Modeling Simultaneous Evolution of Barnyardgrass Resistance to Acetolactate Synthase (ALS)- and Acetyl Coenzyme A Carboxylase (ACCase)-Inhibiting Herbicides in Clearfield® Rice

M.V. Bagavathiannan, J.K. Norsworthy, K.L. Smith, and P. Neve

ABSTRACT

A simulation model was developed to: 1) understand the risk of acetolactate synthase (ALS)-inhibitor-resistant barnyardgrass under a worst-case management scenario in continuous Clearfield® rice, and 2) predict the simultaneous evolution of barnyardgrass resistance to ALS- and acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicides. The model was implemented using the STELLA® modeling software. For each weed management scenario, 1000 model runs were performed over a 30-year period. A population was considered to have evolved resistance when at least 20% of the seedbank consisted of resistant individuals. Under a sole application of ALS-inhibiting herbicides (three applications annually) in continuous Clearfield rice, resistance is predicted within only four years of adopting this program. Model predictions largely corroborate field observations in the mid-South rice production. Cyhalofop applied 14 d postflood helped reduce the risk of ALS-inhibitor resistance. Examination of the seedbank population, however, showed that the number of individuals with resistance to ACCase-inhibiting herbicides steadily increased under this program. When fenoxaprop was applied prior to flooding, the risk of ALS-inhibitor resistance was further reduced; however, there is a risk of simultaneously selecting for multiple resistance. Thus, selection for multiple resistance is possible in barnyardgrass to both ALS- and ACCase-inhibiting herbicides, particularly when ACCase-inhibiting herbicides are heavily relied upon in the Clearfield rice system. There is a need for more diversified barnyardgrass management programs that incorporate all possible herbicide and non-chemical strategies to ensure sustainable weed management in Clearfield rice.
INTRODUCTION

Barnyardgrass (Echinochloa crus-galli) is the prime weed in Arkansas rice fields and the evolution of barnyardgrass populations with resistance to a number of herbicide mechanisms of actions (MOAs) makes it challenging for growers to achieve effective, season-long control of this species. In Arkansas rice, barnyardgrass resistance has been confirmed for some of the major herbicides, including propanil (Carey et al., 1995), quinclorac (Lovelace et al., 2000), clomazone (Norsworthy et al., 2009), and imazethapyr (Wilson et al., 2010). The imazethapyr-resistant barnyardgrass populations also exhibit cross resistance to several other acetolactate synthase (ALS)-inhibitor herbicides such as imazamox, bispyribac, and penoxsulam (Wilson et al., 2010).

In the Clearfield rice production system, which has been widely adopted in the mid-South, barnyardgrass resistance to ALS-inhibiting herbicides is a growing concern. As a result, there is an increasing reliance on some of the acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicides such as fenoxaprop and cyhalofop for barnyardgrass control, ultimately increasing selection pressure on these herbicides. If barnyardgrass evolves resistance to the ACCase-inhibiting herbicides, it will be very challenging to control this species because few herbicide options are left to effectively manage barnyardgrass in rice. Specifically, pendimethalin and thiobencarb are the two other herbicide options available for barnyardgrass control in rice; these herbicides do not provide effective barnyardgrass control and not the ones on which a season-long barnyardgrass management program can be developed.

Thus, the prime management goals for barnyardgrass in mid-South Clearfield rice production system are: a) prevent further spread of ALS-inhibitor-resistant barnyardgrass, and b) prevent simultaneous evolution of resistance to ALS- and ACCase-inhibiting herbicides in barnyardgrass. The focus of this research was to address these management goals using a simulation modeling approach.

PROCEDURES

A mathematical model was developed using the visual programming language STELLA (version 9.1; iSee systems, Lebanon, N.H., USA). The general framework and approach of the model follows Neve et al. (2011), but this model is unique in that it simulates the simultaneous evolution of resistance to two herbicide MOAs. It is a stage-structured model with three distinct life-history stages: seeds, emerged seedlings, and mature plants. The model assumes that resistance is endowed by a single gene, completely dominant trait with Mendelian pattern of inheritance. Some variables were considered to be stochastic in nature, with field-to-field or season-to-season variations. Stochastic variables include: the initial frequency of resistance alleles, initial seedbank size, annual seedling emergence proportion, post-dispersal seed loss, and annual seed-bank loss. The model also accounts for demographic stochasticity when the population size reaches very low levels (<10 plants).

The model simulates resistance evolution in barnyardgrass across 1000 hypothetical rice production fields in Arkansas over a 30-year period. Resistance is considered
to have evolved if at least 20% of the seedbank consisted of resistant individuals for each resistance trait. Barnyardgrass emergence was predicted across three important rice growing regions in eastern Arkansas (Stuttgart, Monticello, and West Memphis), based on growing degree days calculated using historical weather data. Each rice field was considered to be 150 acres in size and it was assumed that barnyardgrass was evenly distributed within the field. Barnyardgrass emergence was categorized into five cohorts: cohort 1 (prior to planting on 1 May), cohort 2 (1 May to 14 May), cohort 3 (15 May to 31 May), cohort 4 (1 June to 14 June), and cohort 5 (15 June to 18 June). The final cohort accounts for the seedlings that emerge during the entire duration of flooding, which takes place six weeks after rice seeding.

Management interventions correspond to each cohort, and are timed as: at-plant (1 May), early-post (EPOST) (15 May), mid-POST (MPOST) (1 June), preflood (PREFLD) (15 June) and postflood (POSTFLD) (22 June). In the initial model analyses, three management programs were considered in a continuous Clearfield rice: 1) the worst-case program [tillage at planting followed by (fb) imazethapyr at EPOST fb imazethapyr at MPOST fb imazamox at 7 d POSTFLD]; 2) the worst-case program with cyhalofop [tillage at planting fb imazethapyr at EPOST fb imazethapyr at MPOST fb imazamox at 7 d POSTFLD fb cyhalofop 14 d POSTFLD]; and 3) the worst-case program with fenoxaprop [tillage at planting fb imazethapyr at EPOST fb imazethapyr at MPOST fb fenoxaprop PREFLD fb imazamox at 7 d POSTFLD]. Efficacies for the various management options were determined based on field observations in Arkansas rice production systems.

RESULTS AND DISCUSSION

Preliminary model outputs suggest that there is a high risk for the evolution of ALS-inhibitor-resistant barnyardgrass in the mid-South rice under the worst-case scenario consisting of three applications of imidazolinone herbicides in a continuous Clearfield rice. The model predicts resistance evolution in four years of adopting this program, with about 40% risk by year 10 (Fig. 1). Inclusion of cyhalofop at 14 d POSTFLD in the worst-case program is valuable in reducing the risks of ALS-inhibitor resistance to about 27% by year 10 (Fig. 2), and ACCase-inhibitor resistance does not evolve within the 30-year period. However, examination of the seedbank revealed that the number of ACCase-resistant individuals in the seedbank increased over time (Fig. 3), meaning that they are less likely to be lost from the seedbank. Application of fenoxaprop prior to flooding helps further reduce the risks of ALS-inhibitor-resistant barnyardgrass to about 14% by year 10, but the risks of resistance to ACCase inhibitors also increase by year 20. This can be attributed to the high efficacy of fenoxaprop when applied prior to flooding (on relatively smaller barnyardgrass seedlings), compared to cyhalofop applied at 14 d POSTFLD (as a salvage treatment on larger barnyardgrass plants). The results suggest that when barnyardgrass management heavily relies upon the two herbicide MOAs (ALS- and ACCase-inhibitors), the risks for multiple resistance is high. More diversified management programs, especially with the inclusion of suitable non-chemical strategies, are vital.
SIGNIFICANCE OF FINDINGS

An understanding of the risk of multiple resistance in barnyardgrass will help develop diverse weed management programs and thereby help preserve the long-term utility of available herbicide options in rice production.

ACKNOWLEDGMENTS

Funding for this research was provided by the Arkansas Rice Research and Promotion Board, USDA Southern-Region Integrated Pest Management Grant, BASF, Monsanto, Valent, Dow AgroSciences, Syngenta Crop Protection, and Bayer CropScience.

LITERATURE CITED

Fig. 1. Risk of barnyardgrass evolving resistance to acetolactate synthase-inhibiting herbicides under a worst-case management scenario in continuous Clearfield rice. The management program consists of tillage at planting followed by (fb) imazethapyr at early-post (EPOST) fb imazethapyr at mid-post (MPOST) fb imazamox at 7 d postflood (POSTFLD).
Fig. 2. Risk of simultaneous evolution of resistance to acetolactate synthase (ALS)- and acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicides in barnyardgrass: A) under a management program consisting of tillage at planting followed by (fb) imazethapyr at early-post (EPOST) fb imazethapyr at mid-post (MPOST) fb imazamox at 7 d postflood (POSTFLD) fb cyhalofop at 14 d postflood (POSTFLD) and B) under a program consisting of tillage at planting fb imazethapyr at EPOST fb imazethapyr at MPOST fb fenoxaprop PREFLD fb imazamox at 7 d POSTFLD.
Fig. 3. The number of acetyl coenzyme A carboxylase (ACCase)-resistant individuals in the seedbank under a management program consisting of tillage at planting followed by (fb) imazethapyr at early-post (EPOST) fb imazethapyr at mid-post (MPOST) fb imazamox at 7 d postflood (POSTFLD) fb cyhalofop at 14 d postflood (POSTFLD).