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SHORT REPORT

Competitiveness of herbicide-resistant and herbicide-susceptible kochia (*Kochia scoparia* [L.] Schrad.) under contrasting management practises

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INTRODUCTION

Worldwide, herbicide resistance has been identified in the biotypes of 183 species, including 24 that are resistant to synthetic auxins (Heap 2006). This represents a serious problem for growers who rely mainly on chemical methods for weed control, particularly when alternative control options are unfeasible or non-existent (Maxwell *et al.* 1990). Herbicide resistance also can alter the ecological fitness attributes of the resistant biotypes (Tranel & Wright 2002), such as growth and competitive ability, thereby affecting the population dynamics and frequency of resistant biotypes within farm fields (Maxwell *et al.* 1990; Vila-Aiub *et al.* 2005).

Initially, herbicide resistance was thought to be associated mainly with a cost to ecological fitness, suggesting that upon the cessation of herbicide selection pressure, the proportion of resistant to susceptible individuals within a population should decrease (Maxwell *et al.* 1990; Holt & Thill 1994; Tranel & Wright 2002). However, it has become increasingly apparent that the relative impacts of herbicide resistance on fitness attributes can vary with the weed species, mechanism of resistance, and environmental context (Weaver & Warwick 1982; Schonfeld *et al.* 1987; Christoffoleti *et al.* 1997; Tranel & Wright 2002; Goss & Dyer 2003; Sibony & Rubin 2003). Thus, understanding the fitness level consequences of herbicide resistance under varying management practises has important implications for the development of predictive models of resistant population persistence and spread and the development of effective weed management strategies (Maxwell *et al.* 1990).

Kochia (*Kochia scoparia* [L.] Schrad.), also known as fireweed, belvedere, burning bush, railroad weed or summer cypress, was first introduced to the USA in the early 1900s as an ornamental plant from Eurasia (Undersander *et al.* 1990). Although it has been grown as a drought-resistant forage crop, this annual plant is a particularly problematic weed in small grain-cropping systems in North America. Kochia is drought-tolerant, has a deep taproot, and its branched stem can grow to a height of almost 2.5 m, making this species an effective competitor for light, nutrients, and soil moisture. Additionally, kochia can produce thousands of seeds per plant and is able to spread these seeds long distances very quickly due to its ability to disperse (as a "tumbleweed") during windstorms.

Although non-chemical methods exist, the management of kochia is achieved mainly with the help of herbicides (Ball & Miller 1990; Blackshaw 1990). As a result of the increased selective pressure, biotypes of kochia resistant to either acetolactate synthase inhibitors, Photosystem II inhibitors, or synthetic auxins, are now present in 16 states in the USA, Canada, and the Czech Republic (Heap 2006).

Previous studies of the ecological fitness consequences of herbicide resistance in kochia suggest that the fitness attributes of resistant biotypes are comparable to (Thompson *et al.* 1994; Christoffoleti *et al.* 1997), or greater than (Dyer *et al.* 1993), those of the susceptible biotypes. This suggests that the release of herbicide-resistant biotypes from herbicide selection pressure might

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not necessarily result in decreased frequencies of resistant individuals over time (Maxwell *et al.* 1990). However, most studies of kochia fitness have been conducted in the greenhouse and under uncompetitive conditions, constraining our ability to make generalizations regarding the relative fitness of herbicide-resistant biotypes and, hence, the probability of the persistence and spread of resistant biotypes under realistic field situations.

The objective of this study was to assess the ecological fitness of three kochia biotypes (two resistant to synthetic auxins and one susceptible to synthetic auxins) under contrasting management practises in the field. Specifically, we sought to: (i) assess whether differences in the fitness components of growth and relative competitive ability exist between the susceptible and resistant biotypes; and (ii) determine the impact of crop and nitrogen (N) addition, and their interaction on kochia fitness under field conditions.

MATERIALS AND METHODS

The study was conducted at the Montana State University Arthur H. Post Agricultural farm near Bozeman, MT, USA (45°47′N, 111°9′W). The soils at the site were an Amsterdam silty clay loam (fine–silty, mixed, superactive, frigid typic Haplustolls, 0–4% slopes) composed of 12% sand, 53% silt, 33% clay, with 2% organic matter and a pH of 7.4 (Holman *et al.* 2004). The mean annual temperature and precipitation at the site were 6.4°C and 41.6 cm, respectively.

The relative fitness of three kochia biotypes was assessed in a replacement series experiment under contrasting wheat (present/absent) and N (added/none) management. The biotypes were dicamba (3,6-dichloro-2-methoxybenzoic acid) (resistant) (HRd), fluroxypyr ([(4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy]acetic acid) (resistant) (HRdf), and susceptible (S). Both dicamba (benzoic acid) and fluroxypyr (pyridine carboxylic acid) are synthetic auxin herbicides that inflict plant mortality by mimicking the plant growth regulator, auxin. The HRd biotype was derived from an agricultural field population in north-central Montana that had been treated with dicamba for several successive years (Cranston *et al.* 2001). The HRdf biotype was derived from a different field population that had been treated with fluroxypyr, dicamba or both and exhibited slight cross-resistance to dicamba (2-fold) (Dyer *et al.* 2001; Goss & Dyer 2003). The seeds used in this study were obtained from plants that had been subjected to multiple generations of recurrent selection in the greenhouse with dicamba or fluroxypyr, as described in Cranston *et al.* (2001). The S biotype was derived from a field population in south-central Montana that had not been treated with any herbicides for at least 50 years (Dyer W., 2006, personal communication). The seeds from the S biotypes were obtained from plants grown under pollen isolation conditions for multiple generations in the greenhouse.

The treatments were applied following a split-plot design, with the wheat and N treatments (whole plots) applied randomly within four blocks in a fully factorial structure. In early May 2004, spring wheat (*Triticum aestivum* L. var. Scholar; MSU-Arthur Post Research Farm, Bozeman, MT, USA) was double disc-drilled at 67.3 kg ha^{-1} to a depth of 5 cm in rows spaced 30.5 cm apart. A compound fertilizer (N: phosphorus, P: potassium; 25:10:10) was applied by hand at a rate of 280 kg ha^{-1} 1 day prior to wheat planting.

The whole-plot treatments (measuring 3.7 m × 22 m) were split into five randomly applied biotype treatments (measuring 3.7 m × 3.7 m). The biotype treatments consisted of populations made up of dicamba-resistant individuals only (HRd), fluroxypyr-resistant individuals only (HRdf), susceptible individuals only (S), half susceptible and half dicamba-resistant individuals (HRdS), and half susceptible and half fluroxypyr-resistant individuals (HRdfS).

The biotype treatments were established ≈ 1 week after planting the wheat. The seeds of either the susceptible, resistant or a 50–50 mix of susceptible and resistant biotypes were planted into the central portion of each 3.7 m × 3.7 m subplot. The seeds were planted 30.5 cm apart using a grid template; in the HRdS and HRdfS treatments, every other seed was a resistant or susceptible individual. Over the 3 weeks following sowing, kochia seedlings were regularly thinned to a final target density of 25 regularly spaced individuals per subplot. The control of other broadleaf and grass weeds was performed in mid-June with clodinafop ([2*R*]-2-[4-([5-chloro-3-fluoro-2-pyridinyl]oxy)phenoxy)propanoic acid) and bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) at the rates recommended for the region. The kochia seedlings were covered with plastic rain gutters during herbicide applications to prevent injury.

The ecological fitness of the kochia biotypes, as well as the impacts of the wheat and fertilizer on the kochia biomass, was assessed by determining the biomass of the individual kochia plants in each of the five biotype treatments. The mean individual biomass was determined in September 2004 by harvesting at least five randomly chosen individuals from each subplot. In the HRdS and

HRdfS treatments, five resistant and five susceptible individuals were harvested. The harvested individuals were dried to a constant biomass and weighed to the nearest 0.01 g.

Differences in the individual biomass among the kochia biotypes and the effects of wheat and N on the mean individual biomass production were analyzed with ANOVA using the MIXED procedure of SAS (Little *et al.* 1996). The treatment means were further analyzed with a protected Least Significant Difference test at $P < 0.05$. The biomass data were log-transformed prior to analysis to increase homoscedasticity. The untransformed data are presented in all the tables and figures.

RESULTS

The presence of wheat had a strong suppressive effect on the kochia biomass (ANOVA: $F_{1,9} = 612$, $P < 0.0001$). The individual biomass of the kochia averaged 283.5 g in the treatments without wheat compared to 1.6 g in the treatments with wheat (Fig. 1). In contrast to wheat, there was no effect of the fertilizer addition (ANOVA: $P = 0.571$) on the kochia biomass. All interactions between the wheat, fertilizer, and biotype on the individual kochia biomass were insignificant (ANOVA: $P > 0.05$).

The relative fitness of the susceptible biotypes, as measured by the mean individual biomass growing in a monoculture and in a mixture with HRd or HRdf biotypes, was unaffected by competition (ANOVA: $P = 0.961$). However, the fitness of these susceptible biotypes did vary dramatically with the wheat treatment (ANOVA: $F_{1,9} = 595$, $P < 0.0001$) (Fig. 2). There was no discernable difference in the relative fitness in either the HRd (ANOVA: $P = 0.794$) or HRdf (ANOVA: $P = 0.285$) biotypes when grown with other resistant individuals or in a mixture with the susceptible biotype (Table 1).

DISCUSSION

This field study suggests that the selection for resistance for two synthetic auxin chemistries, dicamba (HRd) and fluroxypyr (HRdf), in kochia is not associated with a

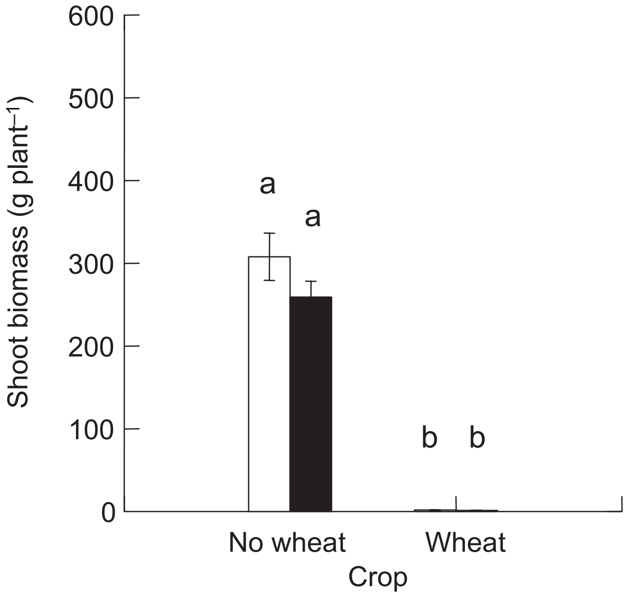

Fig. 1. Effects of wheat and fertilizer application on the above-ground biomass of *Kochia scoparia*. The data are the means pooled over the biotype treatments ± standard error; $n = 40$. The bars sharing the same letter are not significantly different at the $P = 0.05$ level, Least Significant Difference test. (□), no fertilizer; (■), fertilizer added.

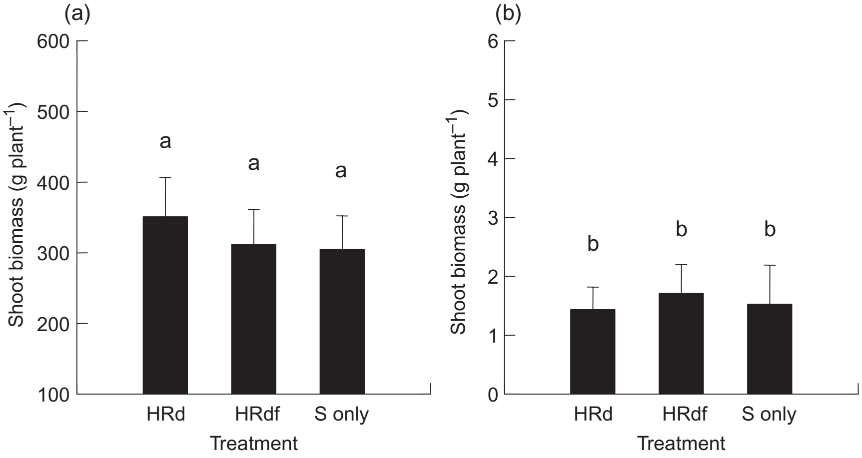

Fig. 2. Relative fitness of susceptible *Kochia scoparia* grown in a monoculture and in a mixture with two resistant biotypes in (a) the absence of wheat and (b) the presence of wheat. The data are the means pooled across the fertilizer treatments ± standard error; $n = 8$. The bars sharing the same letter are not significantly different at the $P = 0.05$ level, Least Significant Difference test. HRd, resistant to dicamba (mixture); HRdf, resistant to fluroxypyr (mixture); S, susceptible.

Table 1. Shoot biomass of resistant *Kochia scoparia* grown with other resistant individuals (mono) or in a mixture (mix) with susceptible individuals

Biotype†	No wheat (g plant^{-1})		Wheat (g plant^{-1})	
	Mono	Mix	Mono	Mix
No fertilizer				
HRd	264.96 ± 76.03	230.99 ± 59.82	1.01 ± 0.07	1.30 ± 0.49
HRdf	287.16 ± 52.10	329.35 ± 48.46	3.18 ± 1.33	0.64 ± 0.14
Fertilizer added				
HRd	265.64 ± 43.66	250.27 ± 45.11	1.56 ± 0.52	1.88 ± 0.97
HRdf	221.87 ± 51.93	242.62 ± 29.42	1.14 ± 0.47	0.98 ± 0.05

† Resistant biotypes: HRd, resistant to dicamba; HRdf, resistant to fluroxypyr. The data are the means ± standard error; *n* = 4.

detectable fitness cost in terms of relative competitive ability. This result has important implications for resistance management in kochia, as it suggests that in the absence of additional management practises, the HRd and HRdf biotypes might be able to persist within an otherwise susceptible population despite the relaxation of herbicide selection pressures. These results are consistent with other studies of kochia showing a lack of a direct fitness cost associated with herbicide resistance (Dyer *et al.* 1993; Thompson *et al.* 1994; Christoffoleti *et al.* 1997). Also, because this study was conducted under field conditions, these findings suggest that the results derived in greenhouse studies may have applicability to field situations.

One strategy for managing herbicide-resistant weeds involves manipulating the competitive pressure by using or rotating highly competitive crops to increase the rate of recovery of the susceptible population (Maxwell *et al.* 1990). Our results suggest that wheat is highly competitive with both the resistant and susceptible biotypes of kochia and can greatly reduce individual kochia biomass. Thus, the rotation of wheat or another highly competitive crop into a system with resistant kochia could be an effective strategy for reducing the fitness of resistant, as well as susceptible biotypes, and thereby their frequency within the farm field. However, the fact that kochia remains a problem weed in small grain-cropping systems in North America suggests that other factors, such as the emergence time relative to crop planting (Hock *et al.* 2006), probably also influence kochia fitness and should be incorporated into an integrated resistant weed management strategy.

The lack of a fertilizer effect on kochia growth and competitive ability was somewhat surprising, but suggests that fertilizer application is unlikely to be a useful tool for management of resistant kochia populations. In other studies, the effect of fertilizer on weed abundance has been shown to vary depending on the source, application method, and environmental context (Blackshaw 2005). For example, the addition of N, but not P, increased the relative abundance of kochia in disturbed rangelands (McLendon & Redente 1991). On a saline prairie soil in Canada, the addition of N fertilizer resulted in a curvilinear yield response in the aboveground kochia biomass (Steppuhn *et al.* 1994). In contrast, in a wheat cropping system, the kochia abundance decreased with the addition of N due to increased crop competitiveness (Anderson *et al.* 1998). Any effects of the fertilizer on kochia fitness in our study might have been obscured by the strong suppressive effect of wheat competition. However, the lack of a fertilizer effect in the treatments without wheat suggests that the kochia abundance was not limited by nutrients in this study. Additional studies will be required to determine the role of nutrient management on resistant kochia fitness under a range of environmental conditions and identify alternative management practises that can be incorporated into the integrated management of resistant weed species.

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