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Modeling shattercane dynamics in herbicide-tolerant grain sorghum cropping systems

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ABSTRACT

Traditional breeding technology is currently being used to develop grain sorghum [*Sorghum bicolor* (L.) Moench *ssp. bicolor*] germplasm that will be tolerant to acetolactate synthase (ALS)-inhibiting herbicides. This technology (Inzen^{TM}, DuPont^{TM}) has the potential to improve sorghum production by allowing for the postemergence control of traditionally hard-to-control grasses. However, grain sorghum and shattercane [weedy *Sorghum* species; *Sorghum bicolor* (L.) Moench *ssp. drummondii* (Nees ex Steud.) de Wet ex Davidse] can interbreed and introduced traits such as herbicide tolerance could increase the weediness of the weedy relative. Our objective was to develop a simulation model to assess management options to mitigate risks of ALS-resistance evolution in shattercane populations in US sorghum production areas. Assuming a single major gene confers resistance and gene frequencies change according to the Hardy-Weinberg ratios we constructed a stage-structured (seedbank, plants) matrix model with annual time steps. The model explicitly considered gene flow from Inzen plants to shattercane populations. The management strategies considered in the model were: a) continuous sorghum, b) sorghum followed by (*fb*) soybeans and c) sorghum *fb* fallow *fb* winter wheat, where postemergence ALS-inhibiting herbicides were only used in Inzen years. During sorghum years two options were tested: continuous Inzen and Inzen *fb* conventional sorghum, for a total of six management strategies. The parameter values used in the model were obtained from our research, the literature, and expert opinion. For each management strategy we ran deterministic and stochastic simulations (with stochastic levels of herbicide efficacy). The time for resistance evolution was predicted to decrease with increased cropping system complexity (more crop diversity than continuous production of Inzen). Evolution of resistance was predicted to occur rapidly if Inzen sorghum is planted continuously because of high selection pressure (ALS-inhibiting herbicide application) and crop-to-weed gene flow. Rotating Inzen with conventional sorghum did not assist with shattercane management. Rotating Inzen with non-sorghum crops where effective herbicide options are available assisted with keeping shattercane density at low levels while postponing resistance evolution to some extent. Crop and herbicide rotation will be key strategies for shattercane management in Inzen sorghum.

1. Introduction

Grain sorghum is economically ranked as the fifth most important cereal crop in the world after wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), corn (*Zea mays* L.), and barley (*Hordeum vulgare* L.), and is the third-most common cereal planted in the US, trailing corn and wheat (DeFelice, 2006; USDA-NASS, 2016). Sorghum is a warm season C4 grass species that is highly efficient in the conversion of solar energy and use of water. Sorghums are cultivated throughout the world for grain, fodder, syrup, and biofuel production. In the US, the crop is primarily used for livestock feed and is ranked second after corn for ethanol production (Paterson, 2008). In spite of the agronomic potential and food value of grain sorghum, the number of acres of sorghum production has declined in many parts of the US (USDA-NASS, 2016), in part because the number of herbicide options for weed management in sorghum is limited. Most post-emergence herbicides labeled for grain sorghum are effective on broadleaf weed species but have only limited activity on annual grasses. Consequently, soil applied herbicides are the primary option for annual grass control in grain sorghum (Hennigh et al., 2010). However, grain sorghum is often grown in dry environments and the absence of adequate soil moisture often reduces

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the activation and efficacy of soil applied herbicides (Hennigh et al., 2010).

Acetolactate synthase (ALS)-inhibiting herbicides, also known as acetohydroxyacid synthase (AHAS)-inhibitors, are commonly used to control grass weeds in certain broadleaf and grass crops (Hennigh et al., 2010). However, conventional grain sorghum is susceptible to ALS-inhibiting herbicides that have grass activity. In 2004, a shattercane population exhibiting resistance to ALS-inhibiting herbicides was identified in Kansas. Using conventional breeding, a project was then initiated by scientists at Kansas State University with the objective to introgress the ALS-resistant gene from the shattercane population into grain sorghum germplasm and ultimately commercialize grain sorghum varieties with tolerance to ALS-inhibiting herbicides (Tuinstra and Al-Khatib, 2008). DuPont® has acquired the license of the ALS-inhibiting herbicide tolerance trait from Kansas State University and has branded the technology as 'Inzen'. Nicosulfuron (Zest™; herbicide in the sulfonylurea family), an effective active ingredient for the control of weedy annual grasses, is the herbicide intended to be labeled for the technology. The ALS-tolerant grain sorghum varieties are expected to be on the market in 2017 (Saunders D. W. and K. L. Carlson, personal communication). This technology has the potential to improve weed control options in grain sorghum production by allowing for post-emergence control of grass weeds (Hennigh et al., 2010). Moreover, the technology has strong potential to increase the use of grain sorghum in crop rotations and expand its production in environments where grain sorghum is better adapted than corn, but where corn is typically cultivated because of the availability of more herbicide options.

Despite the potential of the Inzen technology, the co-existence of sympatric weedy relatives poses some threats to its adoption and potential lifespan. The main concerns are i) crop-to-weed gene flow that would increase the frequency of the ALS-resistance allele in sympatric weedy populations, ii) the difficulty of controlling weeds that are already ALS-resistant and iii) selection for additional resistant biotypes due to overreliance on the technology. Shattercane is a troublesome weedy sorghum in agronomic crops in the USA, especially in grain sorghum production (Hans and Johnson, 2002; Kegode and Pearce, 1998). Shattercane is a wild sorghum relative with many similarities to grain sorghum. Shattercane and grain sorghum are both diploid ($2n = 2x = 20$), sexually compatible, and may be cross-pollinated by wind, which can result in hybridization where flowering synchrony occurs (DeFelice, 2006; Sahoo et al., 2010; Schmidt et al., 2013). Thus, there is apparently no barrier to prevent the transfer of nuclear alleles from sorghum to shattercane (Sahoo et al., 2010; Schmidt et al., 2013). Sahoo et al. (2010) reported that shattercane x sorghum hybrids had similar ecological fitness to the wild-type parents with respect to several metrics (i.e., biomass and seed production). This indicates that any neutral or beneficial trait would likely persist in the weedy relative infesting agricultural fields, even in the absence of selection.

Due to the lack of new herbicide sites-of-action and increased reports of herbicide-resistant weeds, resistance management has become the most concerning topic in the field of Weed Science (Heap, 2016; Norsworthy et al., 2012). Simulation models of weed genetics and population dynamics have been developed to predict herbicide resistance evolution over time and have provided valuable insight on understanding the risks of resistance evolution and the importance of diversified strategies for delaying and managing herbicide-resistance (Bagavathiannan et al., 2013, 2014; Gressel and Segel, 1978; Jasieniuk and Maxwell, 1994; Maxwell et al., 1990; Neve et al., 2011a,b; Renton et al., 2011). These models have focused on genetics and dynamics of species that are not related to crops. To our knowledge, no risk assessment model has been developed to explore population genetics and dynamics in response to several management strategies where a weedy relative poses a threat to the adoption of a novel herbicide tolerant crop because of pollen-mediated gene flow, which may certainly expedite resistance evolution in the weedy relative.

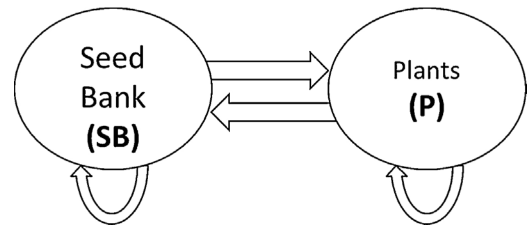

Fig. 1. Annual weed life cycle graph. The arrows indicate the transition rates between seedbank and plant stages.

Risk assessment models provide a means to compare management strategies without the need for long-term and often, impractical field studies (Neve, 2008). They also provide valuable insight in areas where genetic, biological, and ecological knowledge is lacking and indicate where future research efforts should be focused. In the era of genetically modified crops, whether developed by genetic engineering or conventional breeding, risk assessment models have become a valuable tool to support regulatory agencies with their decisions and policies, and industry with their stewardship programs.

We expect that continuous production of herbicide-tolerant sorghum will result in rapid fixation of the resistance allele in shattercane populations because crop-to-weed pollen-mediated gene flow and high selection pressure will favor individuals carrying the resistance trait. Since crop and herbicide rotation are claimed as important strategies to postpone evolution of resistance (Neve, 2008; Norsworthy et al., 2012), our working hypothesis is that more diversified management strategies will lead to more stable cropping systems where evolution of resistance will occur more slowly and population density of the weedy relative will remain at tolerable levels. Thus, our objective was to develop a simulation model to assess management options to mitigate risks of ALS-resistance evolution in shattercane populations in US sorghum production areas where the Inzen technology is likely to be adapted after its commercial deployment. We anticipate that our model will provide valuable insight on resistance management in Inzen sorghum technology and can also be used for risk assessment of novel traits in grain sorghum and other crops that have weedy relatives (e.g., rice [*Oryza sativa* L.], sunflowers [*Helianthus annuus* L.]).

2. Methods

2.1. Model description

We constructed a density dependent, stage-structured matrix model with annual time steps (Caswell, 2001). We assumed weed plants to be at pre-flowering stage at population census (pre-breeding census) and seed production and shattering to take place afterwards. The core structure of our model was based on: i) weed demography, ii) genetics and inheritance of the resistance trait, and iii) crop and weed management strategies. The model accounted for two stage classes: viable weed seeds in the seedbank (SB) and established weed plants (P). In our model, surviving seeds that did not germinate remained seeds in SB (SB → SB), and surviving seeds that germinated became P (SB → P). Surviving plants (P) produced seeds. The newly produced seeds that did not germinate before the next population census were added to SB (P → SB), and those that did geminate were added to P (P → P, Fig. 1).