•综述•

化学除草剂对农田生态系统野生植物多样性的影响

齐 月^{1,2} 李俊生^{2*} 闫 冰^{1,2} 邓贞贞² 付 刚²

1 (北京师范大学水科学研究院, 北京 100875)

2 (中国环境科学研究院环境基准与风险评估国家重点实验室, 北京 100012)

摘要: 农田生物多样性是全球生物多样性的重要组成部分, 除草剂的大量施用对其产生了严重影响。本文综述了化学除草剂对农田生态系统中野生植物多样性的影响, 并分析归纳了其影响机制。除草剂的施用会使敏感植物减少, 抗性植物增多, 从而改变农田生态系统中的野生植物物种组成, 并使其趋同化, 降低遗传多样性和物种多样性, 以致植物功能群单一化, 群落稳定性下降。除草剂的主要影响机制是杀死植物或改变其生长代谢、抗性、繁殖等, 改变生境, 并与人为因素、环境因素等产生协同影响。不同种类的除草剂影响程度不同, 且不同物种间、不同群落间的响应也存在差异。我国化学除草剂使用量持续增长, 应加强除草剂对野生植物多样性的影响及其机制研究, 重视除草剂使用历史记录和野生植物的长期监测, 以及除草剂使用规范和相关政策法律研究, 更好地保护我国农田生态系统中的生物多样性。

关键词: 化学除草剂; 农田生态系统; 遗传多样性; 物种多样性; 植物功能群; 影响机制

Impact of herbicides on wild plant diversity in agro-ecosystems: a review

Yue Qi^{1,2}, Junsheng Li^{2*}, Bing Yan^{1,2}, Zhenzhen Deng², Gang Fu²

1 College of Water Sciences, Beijing Normal University, Beijing 100875

2 State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012

Abstract: Plant diversity in agro-ecosystems is an important component of global biodiversity. However, wild plant diversity in agro-ecosystems is influenced by herbicide use. We reviewed recent studies on the impacts of herbicides on wild plant diversity in agro-ecosystems and the underlying mechanisms. It is found that herbicide application (i) decreases the number of plants that are sensitive to herbicides; (ii) increases the number of plants that are resistant to herbicides; (iii) changes species composition; and (iv) decreases genetic diversity and species diversity of wild plants in agro-ecosystems. Herbicide impacts simplify plant functional groups and hence add instability to communities. The underlying mechanism is that herbicides kill plants or change plant metabolism, resistance, reproduction and the habitat of plants. Furthermore, herbicides, human activities, and environmental factors have interactions. The impacts of herbicides on plants are plant-specific and the responses of various species or communities to the herbicides are also different. At present, the use of herbicides is increasing rapidly in agricultural production in China. We therefore suggest that more studies are needed on the impact of herbicides on wild plants and the underlying mechanisms, and the historical performances of herbicides use should be studied using long-term monitoring of wild plant changes carried out in China's agro-ecosystems. Studies on policies and laws related to the use of herbicides also need to be strengthened, which can help to improve conservation of biodiversity in agro-ecosystem of China.

Key words: herbicide; agro-ecosystem; genetic diversity; species diversity; plant functional groups; influencing mechanism

农田生物多样性是全球生物多样性的重要组成部分(陈欣和唐建军, 2013)。农田生态系统, 包括

半自然生境(田埂、弃耕地等)中的野生植物多样性为我们提供了调节、支持等生态系统服务功能和农

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* 通讯作者 Author for correspondence. E-mail: lijsh@craes.org.cn

业生产服务功能(Isaacs et al, 2008), 如维持较高的营养级水平、促进养分循环、水土保持、害虫防治等(Wyss, 1995; Altieri, 1999; Petit et al, 2011), 同时这些野生植物也是农田生态系统中食物网的最重要组成部分(Rassam et al, 2011)。然而, 农田生态系统中的野生植物多样性正受到人类活动的强烈干扰, 如农药、化肥的施用等, 使农田中珍稀野生植物锐减(Hyvönen & Huusela-Veistola, 2008; Fried et al, 2009b; Storkey et al, 2012; Liopa, 2014)。

化学除草剂由于适合机械化作业, 具有节省劳力和高效等特点, 再加上抗除草剂作物的种植面积不断扩大, 其使用量不断增加(Gianessi & Reigner, 2007; Davis et al, 2012; Young et al, 2013)。化学除草剂对农田生态系统中野生植物的干扰具有频度高、种类多、历史长等特点, 严重威胁其多样性(Heard et al, 2005; Bastiaans et al, 2008)。本文综述了农田生态系统中化学除草剂对野生植物遗传多样性、物种多样性、物种组成和功能群影响的研究, 以期为我国农田生态系统中的生物多样性保护工作提供参考。

1 化学除草剂概况

全球约有233种除草剂(吕秀亭, 2013)。根据其化学结构可分为无机类和有机类。目前前者应用很少, 后者应用广泛。有机类除草剂可再分为磺酰脲类、苯氧羧酸类、苯甲酸类、三氮苯类等十几种类型; 根据其对杂草和作物的选择性, 又可分为非选择性(灭生性)和选择性两种, 前者对作物和杂草都有毒害作用, 如百草枯、草甘膦等, 后者在一定剂量范围内能杀死杂草, 而对作物无毒害或毒害很低, 如麦草畏、苯磺隆等, 多数有机除草剂属于此类(强胜, 2009)。针对植物特有靶标, 已报道的除草剂的主要作用机理包括影响光合色素以及相关组分的合成和代谢、氮的代谢及氨基酸的生物合成、脂类生物合成、光合电子传递系统、细胞壁及其生物合成等(宋倩等, 2008)。

我国已成为世界第一大农药生产国(王正贵, 2011)和第一大农药使用国(梅旭荣, 2011)。近年来, 我国化学除草剂生产量和使用量逐年增加(强胜, 2009), 每年使用除草剂有效成分达 8×10^4 t以上, 施用面积以每年 2×10^6 ha的速度递增, 全国使用除草剂的农田面积已达 0.60×10^8 ha(丁洪等, 2011)。

目前乃至未来较长的时间内, 化学除草剂还没有更好的替代品(Keller et al, 2014), 因此其施用量将保持长期增长的趋势。

2 对野生植物多样性的影响

除草剂是影响农田生态系统中野生植物多样性的主要因素。它不仅直接毒害靶标野生植物, 而且是重要的环境污染源之一, 其对野生植物生境的改变可能是不可逆转的。此外, 除草剂的影响范围并不局限于农田生态系统中的耕作区, 还包括田埂、农田周边荒地、弃耕地等(Boutin & Jobin 1998), 它对植物多样性的影响比化肥更大(McCloskey et al, 1996; Hyvönen & Salonen, 2002), 可在遗传特性、物种和功能群等多个层次上改变野生植物多样性。

2.1 对遗传多样性的影响

大量研究表明, 在农田生态系统中长期使用除草剂会引起植物遗传结构的改变(Imaizumi et al, 2008; Huangfu et al, 2009; Yu et al, 2012; Délye et al, 2013a, b; Xu et al, 2014)。目前的研究认为, 长期施用同种除草剂会造成多种植物遗传多样性的丧失或改变。如Imaizumi等(2013)在分析日本3个地区的异花授粉植物萤蓼(*Schoenoplectus juncooides*)对磺酰脲类除草剂的抗性植株和敏感性植株时发现, 敏感性植株的遗传多样性和总遗传多样性均高于抗性植株; Osuna等(2011)对美国的自花传粉植物水田稗(*Echinochloa oryzoides*)抗禾草丹型和敏感型植株的研究得出相似结论。即使除草剂未降低抗性植株的遗传多样性, 也会造成单倍型多样性减低(Menchari et al, 2007)。但是除草剂对植物种内基因及其功能影响的机理依然所知较少(Begg et al, 2012)。

2.2 对物种多样性的影响

自20世纪40年代以来, 人们开始通过大田长期观测实验来研究耕作区内除草剂对野生植物物种多样性的影响。多数研究认为除草剂降低了物种多样性(Hyvönen et al, 2003; 吴竞伦等, 2006; Grundy et al, 2011; José-María et al, 2013; 张晶旭等, 2014)。Potts等(2010)在英国南部的苏塞克斯郡1968–2005年的观测结果表明, 长期施用除草剂使物种多样性明显降低; 但也有研究认为, 除草剂并未使物种多样性降低, 只是导致物种组成发生变化(Derksen et al, 1995; 吴建荣等, 2001; Andreasen & Stryhn,

2008; Ahrens & Auer, 2012; Leguizamón et al, 2012; Young et al, 2013)。

除草剂对非耕作区(如弃耕地、田埂、农田邻近荒地等)野生植物多样性的影响也受到关注(Boutin & Jobin, 1998), 亚致死剂量的除草剂会造成非耕作区植物多样性下降(Schmitz et al, 2014)。Egan等(2014)选择了3种类型的非耕作区分别施用亚致死剂量浓度的除草剂麦草畏, 观察到植物多样性在不同类型的非耕作区内表现出不同的变化特点。

2.3 对物种组成的影响

除草剂往往改变农田植物群落的物种组成, 使藜(*Chenopodium album*)等对除草剂最敏感的植物成为农田植物群落中数量最少的物种(邱学林等, 1997; Boutin et al, 2014), 而野生堇菜(*Viola arvensis*)、繁缕(*Stellaria media*)、匍匐冰草(*Elymus repens*)、黑麦草(*Lolium rigidum*)等抗药性强的植物则成为优势物种(Hume, 1987; Hyvönen et al, 2003; Grundy et al, 2011; Rassam et al, 2011; Malone et al, 2014; Owen et al, 2014)。长期使用单一除草剂或防除植物种类相近的除草剂可能引起物种组成趋同化(高君等, 1992)。例如, 在加拿大安大略湖西南部, 多年使用草甘膦使不同地区的农田物种组成相同, 与使用多种除草剂的农田物种组成具有很大差异(Gulden et al, 2010)。但也有研究表明, 除草剂不一定改变物种组成(Egan et al, 2014)。因此除草剂对物种组成的影响依然值得进一步探究。

农田生态系统中植物物种组成的改变不仅影响植物多样性, 而且也影响动物多样性(Hawes et al, 2003; Smith et al, 2008; Storkey et al, 2013), 包括农业害虫天敌和传粉动物, 从而影响农业生产, 其对生态系统服务功能的影响可能更为严重。

2.4 对野生植物功能群的影响

除草剂使农田生态系统中的野生植物功能群单一化, 使群落稳定性下降。例如, Fried等(2009a)观测了使用除草剂30年以上的向日葵(*Helianthus annuus*)农田内野生植物群落的17个特征, 发现2/3的群落形成了嗜氮、适光、对除草剂不敏感、夏季速生生活史的功能群。而具有植株矮小、大种子、低氮需求、起始花期较晚、晚冬或早夏出现的一年生以及短花期等特征的功能群, 不易在施用除草剂的集约化农业环境中竞争存活(Storkey et al, 2010; Pinke & Gunton, 2014)。

目前, 虽然功能群特征的筛选方法逐步由以人为主规划定(Hume, 1987; Puricelli & Tuesca, 2005)向模型分析转变(Colbach et al, 2014; Gaba et al, 2014; Pinke & Gunton, 2014), 但还没有公认的功能群特征指标, 因此很难对比不同的研究成果。农田生态系统中野生植物功能群的特征指标及其筛选方法的研究还有待深入开展。

3 影响机制浅析

除草剂可杀死植物或改变植物生长代谢、抗性、繁殖等特征, 并改变植物生境, 还可与其他因素产生协同影响, 但不同种类的除草剂影响程度不同(Rassam et al, 2011; Leguizamón et al, 2012; José-María et al, 2013), 且不同物种间、不同群落间的响应也存在差异(图1)。

3.1 物种响应特征

除草剂对植物最显著的影响是致死, 即使亚致死剂量也会抑制植物生长(Boutin et al, 2004), 而未被杀死的植物会自我修复。但是不同物种对除草剂的敏感程度及自我修复能力均存在差异(Carpenter et al, 2013)。此外, 植物也会调整生活史以应对除草剂的影响(Abe & Kameya, 1986)。

长期、大量使用化学除草剂特别是单一除草剂, 给野生植物施加了强大的选择压力(Gulden et al, 2010), 使抗单一除草剂甚至抗多种除草剂的植物种类和数量不断增加(<http://www.weedscience.org/Summary/home.aspx>)。植物可通过由于除草剂作用而导致的基因突变、新陈代谢增强、吸收减少和(或)迁移、隔离、基因过量表达, 甚至多重模式共同作用等, 而改变个体抗性, 降低除草剂的作用(Mortensen et al, 2012; Délye et al, 2013a), 并且抗性的改变会持续进化(Busi et al, 2013)。但是并非所有农田的野生植物均可产生抗药性, 或许在进化时间上也存在种间差异。

长期施用除草剂会引起植物遗传结构的改变, 从而影响其繁殖(Délye et al, 2013b), 即使短时间内没有遗传上的变化, 也会引起繁殖物候适应性变化(Gundel et al, 2008; Mortimer, 1997), 或因植物营养不足而改变植物个体的繁殖状况(Carpenter & Boutin, 2010)。植物可通过改变整体结实量(Boutin et al, 2012)和单株结实量(吴建荣等, 2001)、种子大小(Pinke & Gunton, 2014)、萌发率(Andersson, 1996;

图1 除草剂对农田生态系统中野生植物多样性的影响机制

Fig. 1 The possible mechanisms that herbicides affect wild plant diversity in agro-ecosystems

Hurst & John, 1999; Carrithers et al, 2004)以及出苗期、花期等性状(Colbach et al, 2014; Boutin et al, 2014; Délye et al, 2013b)来应对除草剂的影响。

3.2 群落响应特征

(1)土壤种子库的改变。这会直接影响地上植物多样性及其恢复能力。在除草剂的作用下, 土壤种子库中的种子数量和种类组成会发生变化(Ball, 1992), 靶标植物的种子量在除草剂施用期间维持在稳定或较低的水平, 使得原本为中等竞争力的植物种子数量迅速增加(Squire et al, 2000)。除草剂会导致种子休眠缩短, 进而加速其土壤种子库消耗(Storkey et al, 2010)。停止使用除草剂利于土壤种子库的恢复, 但是不同群落的恢复能力不同(Burnside et al, 1986; Schweizer & Zimdahl, 1984)。

(2)群落抗性的改变。农田生态系统中不同群落的植物多样性并不一致, 耕作区边缘的植物多样性一般高于耕作区中心(Gabriel et al, 2006), 使得群落不同区域间的抗干扰能力存在差异。除草剂在改变物种多样性的同时, 可能引发群落某些功能、作用的改变, 群落的抗性和稳定性可能会受到影响, 从而改变群落抵抗其他干扰的能力。当群落受到其他干扰时, 除草剂对多样性的影响可能更为严重。通过室内模拟群落作为实验对象或许是可以避免外界复杂干扰的有效途径之一, 可更好地揭示群落对除草剂的响应特征(Watrud et al, 2011)。

目前关于植物群落的响应机制还缺乏深入研究。不同群落对同种除草剂的响应不尽相同(Egan et al, 2014), 因而依据某一研究区域的结论推测除草

剂对整个农田生态系统野生植物多样性的影响并不科学。

3.3 生境的改变

除草剂除了直接影响植物多样性以外, 其本身及其部分次生代谢物还是环境的重要污染物, 会改变植物生境, 从而引起野生植物的不同响应, 进而影响甚至严重威胁野生植物多样性。除草剂改变植物生境至少体现在3个层次。在时间上, 因受理化属性、使用数量和频率、施用方式以及环境条件的影响(Freemark & Boutin, 1995; Melo et al, 2010), 除草剂在土壤中的半衰期从数天到数年不等, 不同残留时期的除草剂对野生植物的影响存在差异(Raimondi et al, 2010)。在空间上, 除草剂不仅改变其直接使用区域的植物生境, 包括耕作区和人为操作扩大的区域(如飞机等大型机械喷施除草剂涉及农田周边荒地), 而且除草剂可随水、风、土壤流失等漂移到邻近非耕作区(Steen et al, 1999; Egan et al, 2014), 甚至跨地区的更远范围(Hill et al, 2002), 并改变当地的植物生境。在肥力上, 长期使用除草剂会影响土壤肥力(Storkey et al, 2010; 丁洪等, 2011), 如草甘膦增加了土壤中的硝酸盐浓度(Ahrens & Auer, 2012)。但相关研究尚有待深入开展。

3.4 协同影响机制

(1)人为因素。选种作物、播种时间、耕作制度、轮作方式等种植制度对野生植物多样性的影响存在较大差异(Gunton et al, 2011; Davis et al, 2012; 丁娜等, 2014), 这些因素均会干扰除草剂对植物多样性的影响(McCloskey et al, 1996; Hyvönen & Salo-

nen, 2002; 刘方明等, 2005)。此外, 除草剂的施用浓度、频度、时间、年限等差异也影响农田植物群落, 如高浓度、混用的除草剂的影响与低浓度、单一除草剂的影响差异较大(Puricelli & Tuesca, 2005; 吴竞仑等, 2006; Grundy et al, 2011)。同时, 人为因素之间存在着多样而复杂的交互作用(Swanton et al, 2006), 给除草剂对农田生态系统中植物多样性影响的变化趋势预测增加了难度(Grundy et al, 2011), 人为因素与除草剂间的共同作用机理有待深入研究。

(2)环境因素。气候因素包括温度、光照、水分等与除草剂相互作用, 对植物及其多样性具有协同影响的效应(Riethmuller, 2006; Grundy et al, 2011; Pinke et al, 2011; Rodenburg et al, 2011)。但是针对除草剂和单一气候因素的协同影响, 已有研究多在物种的生理生化水平上开展(Alkhatib et al, 1992; Dark et al, 1996; Plowman & Richards, 1997; Dulai et al, 1998; Hola et al, 2004), 针对多个物种组合或群落水平的研究还十分有限。除草剂与土壤养分相互作用对植物及其多样性的协同影响备受关注, 特别是除草剂与土壤碳、氮的相互作用(Cathcart et al, 2004; Zhang et al, 2010; Damgaard et al, 2011; Sonderskov et al, 2012; Bai et al, 2014)。土壤盐离子交换量和pH值也影响着植物对除草剂的耐受能力(Kerr et al, 2004)。

4 展望

越来越多的国家和地区, 特别是欧洲国家, 对农田生态系统中的生物多样性开展了大规模、常规化的基础调研, 重视长期定位观测除草剂的影响, 并且国家间的观测数据对比分析也开始受到关注。这有利于深入了解施用除草剂的农田生态系统中野生植物多样性的长期动态及区域间的变化规律并制定相应措施。然而, 农田生态系统中复杂的人为活动和环境因素增加了研究难度, 除草剂对野生植物遗传多样性、非耕作区的物种多样性、功能群多样性等影响的研究还较为有限。影响机制研究依然存在很多空白, 特别是关于植物群落对除草剂的响应特征, 除草剂对于土壤肥力的影响, 以及除草剂与环境因素对植物多样性的协同影响等, 值得进一步研究重视。

目前, 已培育出近300种抗除草剂的转基因作

物(如抗除草剂转基因大豆(*Glycine max*)、棉花(*Gossypium* spp)、玉米(*Zea mays*)等), 并已涉及10个类别的除草剂, 由单一抗除草剂性状向抗(耐)除草剂和抗虫及其他复合性状发展, 且其全球种植面积不断扩大, 这将导致除草剂的使用面积及使用量增加(强胜等, 2010)。同时, 除草剂面临着安全、环境风险以及抗除草剂植物进化等挑战, 对除草剂的减量使用(Davis et al, 2012; Power et al, 2013)及减少使用(Deytieux et al, 2012)的研究, 寻找新的除草剂作用位点, 研发针对多重耐药性植物的除草剂, 开发廉价的自动化、智能化施用技术, 以及利用生物工程研制生物除草剂将依然受到关注(Keller et al, 2014)。除草剂对农田生态系统中野生植物多样性的影响也会随着除草剂及其施用技术的变化而变化, 相关研究依然面临着诸多挑战。

随着我国经济的快速发展, 除草剂的使用量不断增加, 其对我国农田生态系统中野生植物多样性的影响程度也在不断增加, 而我国在这方面的研究相对较少、资料缺乏, 虽然部分地区或针对某些植物种属已经开展了一些田间调研工作(王云等, 2013), 但是至今未能形成规范的、大范围的、长期的调研成果。笔者认为, 今后我国亟待加强以下3个方面的研究:

(1)重视我国农田生态系统中除草剂使用历史记录工作和野生植物状况的基础调研, 建设长期观测场地, 开展定期监测工作, 并基于我国自然条件与农业生产情况, 针对耕作区和非耕作区, 深入开展除草剂对野生植物遗传多样性、物种多样性和功能群等多角度多层次的影响及其机理研究, 为模型分析和预测提供基础, 以利于更加科学地使用化学除草剂。

(2)重视我国化学除草剂减量化使用技术以及环境友好型除草剂的研究, 降低化学除草剂对农田生态系统中野生植物多样性的生态风险, 为我国农田生态系统中的生物多样性保护工作和合理优化我国农业生产水平提供基础。

(3)加强我国农田生态系统中除草剂使用规范和相关补偿、鼓励政策, 以及生物多样性保护工作的政策和法律研究, 以期实现农业可持续发展。

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