Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Guo-qi C, Yang C, Masoom A, Jia-jun W, Hai-yan W (2025) Baseline sensitivity of *Echinochloa glabrescens* to florpyrauxifen-benzyl on a regional scale: A case study of Jiangsu Province, China. Weed Technol. **39**(e35), 1–7. doi: 10.1017/wet.2025.3

Received: 7 September 2024
Revised: 13 December 2024
Accepted: 16 January 2025

Associate Editor:
R. Joseph Wuerffel, Syngenta

Nomenclature:
Barnyardgrass; *Echinochloa glabrescens* Munro ex Hook. f.; florpyrauxifen-benzyl; rice; *Oryza sativa* L.

Keyword:
Baseline sensitivity; *Echinochloa glabrescens*; florpyrauxifen-benzyl; paddy field; resistance

Corresponding author:
Chen Guo-qi; Email: chenguoqi@yzu.edu.cn

*These authors contributed equally to this study.

Baseline sensitivity of *Echinochloa glabrescens* to florpyrauxifen-benzyl on a regional scale: A case study of Jiangsu Province, China

Chen Guo-qi[1,*], Chen Yang[2,*], Aatiqa Masoom[2], Wu Jia-jun[3] and Wei Hai-yan[4]

[1]Associate Professor, Jiangsu Key Laboratory of Crop Genetics and Physiology/Jiangsu Key Laboratory of Crop Cultivation and Physiology, Agricultural College (Research Institute of Rice Industrial Engineering Technology) of Yangzhou University, and Jiangsu Co-Innovation Center for Modern Production Technology of Grain Crops, Yangzhou University, Yangzhou, China; [2]Graduate student, Agricultural College, Yangzhou University, Yangzhou, China; China; [3]Manager, Corteva Agriscience, 201203, Shanghai, China and [4]Professor, Agricultural College of Yangzhou University, Yangzhou, China

Abstract

Systematically monitoring the baseline sensitivity of troublesome weeds to herbicides is a crucial step in the early detection of their market lifespan. Florpyrauxifen-benzyl is one of the most important herbicides used in rice production throughout the world, and has been used for 5 yr in China. Barnyardgrass is one of the main targeted weed species of florpyrauxifen-benzyl. In total, 114 barnyardgrass populations were collected from rice fields in Jiangsu Province, China, and using whole-plant bioassays they were screened for susceptibility to florpyrauxifen-benzyl. The GR_{50} values (representing the dose that causes a 50% reduction in fresh weight of aboveground parts) of florpyrauxifen-benzyl for all populations ranged from 1.0 to 34.5 g ai ha^{-1}, with an average of 6.8 g ai ha^{-1}, a baseline sensitivity dose of 3.3 g ai ha^{-1}, and a baseline sensitivity index of 34.5. Twenty-one days after treatment with florpyrauxifen-benzyl at the labeled dose (36 g ai ha^{-1}), 90% of the barnyardgrass populations exhibited >95% reductions in fresh weight of aboveground parts. Compared with the baseline sensitivity dose, 63, 44, and 7 populations had, respectively, no resistance (55%), low resistance (39%), and moderate resistance (6%) to florpyrauxifen-benzyl. Furthermore, the GR_{50} distribution of barnyardgrass populations did not show a significant correlation with collection location, planting method (direct-seeding or transplanting), or rice species (*Oryza sativa* L. ssp. *indica* or ssp. *japonica*) at any of rice fields where seeds had been collected ($P > 0.05$). In conclusion, florpyrauxifen-benzyl remains effective for barnyardgrass control in rice fields despite serious resistance challenges.

Introduction

Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], a C_4 plant, is one of the most troublesome weeds in agricultural systems (Alberto et al. 1996). In paddy fields, it is highly competitive with rice for space, sunlight, and soil nutrients. Morphological similarity between barnyardgrass and rice seedlings has made identification difficult (Chauhan and Johnson 2009). When barnyardgrass was easily distinguished by farmers, rice yield losses were inevitable: by 7% and 87% at weed infestation levels of 5% and 50% coverage, respectively (Diop and Moody 1984). Barnyardgrass has been reported in China, India, and Philippines (Chauhan and Abugho 2013; Donayre et al. 2014; Zhang et al. 2023). A survey of rice fields in China indicated that barnyardgrass is common found in East China but seldom found in southern and northwestern China (Chen et al. 2019).

Herbicides are the most effective weed control tools, providing >85% control of the targeted weeds (Chen et al. 2023). Nonchemical weeding may achieve similar efficacy but only by combining multiple methods, each of which is generally far more labor-intensive than applying herbicides (Delye et al. 2013). Long-term and excessive use of herbicides has led to the emergence and increasing trend of resistance to herbicides by weeds (Iwakami et al. 2012; Zhu et al. 2020), including barnyardgrass, which has been reported to be resistant to penoxsulam, a herbicide that inhibits acetolactate synthase (ALS); metamifop and cyhalofop-butyl, which inhibit acetyl-CoA carboxylase (ACCase); and quintrione, which inhibits 4-hydroxyphenylpyruvate dioxygenase (HPPD) (Li et al. 2023; Yan et al. 2019; Zhang et al. 2022). Developing a new herbicide is costly and usually takes more than 10 yr; accordingly, the scientific and reasonable use of herbicides in rice production to extend their effective life is the foundation for sustainable chemical control. Baseline sensitivity refers to a continuous distribution of weed isolates using a range of herbicides (Thomas et al. 2012; Wang et al. 2022). Knowing the baseline sensitivity of barnyardgrass to various herbicides can provide a basis for weed control by monitoring the evolution of weed resistance to herbicides (Moss 2001), and thereby supporting the promotion and application of newly developed herbicides.

Florpyrauxifen-benzyl (benzyl-4-amino-3-chlor-6-[4-chlor-2-fluor-3-methoxyphenyl]-5-fluor-2-pyridincarboxylate) is an important herbicide used worldwide in rice production to target the postemergence control of barnyardgrass. As a novel structural class of synthetic auxin herbicides, the herbicide has been used for managing weeds in rice fields since 2018, and has exhibited high efficacy in controlling susceptible and herbicide-resistant barnyardgrass biotypes. Nevertheless, barnyardgrass that is resistant to florpyrauxifen-benzyl has been found in the United States and China (Chen et al. 2024; Hwang et al. 2022b; Miller et al. 2018).

Farmers in Jiangsu Province, China, practice state-of-the-art rice and wheat planting, mainly by adopting the two-cropping pattern of rice-wheat rotation (Ren et al. 2023), with 2.22 million ha of paddy fields with 8,940 kg ha^{-1}. Due to the large rice market in Jiangsu Province, any new herbicide for use in rice production would be applied in Jiangsu Province once it is registered. Therefore, Jiangsu Province can serve as a typical region for studying the baseline sensitivity of regional weeds to important herbicides. Since 2017, florpyrauxifen-benzyl has been applied to control rice weeds in Jiangsu Province. In 2022, 114 barnyardgrass populations were collected from rice fields in Jiangsu Province. The objectives of this study were to 1) assess the sensitivity of barnyardgrass populations collected from paddy fields to florpyrauxifen-benzyl on a regional scale and 2) establish baseline sensitivity for monitoring the variation of resistance to florpyrauxifen-benzyl in the future.

Material and Method

Plant Materials

In October 2022, seeds were collected from paddy fields across 13 cities in Jiangsu Province, representing 114 populations. Sampling sites were not predetermined or selected based on the presence of barnyardgrass during collection. Therefore, herbicide application histories of the collecting fields were unknown. Seeds of each population were randomly collected from more than 100 mature plants, air-dried, and stored in a laboratory at room temperature before using. Barnyardgrass was identified based on its morphological traits (Chen et al. 2019).

Whole-Plant Dose–Response Bioassay

Seeds of each population were sown into a 9-cm-diam Petri dish containing two pieces of filter paper moistened with 6 mL distilled water and placed in a chamber at 30 /25 (light/dark) with a 12-h light/dark cycle. Twelve germinated seedlings were transplanted per plastic pot ($7 \times 7 \times 8$ cm) with a 2:1 mixture of natural soil and pH 5.6 nutritional soil (Nanjing Duole Horticulture Co., Ltd.), and grown in a greenhouse at Yangzhou University. Seedlings were thinned to nine uniform-sized plants per pot. At the 3- to 4-leaf stage, herbicides were applied using a laboratory sprayer (TBSHIELD) equipped with a flat-fan nozzle (1.1 mm diameter and jet angle 15 degrees), delivering 450 L ha^{-1} at 230 kPa. Florpyrauxifen-benzyl 3% emulsifiable concentrate (36 g ai ha^{-1}; Corteva Agriscience, Shanghai, China) was sprayed at 0, 7.5, 15, 30, 60, 120, 240, or 480 g ai ha^{-1}. Aboveground fresh weight was measured 21 d after herbicide applications. Each treatment was replicated four times, and the trial was repeated one additional time. Both trials were conducted between May and October 2023.

Data Analysis

Data from the two repeated trials were compared through ANOVA using SPSS software (v. 26.0). The data were pooled due to the nonsignificant interaction between the two repeated trials.

A four-parameter logistic function was fitted to test responses of fresh weight to herbicide treatments (Seefeldt et al. 1995), using the DRC add-on package in R 3.1.3 (Ritz and Streibig, 2005) as follows:

$$Y = d + (a - d)/[1 + (x/GR_50)^{\mathrm{b}}] \quad (1)$$

where Y denotes the fresh weight reduction response at dose x of the herbicide, a is the upper limit, d is the lower limit, GR_{50} is the dose of herbicide causing a 50% reduction in fresh weight, and b is the slope. Fresh weight reduction was generated using the fresh weights and then ranked within the different responses according to the method reported by Chen et al. (2023) as follows: 100% = no survival individual of the target weed species observed; 95%–99% = very good control efficacy with sporadic individuals of the target weed species; 85%–94% = acceptable control efficacy with an obvious decrease in weed occurrence compared with the control; 70%–84% = general control efficacy and not enough to control the target weed species; 60%–69% = certain control efficacy without commercial value; and <60% = poor control efficacy and thus offering no commercial value. Resistance factors (RFs) were calculated by dividing the GR_{50} value of each population by the most sensitive population to the herbicide. Using criteria reported by Beckie and Tardif (2012), populations were described as having no resistance (RF<2); low resistance (RF2–5); moderate resistance (RF6–10); and high resistance (RF>10).

The Shapiro-Wilk test was used to test for frequency distribution of GR_{50} values of florpyrauxifen-benzyl in Origin 2021 software. A Gaussian function was fitted to the baseline sensitivity to florpyrauxifen-benzyl of barnyardgrass as follows:

$$y = y_0 + \frac{A}{\left(\omega\sqrt{\frac{\pi}{2}}\right)} e^{-2\left(\frac{x - x_c}{\omega}\right)^2} \quad (2)$$

where y_0 is the offset, x_c is the center, ω is the width, and A is the area.

To compare significant differences in the average GR_{50} value for the 13 cities, least significant differences were used when variances were homogeneous, and Dunnett's T3 test was used if variances were not homogeneous. Correlation between the longitudes and latitudes of seed collection sites and GR_{50} values of barnyardgrass were determined with SPSS software using correlate analysis. To analyze the influence of environmental factors on the sensitivity of barnyardgrass, a general linear model was applied, where the GR_{50} value was the dependent variable, and independent variables including city, planting method, and subspecies of rice in locations where rice seeds were collected. The data presented are mean ± SE.

Results and Discussion

Sensitivity to Florpyrauxifen-Benzyl

Fresh weight reduction with a half-labeled (0.5×) dose of florpyrauxifen-benzyl (18 g ai ha^{-1}) ranged from 19.2% to 100%

https://doi.org/10.1017/wet.2025.3 Published online by Cambridge University Press

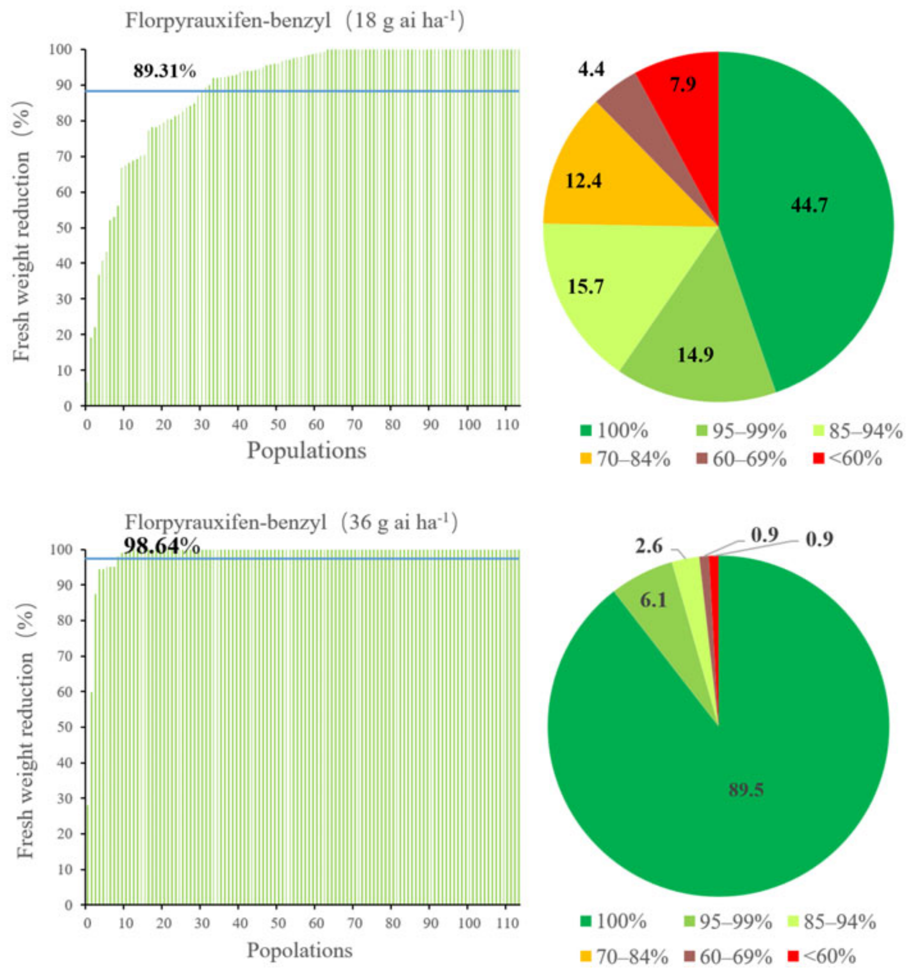


Figure 1. Control efficacy of florpyrauxifen-benzyl at different doses against 114 barnyardgrass populations. The blue horizontal lines represent the average fresh weight reduction of florpyrauxifen-benzyl to barnyardgrass populations. The pie chart represents six classes of control efficacy in 114 studied populations.

(89.3% on average) (Figure 1). Seedlings of 45% of the populations were completely killed, and 7.9% of the populations exhibited <60% fresh weight reduction. When the florpyrauxifen-benzyl dose increased to 36 g ai ha^{-1} (1× dose), fresh weight reduction ranged from 28.0% to 100% (98.6% on average). Seedlings of 90% of the populations were completely killed, and 98.6% of the populations showed fresh weight reductions of >85%. Only 0.9% of the populations showed fresh weight reductions of <60%.

Florpyrauxifen-benzyl provides excellent control of barnyardgrass in paddy fields despite being used for the past 5 yr. When using 1× florpyrauxifen-benzyl, a whole-plant bioassay indicated that the herbicide controlled 96% of the 114 populations with very good efficacy (fresh weight reduction >95%). Florpyrauxifen-benzyl was reported to be highly effective in controlling barnyardgrass that is demonstrating resistance to ACCase- or ALS-inhibiting herbicides or to quinclorac (Miller et al. 2018; Yang et al. 2022). Considering the 98.6% average fresh weight reduction among the total barnyardgrass populations evaluated, florpyrauxifen-benzyl was still an important rice herbicide in the area surveyed.

Baseline Sensitivity to Florpyrauxifen-Benzyl

The GR_{50} values of florpyrauxifen-benzyl ranged from 1.0 to 34.5 g ai ha^{-1} through 114 barnyardgrass populations (6.8 average, 4.6 median), and the average R^2 value was 0.90, and a value of > 0.80 for 99 populations (Table S1). All values were lower with 1× florpyrauxifen-benzyl (36 g ai ha^{-1}; Figure 2), and 107 out of 114 GR_{50} values of the populations were lower than those when the 0.5× dose of florpyrauxifen-benzyl was used. The GR_{50} values obtained were grouped into class intervals of 2 g ai ha^{-1} (Figure 3), with a baseline sensitivity dose of florpyrauxifen-benzyl of 3.3 g ai ha^{-1}, and a baseline sensitivity index of 34.5.Twenty-nine of the 114 populations exhibited GR_{50} values that were less than the baseline sensitivity dose.

The baseline sensitivity test was used primarily for determining the variation in sensitivity, and the baseline sensitivity value was a more practical parameter for baseline sensitivity (Wang et al. 2022). This study of 114 barnyardgrass populations collected from overall rice planting counties could be important data for reflecting the full view of the sensitivities of barnyardgrass to florpyrauxifen-benzyl in rice fields in Jiangsu Province. The baseline sensitivity dose of florpyrauxifen-benzyl could provide a reference base for studies on barnyardgrass that is resistant to florpyrauxifen-benzyl and for determining time-dependent changes in florpyrauxifen-benzyl sensitivity of barnyardgrass in rice paddy fields (Escorial et al. 2019).

Compared with the baseline sensitivity dose (2.53 g ai ha^{-1}) to florpyrauxifen-benzyl in Korea in 2021 (Lim et al. 2021), the baseline sensitivity dose (3.34 g ai ha^{-1}) of barnyardgrass in China

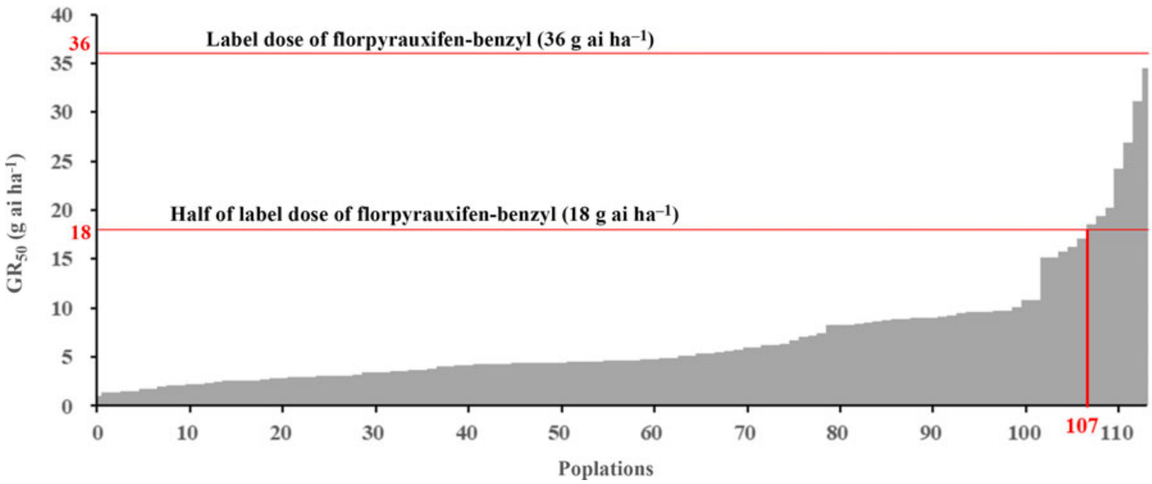
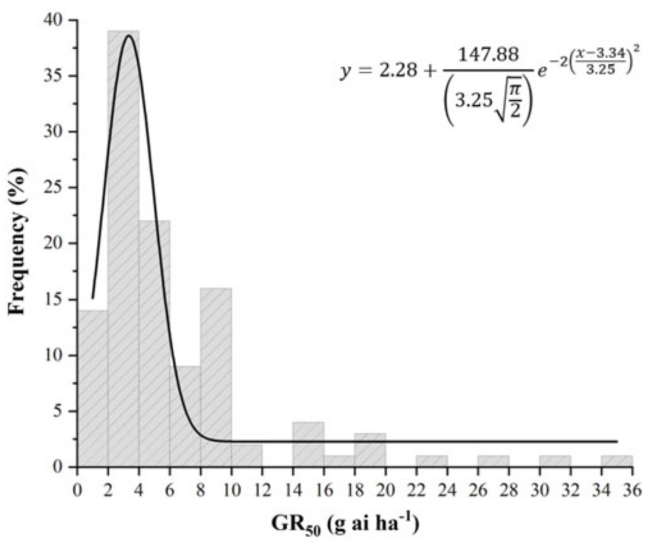


Figure 2. GR_{50} values of florpyrauxifen-benzyl against 114 barnyardgrass populations. The red horizontal lines represent the various doses of florpyrauxifen-benzyl. The red vertical line represents the number of populations.



$$y = 2.28 + \frac{147.88}{\left(3.25\sqrt{\frac{\pi}{2}}\right)} e^{-2\left(\frac{x-3.34}{3.25}\right)^2}$$

Figure 3. Frequency distribution of florpyrauxifen-benzyl doses that caused a 50% growth reduction (GR_{50}) in barnyardgrass populations. Individual isolates are grouped in class intervals of 2 g ai ha^{-1}.

in 2023 was slightly higher. In another *Echinochloa* rice weed species, Chen et al. (2024) and Gao et al. (2022) reported that the GR_{50} values of barnyardgrass that is susceptible to florpyrauxifen-benzyl were 4.2, and 4.1 g ai ha^{-1}, respectively. Therefore, the current baseline sensitivity dose of barnyardgrass could serve as a fixed sensitivity value in the study of barnyardgrass resistance to florpyrauxifen-benzyl.

The establishment of baseline sensitivity data was critical in managing fungicide resistance because the results can be used to illustrate shifts in pathogenic sensitivity and provide evidence that control failures occurring in the future can be correlated with the appearance of resistance in the population (Russel 2004; Veloukas and Karaoglanidis 2012). Baseline sensitivity is also applicable to weed resistance management. Subsequent surveys of weed sensitivity to herbicides on a regional scale will be necessary to prevent resistance evolution to the level at which control fails (Avenot and Michailides 2010). Systematically monitoring the baseline sensitivity of troublesome weeds to important herbicides is the basis for developing an early warning system for the market lifespan of herbicides.

Florpyrauxifen-Benzyl Resistance

Compared with the baseline sensitivity dose (3.3 g ai ha^{-1}), 63, 44, and 7 barnyardgrass populations had, respectively, no resistance (55%), low resistance (39%), and moderate resistance (6%) to florpyrauxifen-benzyl (Figure 4). Barnyardgrass populations in the southwest Jiangsu Province exhibited high resistance, especially populations with the highest proportion of low resistance collected from Suzhou (Table 1). However, the most resistant population (YC5, $GR_{50} = 34.5$ g ai ha^{-1}) was found in Yancheng.

Herbicide resistance is an inevitable problem in agricultural intensification due to its excessive use (Hulme, 2023; Owen, 2016). Developing an effective and feasible herbicide is a difficult process that takes a great deal of time and money (Rueegg et al. 2007). Additionally, herbicide resistance evolution is accelerating with their repeated use on cereal crops. Some populations of troublesome weeds might even show resistance to new herbicides that have never been used against them (Baucom 2019; Takano et al. 2023). Before the commercialization of florpyrauxifen-benzyl, barnyardgrass had evolved resistance to the herbicides quinclorac, penoxsulam, metamifop, and bispyribac-sodium, all of which are used to control weeds in rice production (Choudhary et al. 2023; Damalas and Koutroubas 2023; Xia et al. 2016). Thus, florpyrauxifen-benzyl resistance by barnyardgrass might be a result of multiple resistance being caused by applications of other rice herbicides (Takano et al. 2023).

The average GR_{50} values for florpyrauxifen-benzyl recorded from 13 cities ranged from 3.4 to 11.7 g ai ha^{-1}. Neither city, rice planting method (direct seeding or transplanting), or rice subspecies (*Oryza sativa* subsp. *japonica* or *O. sativa* subsp. *indica*) at the seed-collecting site showed any significant influences on the distributions of GR_{50} values (Table S2). The median GR_{50} values were consistent with the average value. Moreover, neither longitude nor latitude of the seed-collecting sites had any significant ($P > 0.05$) correlations with the GR_{50} value of tested populations (Figure S1), with low R^2 values of 0.026 and 0.006, respectively.

Barnyardgrass escaping chemical control in rice fields may be attributable to inappropriate agronomic practices, such as uneven

https://doi.org/10.1017/wet.2025.3 Published online by Cambridge University Press

Table 1. GR_{50} values and resistance factors of florpyrauxifen-benzyl for barnyardgrass collected from 13 cities.[a–c]

City	No. of populations	Florpyrauxifen-benzyl		
		GR_{50}	Median of GR_{50}	Proportion of resistance factors
		g ai ha^{-1}	g ai ha^{-1}	NR:LR:MR:HR
Huaian	8	3.4 ± 0.4 c	3.5	8:0:0:0
Lianyungang	9	3.9 ± 0.8 c	3.4	8:1:0:0
Changzhou	8	5.0 ± 0.7 bc	5.0	4:4:0:0
Xuzhou	8	5.4 ± 1.1 abc	5.4	4:4:0:0
Nanjing	6	5.7 ± 1.3 abc	4.3	4:2:0:0
Yangzhou	12	6.7 ± 2.5 abc	3.1	8:3:1:0
Suqian	14	6.0 ± 1.3 abc	4.3	10:3:1:0
Nantong	8	6.1 ± 0.9 abc	6.1	3:5:0:0
Taizhou	8	6.3 ± 1.8 abc	5.0	4:4:0:0
Wuxi	6	7.5 ± 2.5 abc	6.0	3:2:1:0
Zhenjiang	6	9.4 ± 3.5 abc	4.9	3:2:1:0
Suzhou	14	10.6 ± 1.8 ab	9.4	3:9:2:0
Yancheng	7	11.7 ± 3.9 a	8.8	7:3:1:0

[a]Abbreviations: NR, no resistance; LR, low resistance; MR, moderate resistance; HR, high resistance.
[b]Different letters in the same column indicate significant differences among 13 cities at $P < 0.05$, the maximum value noted letter a, compared in turn.
[c]GR_{50} represents the dose of herbicide that causes a 50% reduction in fresh weight.

land, failure to maintain flood depth, and inappropriate application of herbicides. Late-emerging weed seeds may avoid chemical control. Among 13 cities, barnyardgrass populations from Suzhou and Yancheng clearly exhibited higher median resistance; however, some other cities also contained high resistant populations. These results provide insight for producers to focus specific ways they can mitigate herbicide resistance.

Practical Implications

After 5 yr of florpyrauxifen-benzyl being used in Jiangsu province, China, the herbicide is still highly effective at controlling a majority of barnyardgrass populations. To date, florpyrauxifen-benzyl is an outstandingly useful herbicide in many rice planting areas worldwide. On the other hand, reports are beginning to reveal that barnyardgrass is beginning to show resistance to florpyrauxifen-benzyl (Chen et al. 2024;Hwang et al. 2022a; Yang et al. 2022). Additionally, 45% of the barnyardgrass populations showed resistance to this herbicide. Florpyrauxifen-benzyl had low efficacy against a few populations of barnyardgrass when it was applied at the 1× dose (36 g ai ha^{-1}). Hence, resistance to florpyrauxifen-benzyl could be a challenge if this herbicide continues to be used. Considering the serious resistance to ACCase- and ALS-inhibiting herbicides in *Echinochloa* weeds, the effectiveness of florpyrauxifen-benzyl against *Echinochloa* species is important for weed management in rice. Therefore, an integrative management approach to control weeds that are resistant to florpyrauxifen-benzyl should be implemented (Lim et al. 2021; Miller and Norsworthy 2018; Wang et al. 2021). For example, preemergence chemical control; agronomic measures that target the suppression of weed emergence such as deep tillage, crushing, and deep burying of previous crop straw; leveling planting areas; and removing panicles could also be useful (Chen et al. 2022).

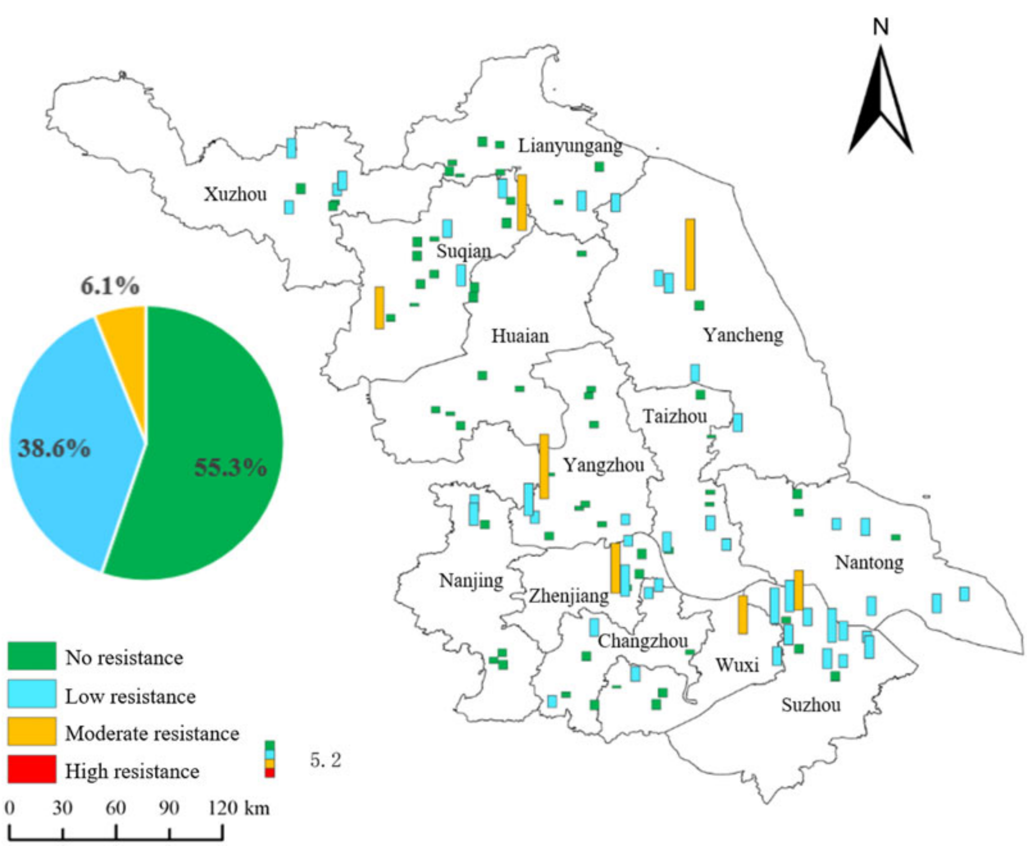


Figure 4. Distribution of resistance factors and resistance levels to florpyrauxifen-benzyl among 114 barnyardgrass populations. The pie chart represents the proportions of the four resistance levels.

https://doi.org/10.1017/wet.2025.3 Published online by Cambridge University Press

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2025.3

Acknowledgments. We thank Huang Zeyue and Xue Jiahao for their help with transplanting the seedlings and applying herbicides.

Funding. This study was funded by the Key Research Program of Shandong Province, China through agreement 2021LZGC020, by the Jiangsu Key R&D Plan via agreement BE2022338, and by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

Competing Interests. The authors declare they have no conflicts of interest.

References

Alberto AMP, Ziska LH, Cervancia CR, Manalo PA (1996) The influence of increasing carbon dioxide and temperature on competitive interactions between a C-3 crop, rice (*Oryza sativa*) and a C-4 weed (*Echinochloa glabrescens*). Aust J Plant Physiol 23:795–802

Avenot HF, Michailides TJ (2010) Progress in understanding molecular mechanisms and evolution of resistance to succinate dehydrogenase inhibiting (SDHI) fungicides in phytopathogenic fungi. Crop Prot 29: 643–651

Baucom RS (2019) Evolutionary and ecological insights from herbicide-resistant weeds: What have we learned about plant adaptation, and what is left to uncover? New Phytol 223:68–82

Beckie HJ, Tardif FJ (2012) Herbicide cross resistance in weeds. Crop Prot 35:15–28

Chauhan BS, Abugho SB (2013) Growth of *Echinochloa glabrescens* in response to rice cultivar and density. J Crop Improv 27:391–405

Chauhan BS, Johnson DE (2009) Seed germination ecology of junglerice (*Echinochloa colona*): A major weed of rice. Weed Sci 57:235–240

Chen G, An K, Chen Y, Zhuang X (2023) Double-spraying with different routes significantly improved control efficacies of herbicides applied by unmanned aerial spraying system: A case study with rice herbicides. Crop Prot 167:106503

Chen G, Chen Y, Yu H, Zhou L, Zhuang X (2022) Accumulated temperature requirements of *Echinochloa crus-galli* seed-setting: A case study with populations collected from rice fields. Weed Biol Manag 22:47–55

Chen G, Tang W, Li J, Lu Y, Dong L (2019) Distribution characteristics of *Echinocloa* species in rice fields in China: A case survey on 73 sites from nine provincial administrative regions. Chin J Rice Sci 33:368–376

Chen G, Zhuang X, Masoom A, Chen Y, Gu Y, Zhang J (2024) *Echinochloa crus-galli* seedlings surviving florpyrauxifen-benzyl applications have a greater potential to produce resistant seeds. Weed Technol doi: 10.1017/wet.2023.87

Choudhary VK, Reddy SS, Mishra SK, Gharde Y, Kumar S, Yadav M, Barik S, Singh PK (2023) First report on ALS herbicide resistance in barnyardgrass (*Echinochloa crus-galli*) from rice fields of India. Weed Technol 37:236–242

Damalas CA, Koutroubas SD (2023) Herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in global rice production. Weed Biol Manag 23:23–33

Delye C, Jasieniuk M, Le Corre V (2013) Deciphering the evolution of herbicide resistance in weeds. Trends Genet 29:649–658

Diop A, Moody K (1984) Effect of seeding depth and flooding regime on germination and growth of *Echinochloa glabrescens*. Phil J Weed Sci 11:65–69

Donayre DKM, Endino CA, Seville CU, Ciocon IMG (2014) Major weeds and farmers' weed management practices in rainfed ricefields of Negros Island, Philippines. Asia Life Sci 23:137–148

Escorial M-C, Chueca R-C, Perez-Fernandez A, Loureiro I (2019) Glyphosate sensitivity of selected weed species commonly found in maize fields. Weed Sci 67:633–641

Gao Y, Li J, Shen G, Tian Z (2022) Differences in the mode of action of florpyrauxifen-benzyl between barnyardgrass and yerbadetajo. Agronomy-Basel 12:2656

Hulme PE (2023) Weed resistance to different herbicide modes of action is driven by agricultural intensification. Field Crops Res 292:108819

Hwang JI, Norsworthy JK, Gonzalez-Torralva F, Piveta LB, Priess GL, Barber LT, Butts TR (2022a) Absorption, translocation, and metabolism of florpyrauxifen-benzyl and cyhalofop-butyl in cyhalofop-butyl-resistant barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]. Pestic Biochem Physiol 180:104999

Hwang JI, Norsworthy JK, González-Torralva F, Priess GL, Barber LT, Butts TR (2022b) Non-target-site resistance mechanism of barnyardgrass *Echinochloa crus-galli* (L.) P. Beauv. to florpyrauxifen-benzyl. Pest Manag Sci 78:287–295

Iwakami S, Uchino A, Watanabe H, Yamasue Y, Inamura T (2012) Isolation and expression of genes for acetolactate synthase and acetyl-CoA carboxylase in *Echinochloa phyllopogon*, a polyploid weed species. Pest Manag Sci 68:1098–1106

Li Q, Zhao N, Jiang MH, Wang ML, Zhang JX, Cao HQ, Liao M (2023) Metamifop resistance in *Echinochloa glabrescens* via glutathione *S*-transferases-involved enhanced metabolism. Pest Manag Sci 79:2725–2736

Lim S, Kim H, Noh T, Lim J, Yook M, Kim J, Yi J, Kim D (2021) Baseline sensitivity of *Echinochloa crus-galli* and *E. oryzicola* to florpyrauxifen-benzyl, a new synthetic auxin herbicide, in Korea. Front Plant Sci 12:656642

Miller MR, Norsworthy JK (2018) Florpyrauxifen-benzyl weed control spectrum and tank-mix compatibility with other commonly applied herbicides in rice. Weed Technol 32:319–325

Miller MR, Norsworthy JK, Scott RC (2018) Evaluation of florpyrauxifen-benzyl on herbicide-resistant and herbicide-susceptible barnyardgrass accessions. Weed Technol 32:126–134

Moss S (2001) Baseline sensitivity to herbicides: a guideline to methodologies. Pages 769–774 in Proceedings of the Brighton Crop Protection Conference. Brighton, UK, November 12–15, 2001.

Owen MDK (2016) Diverse approaches to herbicide-resistant weed management. Weed Sci 64:570–584

Ren X, Chai Y, Zhang Y, Xie K, Wang M, Guo J, Guo S (2023) Carbon footprint analysis of rice-wheat rotation system at county level: A case study of Xinghua, Jiangsu province. Soils and Fertilizers Sciences in China 4:67–75

Ritz C, Streibig JC (2005) Bioassay analysis using R. J Stat Softw 12:1–22

Rueegg WT, Quadranti M, Zoschke A (2007) Herbicide research and development: Challenges and opportunities. Weed Res 47:271–275

Russel P (2004) Sensitivity baselines in fungicide resistance research and management: FRAC Monograph No. 3.Brussels, Belgium: Fungicide Resistance Action Committee

Seefeldt SS, Jensen JE, Fuerst EP (1995) Log-logistic analysis of herbicide dose-response relationships. Weed Technol 9:218–227

Takano HK, Greenwalt S, Ouse D, Zielinski M, Schmitzer P (2023) Metabolic cross-resistance to florpyrauxifen-benzyl in barnyardgrass (*Echinochloa crus-galli*) evolved before the commercialization of Rinskor™. Weed Sci 71:77–83

Thomas A, Langston DB Jr, Stevenson KL (2012) Baseline sensitivity and cross-resistance to succinate-dehydrogenase-inhibiting and demethylation-inhibiting fungicides in *Didymella bryoniae*. Plant Dis 96:979–984

Veloukas T, Karaoglanidis GS (2012) Biological activity of the succinate dehydrogenase inhibitor fluopyram against *Botrytis cinerea* and fungal baseline sensitivity. Pest Manag Sci 68:858–864

Wang H, Li Y, Wang L, Liu W, Wang J (2022) Baseline sensitivity of *Echinochloa crus-galli* (L.) P. Beauv. to tripyrasulfone, a new HPPD-inhibiting herbicide, in China. Crop Prot 158:105993

Wang H, Sun X, Yu J, Li J, Dong L (2021) The phytotoxicity mechanism of florpyrauxifen-benzyl to *Echinochloa crus-galli* (L.) P. Beauv and weed control effect. Pestic Biochem Physiol 179:104978

Xia XD, Tang WJ, He S, Kang J, Ma HJ, Li JH (2016) Mechanism of metamifop inhibition of the carboxyltransferase domain of acetyl-coenzyme A carboxylase in *Echinochloa crus-galli*. Sci Rep 6:34066

Yan BJ, Zhang YH, Li J, Fang JP, Liu TT, Dong LY (2019) Transcriptome profiling to identify cytochrome P450 genes involved in penoxsulam resistance in *Echinochloa glabrescens*. Pestic Biochem Physiol 158: 112–120

Yang Q, Yang X, Zhu JL, Wei T, Lv M, Li YF (2022) Metabolic resistance to acetyl-CoA carboxylase-inhibiting herbicide cyhalofop-butyl in a Chinese *Echinochloa crus-galli* population. Agronomy-Basel 12:2724

Zhang Y, Wu M, Bao S, Li J, Liu D, Dong L, Li J (2023) Detection of resistance in *Echinochloa* spp. to three post-emergence herbicides (penoxsulam, metamifop, and quinclorac) used in China. Agronomy-Basel 13:841

Zhang YH, Gao HT, Fang JP, Wang H, Chen JY, Li J, Dong LY (2022) Up-regulation of bZIP88 transcription factor is involved in resistance to three different herbicides in both *Echinochloa crus-galli* and *E. glabrescens*. J Exp Bot 73:6916–6930

Zhu J, Wang J, DiTommaso A, Zhang C, Zheng G, Liang W, Islam F, Yang C, Chen X, Zhou W (2020) Weed research status, challenges, and opportunities in China. Crop Prot 134:104449

https://doi.org/10.1017/wet.2025.3 Published online by Cambridge University Press