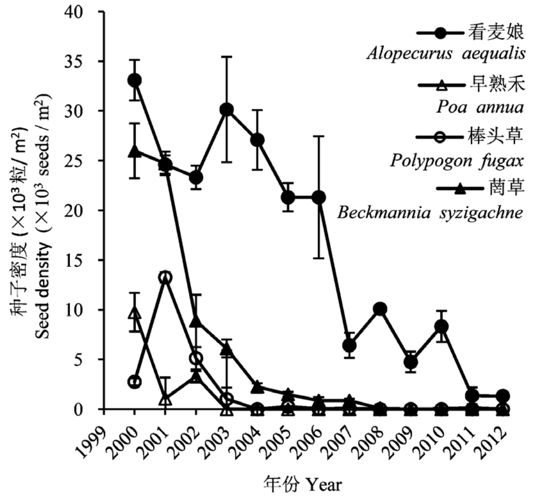
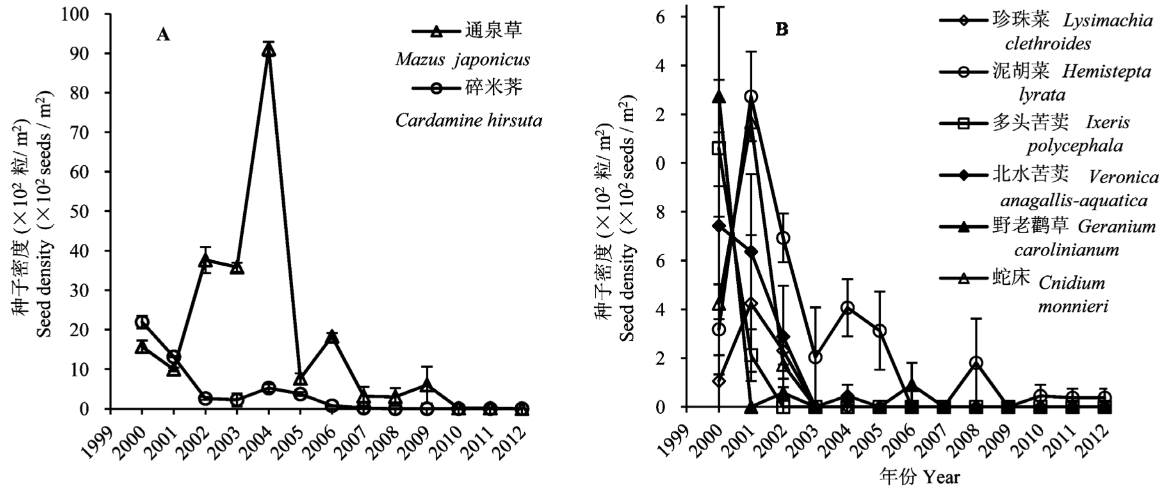


图2 连续13年稻鸭共作兼秸秆还田措施下麦田主要禾本科杂草种子密度的变化

Fig. 2 Changes in weed seed density of major grass weed species in wheat fields under continuous 13 years of rice-duck and straw returning system



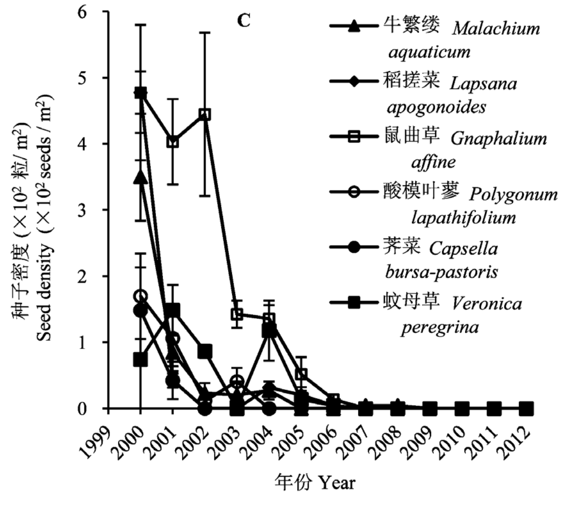


图3 连续13年稻鸭共作兼秸秆还田下麦田主要阔叶杂草种子密度的变化。**(A)**最大值大于**5,000**粒**/m²; (B)**最大值小于**1,300**粒**/m²; (C)**最大值介于**1,300–5,000**粒**/m²**之间。由图可见, 除个别年略有波动外, 主要麦田阔叶杂草种子密度都呈下降趋势。

Fig. 3 Changes in the density of weed seed of major broad-leaf weed species in wheat fields under the consecutive 13 years of rice-duck and straw returning system. (A) With the maximum density above 5,000 seeds/m²; (B) With the maximum density below 1,300 seeds/m²; (C) With the maximum density between 1,300 and 5,000 seeds/m². The density of weed seed of major broad-leaf weed species decreased

种子库的基数已趋近于0。阔叶杂草中, 除泥胡菜和通泉草在种子库中还有少量存在外, 其余12种杂草土壤种子库的基数均降低到0左右。其中, 碎米荠和棒头草经过8年后种子库基数趋近于0; 蚊母草、鼠曲草、稻搓菜、野老鹳草种子库耗竭期为7年, 牛繁缕、酸模叶蓼、北水苦荬的种子库基数在5年后接近为0; 蛇床、早熟禾、珍珠菜为3年; 多头苦荬和荠菜的种子库耗竭仅需2年(图3)。

2.3 麦田杂草物种多样性的变化

连续13年稻鸭共作与秸秆还田措施条件下, 各年杂草的Shannon-Wiener指数(*H'*)、Margalef丰富度指数(*R*)、Simpson优势度指数(*D*)除个别年份略有波动外, 整体呈下降趋势(图4)。

Simpson优势度指数(*D*)在2000–2004年持续降低, 2005年以后则处于波动状态, 但与2000年相比差异不显著, 说明稻鸭共作控草体系的选择性不强, 不会很快导致田间单优杂草种群的形成。Pielou均匀度指数(*E*)从2004年急剧下降后又出现小幅回升, 之后一直处于波动状态, 于2012年达到最大值, 说明杂草群落中优势种的地位有所降低, 各杂草种群在田间的分布趋于均匀。

总之, 从各个多样性指标13年的变化情况来看, 长期的稻鸭共作与秸秆还田的控草措施使得麦田杂草种子库物种向杂草种类少、多样性低的方向

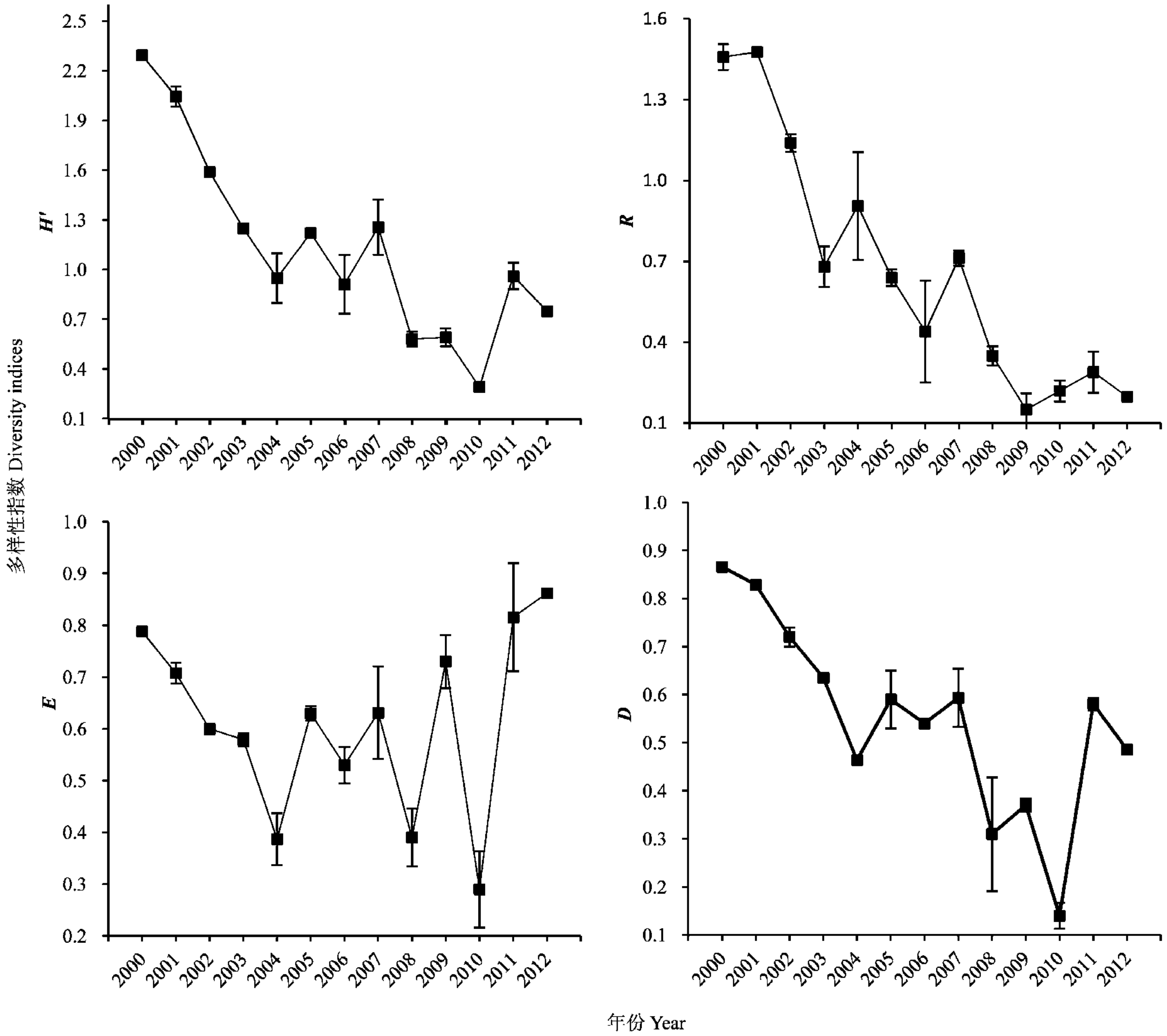


图4 连续13年稻鸭共作兼秸秆还田体系中麦田杂草种子库群落的多样性指数。*H'*: Shannon-Wiener指数; *R*: Margalef丰富度指数; *E*: Pielou均匀度指数; *D*: Simpson优势度指数。

Fig. 4 Species diversity of the weed seed bank in the wheat field during 13 years' rice-duck and straw returning system. *H'*, Shannon-Wiener index ; *R*, Margalef richness index ; *E*, Pielou evenness index ; *D*, Simpson's diversity index.

表1　连续13年稻鸭共作兼秸秆还田对麦田杂草群落相似性的影响(对角线下方的数值为Bray-Curtis指数，对角线上方的数值为Jaccard相似性指数)

Table 1　Influence of consecutive 13 years' rice-duck and straw returning system on the similarity of weed seed communities in wheat fields. Figures at the lower-left corner are the values of the Bray-Curtis coefficient, and those at the upperright corner are the values of the Jaccard's similarity index.

Jaccard Bray-Curtis	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
2000	/	0.86	0.77	0.45	0.52	0.43	0.41	0.28	0.22	0.14	0.18	0.18	0.14
2001	0.11	/	0.81	0.55	0.55	0.52	0.43	0.35	0.29	0.15	0.25	0.25	0.14
2002	0.18	0.12	/	0.61	0.6	0.5	0.47	0.38	0.32	0.17	0.28	0.28	0.16
2003	0.40	0.30	0.24	/	0.56	0.64	0.4	0.47	0.38	0.17	0.33	0.33	0.15
2004	0.35	0.30	0.25	0.27	/	0.73	0.5	0.32	0.31	0.13	0.27	0.27	0.12
2005	0.42	0.33	0.33	0.22	0.16	/	0.57	0.35	0.27	0.15	0.31	0.31	0.14
2006	0.47	0.43	0.37	0.42	0.34	0.27	/	0.4	0.31	0.3	0.36	0.36	0.17
2007	0.59	0.50	0.46	0.38	0.52	0.47	0.42	/	0.64	0.27	0.45	0.45	0.25
2008	0.66	0.58	0.54	0.46	0.53	0.57	0.51	0.22	/	0.43	0.71	0.71	0.37
2009	0.76	0.74	0.71	0.69	0.74	0.70	0.52	0.55	0.37	/	0.6	0.6	0.4
2010	0.72	0.63	0.60	0.54	0.60	0.55	0.48	0.38	0.18	0.26	/	1	0.50
2011	0.72	0.64	0.60	0.54	0.61	0.56	0.48	0.38	0.19	0.27	0.03	/	0.50
2012	0.78	0.77	0.75	0.76	0.79	0.76	0.72	0.59	0.46	0.44	0.34	0.32	/

演变。

2.4　麦田杂草群落相似性的变化

从表1中可以看出，与2012年相比，各年度的Bray-Curtis指数逐渐降低，表明杂草群落越来越单一，种数越来越少。与2000年相比，各年Jaccard相似性指数逐渐减小，说明差异性越来越大，显示杂草群落发生了较大变化，杂草群落的种类越来越少。Bray-Curtis指数普遍比Jaccard相似性指数要低，说明它能更灵敏地反映控草措施对杂草群落结构的微小影响。

3　讨论

3.1　稻鸭共作显著降低了麦田杂草种子库的种类和数量

在稻麦连作耕作制度下，麦田杂草的发生受上茬水稻的灌水时间、轮作方式、除草剂的使用、地域及土壤等环境条件影响(强胜等, 2000; Qiang, 2005; Fried *et al*., 2008; 俞琦英和周伟军, 2010)。稻鸭共作明显延长了灌水时间，使得那些喜旱或不耐水淹的杂草如荠菜种子腐烂失活，使杂草种类大量减少(Qiang, 2005)。然而由于看麦娘等杂草喜湿且植株结实量多(强胜, 2009)，种子在土壤中基数较大，其种子密度下降速度相对也就较慢。此外，看麦娘、泥胡菜、茼草的种子均可漂浮于水面，也可以随着水流进入农田，额外增大了种子库的基数，较难防除。

在农田生态系统中，土壤种子库的产生与亲代杂草群落显著正相关，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，取决于杂草种子所处的土壤环境条件及其种类(Roberts & Ricketts, 1979; Forcella, 1992; Cardina & Sparrow, 1996; Zhang *et al*., 1998)。地面杂草群落是种子库输入的主要方式，杂草种子库是当季杂草向下一季转换的纽带(Cavers, 1995)。相对于地面杂草群落，地下杂草种子库更能灵敏地反映出农艺措施对杂草群落的影响。作物轮作(如稻麦轮作或稻油轮作)作为一种经典的农艺措施，会使杂草的生存环境趋于多样化，能够限制某些已适应单一种植系统的杂草生长，而不同的作物组合及轮作序列可导致种子库中杂草的种类和组成发生变化，从而影响未来杂草的发生(Mayor & Dessaint, 1998; 魏守辉等, 2005a)。

有关稻鸭共作条件下稻田杂草群落的演替规律已有报道(魏守辉等, 2005c; Li *et al*., 2012)，生态控草措施下稻鸭共作对麦田杂草种子库也具有同样的影响。此措施除可通过杂草种子的耗竭而减少种子库的输入外，还增加了种子库的输出，即"断源"、"竭库"，切断了杂草发生与转换的纽带，减少了麦田杂草发生基数。在杂草群落结构演变过程中，

多样性指数及相似性指数表明，杂草在数量上的变化比种类变化要快，麦田杂草群落的种类越来越少，向着多样性低的方向演替。从连续13年的实验结果中可以看出，杂草种子库物种的种类到2012年只有4种，与2000年的18种相比下降了77.78%，其密度以平均14.88%的速率逐年减少，到2012年只有4,074.37粒/m^2，仅占稻鸭共作前的3.79%，说明杂草种子库基数有了较大程度的降低。如果随水流传播的杂草种子再得到有效控制(即“截流”)，则杂草种子库最终将被耗竭(魏守辉等，2005a；强胜，2009)。然而，如果管理不善，比如淹水天数不足，灌水太浅，使得阳光照射透光率增加，反而会引起杂草暴发。可见，掌握杂草种子库的耗竭规律，对于杂草的综合管理(Fried *et al.*, 2008)和可持续管理(Légère & Samson, 1999)有重要意义。

3.2 稻鸭共作兼秸秆还田影响麦田杂草种类的机制

稻鸭共作兼秸秆还田处理措施导致农田杂草种子存留的环境条件发生了显著改变：如与传统水稻种植间隙灌水不同，稻鸭共作须持续3个月保持田间15 cm左右的水层，会使光照、温度等环境因素发生变化，影响原本适应于麦田生长的杂草种子在稻田的休眠与存留(郭宪等，2007)。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，打乱其生活周期，导致其死亡。另外，鸭群不停地搅拌土壤，杂草种子被翻出土壤，漂浮于水面，直接被取食或者腐烂死亡，田间浑水作用也会引起水层的光、热变化，进而影响杂草种子的萌发与存活，改变其生命周期，从而减少了次年麦田杂草发生的基数(魏守辉等，2005c；Li *et al.*, 2012；Usman *et al.*, 2012)。当然，不同的杂草种子的活力、存活期和种子萌发习性等存在差异，对环境改变的承受能力也不同，因而不同杂草种子库降低的程度也不同(万开元等，2010)。

综上，稻鸭共作和秸秆还田使存留于土壤中的杂草种子基数不断被耗竭，直接影响了地面杂草的群落构成，进而减轻了下年农田草害。作物轮作也会间接影响种子库的密度和种类组成，综合防治措施能够大大降低田间杂草的结实，从而减小其种子库的规模。作为一项种养复合、环保生态型的综合农业生产技术，稻鸭共作和秸秆还田的有机轻简栽培措施极大地发挥了稻田的生产、养殖以及生态调控功能，并且减少了麦田除草剂的使用，有利于绿色生态农业的发展。

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