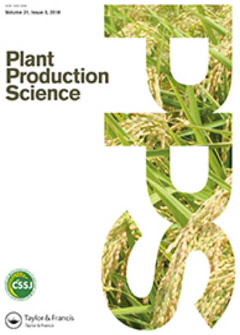

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Interaction of foramsulfuron or nicosulfuron with 2,4-D + MCPA on important broadleaf weeds in corn (*Zea mays* L.)

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ABSTRACT

Interaction of binary mixture of the two sulfonylurea herbicides: foramsulfuron or nicosulfuron with 2,4-D + MCPA, was evaluated in greenhouse experiments during 2010 and 2011 applying the additive dose model. Plants of redroot pigweed, common lambsquarters, common purslane and black nightshade were sprayed with seven doses of herbicides alone and in binary fixed-ratio mixtures. In total, 35 binary mixtures were studied in 7 separate experiments at ED_{90} response level. Results indicated that mixture of foramsulfuron + 2,4-D + MCPA was synergistic on redroot pigweed compared to additive interaction between nicosulfuron and 2,4-D + MCPA. Mixture of foramsulfuron + 2,4-D + MCPA was slightly antagonistic on common lambsquarters and an additive interaction was observed with both foramsulfuron and nicosulfuron + 2,4-D + MCPA on common purslane. Finally, the mixture of foramsulfuron or nicosulfuron + 2,4-D + MCPA on black nightshade was antagonistic especially in mixtures where the ratio of sulfonylurea herbicides was more than 2,4-D + MCPA. Totally, 2,4-D + MCPA in mixture with sulfonylurea herbicides especially foramsulfuron provided better control of redroot pigweed in comparison with herbicides applied alone and other herbicide mixtures on weeds.

Abbreviations: 2,4-D + MCPA: ((2,4-Dichlorophenoxy) acetic acid plus (4-chloro-2-methylphenoxy) acetic acid); ADM: additive dose model; a.i.: active ingredient; ALS: acetolactate synthase; DAT: days after treatment; ED: effective dose; Foramsulfuron: (2-(*N*-((4,6-dimethoxypyrimidin-2-yl) carbamoyl)sulfamoyl)-4-formamido-*N*,*N*-dimethylbenzamide); Nicosulfuron: (2-[(4,6-dimethoxypyrimidin-2-yl)carbamoylsulfamoyl]-*N*,*N*-dimethylpyridine-3-carboxamide).

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Introduction

A few herbicides have been registered for broadleaf weeds control in corn (*Zea mays* L.) in Iran. Currently, herbicides used for weeds control include preplant incorporated application of atrazine plus alachlor, ethyl dipropylthiocarbamate (EPTAM) and postemergence application of 2,4-D plus MCPA (Hadizadeh, Alimoradi, & Fereidoonpour, 2006; Mousavi, 2001). Foramsulfuron and nicosulfuron are sulfonylurea herbicides inhibiting acetolactate synthase (ALS); the first enzyme in the pathway in the biosynthesis of branched-chain amino acids; valine, leucine and isoleucine in chloroplasts (Rao, 2000). These herbicides control many grass and some broadleaf weeds in corn, but they control grasses and sedges better than broadleaf weeds. Hence, it is better to mix these herbicides with other broadleaf herbicides by different site of action to achieve broad-spectrum weed control. The synthetic auxin herbicides like 2,4-D + MCPA have been widely used in monocotyledonous crops for many years and effectively control a broad spectrum of broadleaf weeds in corn fields of Iran. Studies have shown that synthetic auxin herbicides like 2,4-D complement ALS-inhibitor herbicides for POST broadleaf weed control (Hart, 1997; Isaacs, Wilson, & Toler, 2002; Kalnay, Glenn, & Phillips, 1995; Parks, Curran, Roth, Hartwig, & Calvin, 1995). Nevertheless, previous research has demonstrated that herbicides may interact before or after entering the plants and the outcome of the interaction can be synergistic, additive or antagonistic (Hatzios & Penner, 1985; Olson & Nalewaja, 1981). It would be ideal to select herbicide combinations that have synergistic effects on weeds and/or antagonistic effects on crops (Schuster, Al-Khatib, & Dille, 2008). Synergistic herbicidal activity has the potential to reduce cost and the amount of pesticides entering the environment (Kudsk & Mathiassen, 2004; Streibig & Jensen, 2000). For example, common ragweed (*Ambrosia artemisiifolia* L.) control was improved when dicamba was

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added to rimsulfuron plus thifensulfuron-methyl (Himmelstein & Durgy, 1996; Kalnay & Glenn, 1997, January). Similarly, tank mixtures of nicosulfuron with dicamba improved hemp dogbane (*Apocynum cannabinum* L.) control compared to either herbicide applied alone (Glenn & Anderson, 1993; Glenn, Phillips, & Kalnay, 1997; Ransom & Kells, 1998). Preliminary research with metsulfuron-methyl + 2,4-D has shown good control of palmer amaranth (*Amaranthus palmeri* S. Wats.), redroot pigweed [*Amaranthus retroflexus* (L.)], velvetleaf (*Abutilon theophrasti* Medik.) and ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.] (Regehr, 1997). However, tank-mixing herbicide does not always result in the effective control of weeds; for instance, studies have shown that interactions between herbicides in tank-mix can be antagonistic (Zhang, Hamill, & Weaver, 1995). Mathiassen and Kudsk (1993) observed extreme antagonism at the ED_{50} and ED_{90} response levels for foliar applied mixtures of chlorsulfuron or metsulfuron-methyl and MCPA, similar to dimethylamine salts on chickweed [*Stellaria media* (L.) Vill.]. In another study, common lambsquarters [*Chenopodium album* (L.)] control was reduced when imazamox was tank-mixed with lactofen (Nelson, Renner, & Penner, 1998).

Many models exist for predicting interaction of mixtures of two or more herbicides (Streibig & Jensen, 2000). One widely used reference model is the additive dose model (ADM) assuming additivity of doses, i.e. one herbicide can be replaced wholly or in part by another herbicide at equivalent biological dose rate (Green & Streibig, 1993). Therefore, we evaluated interaction of sulfonylurea herbicides and 2,4-D + MCPA to achieve effective control of problematic broadleaf weeds in corn and strengthening the power of this herbicide group against weeds. In the present study, we examined the joint action of binary mixtures of foramsulfuron or nicosulfuron with 2,4-D + MCPA, applying ADM as reference model, on four important broadleaf weeds.

Materials and methods

Plant material

Seven greenhouse experiments were conducted during 2010 and 2011 at the Agricultural Faculty, Ferdowsi University of Mashhad, Iran (36° 15′ N, 59° 28′ E; 985 m altitude). The research greenhouse of the faculty of Agriculture with an area of 1100 sq. m consists of 16 independent units (60 sq. m each) made by the Netherlands (glass and aluminum have been used to make this greenhouse; actual light transmittance and radiation level in the greenhouse was about 84–87% of available visible light). The greenhouse is equipped with an intelligent meteorological system and each greenhouse unit can be controlled and programmed in terms of temperature, relative humidity, carbon dioxide, light and irrigation. Dose–response experiments were conducted with foramsulfuron (Equip, OD 2.25%; 45 g a.i. ha^{-1} with the safener isoxadifen-ethyl), nicosulfuron (Accent, SC 4%; 80 g a.i. ha^{-1}) and 2,4-D + MCPA (U46 Combi Fluid as premix, SL 67.5%; 1012.5 g a.i. ha^{-1}) at four to six-true leaf stage on redroot pigweed, common lambsquarters, common purslane [*Portulaca oleracea* (L.)] and black nightshade [*Solanum nigrum* (L.)]. Weed seeds were collected from corn fields and planted into 200 multicell plant trays (length 54 cm, width 28 cm and depth 4.2 cm) filled with black sphagnum white peat produced by Terracult company in 300 L bag containing all necessary nutrients (NPK fertilizer 14-16-18 + microelements: 0.5 kg/m^3; total nitrogen: 70 mg/L; phosphate: 80 mg/L; potassium: 90 mg/L; EC 0.5–0.8 mS/cm and a pH of 5.5–6.5). Seedlings were transferred to 1 L plastic pots (top diameter 13 cm, base diameter 10 cm and height 11 cm) at two-leaf stage. Plants grown in greenhouse conditions having a light/dark period of 16/8 h with temperatures maintained at 24/18°C and 45/65% for relative humidity (temperature accuracy of ±0.5°C for −20°C to +50°C, and relative humidity accuracy of ±5% for −20°C to +60°C, 0–95% relative humidity noncondensing). Natural sunlight was supplemented with metal halide lamps producing 16 h of photoperiod. To supplement natural sunlight and to extend the day length was used lamp light (400 W, Vialox® Nav®-T High-Pressure Sodium Vapor Lamp, Osram Co., Germany) with amount of illumination 2250 lx. At two to four-true leaf stage, plants with uniform height were selected and thinned to three plants per pot for greenhouse studies. The soil texture was silt loam (19.8% sand, 20.1% clay, 56% silt, 4.1% organic matter and a pH of 6.7) and was sterilized at 180°C for 2.5 h. A commercial fertilizer with 60 ml of a solution containing 20:20:20 (N:P:K) at concentration of 300 g of fertilizer L^{-1} of tap water was used to supply nutrients as needed by the plants (each pot was fertilized corresponding to 60 kg ha^{-1} of NPK) and the soil moisture was kept near field capacity.

Herbicide application

Weeds were sprayed at four to six-true leaf stage using a greenhouse bench sprayer equipped by 8002 single nozzle with an even spray pattern delivering 200 L ha^{-1} at 300 kPa and boom height of 50 cm. Weed plants were sprayed with seven dose of 2,4-D + MCPA (50.625, 101.25, 202.5, 405, 607.5, 810 and 1012.5 g a.i. ha^{-1}), foramsulfuron (2.25, 4.5, 9, 18, 27, 36 and 45 g a.i. ha^{-1}) and nicosulfuron (4, 8, 16, 32, 48, 64 and 80 g a.i. ha^{-1}) either applied alone. ED_{90} doses of sulfonylurea herbicides and 2,4-D + MCPA applied alone were provided as published paper in *International Journal of Plant Production* (Sarabi, Ghanbari, Rashed Mohassel, Nassiri Mahallati, & Rastgoo, 2014). Based on joint action model calculations, the adjusting ratio of the herbicides in binary mixtures and maximum herbicide doses used for foramsulfuron + 2,4-D + MCPA were 66:34 (38.94 + 20.06 g a.i. ha^{-1}), 43:57 (37.84 + 50.16 g a.i. ha^{-1}), 17:83 (33.83 + 165.17 g a.i. ha^{-1}) and 6:94 (271 + 423 g a.i. ha^{-1}) to 3:97 (20.25 + 654.75 g a.i. ha^{-1}) and for nicosulfuron + 2,4-D + MCPA were 69:31 (63.51 + 28.53 g a.i. ha^{-1}), 47:53 (60.93 + 68.71 g a.i. ha^{-1}), 21:79 (54.11 + 203.53 g a.i. ha^{-1}) and 7:93 (35.79 + 475.56 g a.i. ha^{-1}) to 3:97 (21.54 + 696.54 g a.i. ha^{-1}) on redroot pigweed. The adjusting ratio of the herbicides in binary mixtures and maximum herbicide doses used for foramsulfuron + 2,4-D + MCPA were 66:34 (43.11 + 22.21 g a.i. ha^{-1}), 43:57 (41.54 + 55.07 g a.i. ha^{-1}), 17:83 (35.93 + 175.44 g a.i. ha^{-1}) and 6:94 (27.87 + 436.57 g a.i. ha^{-1}) to 2:98 (13.68 + 670.44 g a.i. ha^{-1}) on common lambsquarters. Nicosulfuron did not control common lambsquarters sufficiently in preliminary experiments and hence, binary mixture experiments were not done between this herbicide and 2,4-D + MCPA. The adjusting ratio of the herbicides in binary mixtures and maximum herbicide doses used for foramsulfuron + 2,4-D + MCPA were 73:27 (98.68 + 36.5 g a.i. ha^{-1}), 52:48 (93.68 + 86.48 g a.i. ha^{-1}), 25:75 (80.1 + 240.31 g a.i. ha^{-1}) and 9:91 (51.48 + 520.55 g a.i. ha^{-1}) to 4:96 (30.45 + 730.82 g a.i. ha^{-1}) and for nicosulfuron + 2,4-D + MCPA were 73:27 (108.22 + 40.03 g a.i. ha^{-1}), 53:47 (103.39 + 91.69 g a.i. ha^{-1}), 25:75 (84.38 + 253.13 g a.i. ha^{-1}) and 10:90 (58.53 + 526.73 g a.i. ha^{-1}) to 4:96 (30.92 + 741.98 g a.i. ha^{-1}) on common purslane. Finally, the adjusting ratio of the herbicides in binary mixtures and maximum herbicide doses used for foramsulfuron + 2,4-D + MCPA were 70:30 (74.21 + 31.81 g a.i. ha^{-1}), 49:51 (71.69 + 74.61 g a.i. ha^{-1}), 22:78 (61.36 + 217.56 g a.i. ha^{-1}) and 8:92 (42.63 + 490.26 g a.i. ha^{-1}) to 3:97 (22.01 + 711.68 g a.i. ha^{-1}) and for nicosulfuron + 2,4-D + MCPA were 74:26 (122.23 + 42.94 g a.i. ha^{-1}), 54:46 (115.59 + 98.46 g a.i. ha^{-1}), 27:73 (97.29 + 263.03 g a.i. ha^{-1}) and 10:90 (60.63 + 545.65 g a.i. ha^{-1}) to 5:95 (39.24 + 745.64 g a.i. ha^{-1}) on black nightshade. To produce ED_{90} doses of the herbicides in the mixture, we just dilute the maximum doses. The adjusting ratios of the herbicides in binary mixtures and herbicides doses used for weeds control were included in Tables 1–4, too. Experiments were conducted as a randomized complete block design with seven doses of each herbicide and herbicide mixtures and four replicates of each treatment. Visual control ratings were recorded 14 and 28 days after treatments (DAT). The scale used for injury percent ranged from 0% (no visible injury) to 100% (complete death), a protocol approved by the Weed Science Society of America. Then, all aboveground plant parts were cut 4 weeks after spraying and oven-dried at 70° C for 48 h and weighed.

Visual control ratings data were subjected to ANOVA using Minitab ver. 17.1.0 statistical software. The assumptions of the variance analysis were tested by ensuring that the residual was random, homogeneous, and with a normal distribution about a mean of zero using residual plots and the Anderson–Darling normality test. Means were separated using Fisher's least significant difference test set at a 0.01 significance threshold.

Dose–response models

The dose–response curves for each herbicide applied alone or in binary fixed-ratio mixture were fitted simultaneously within each experiment using a four parameter log-logistic model available in the drc package in R:

$$U_{ij} = \frac{D - C}{1 + \exp[b_i(\log(z_{ij}) + 1.099/b_i - \log(ED_{90(i)}))]} + C \quad (1)$$

where U_{ij} denotes the aboveground dry matter at the jth dose of herbicides preparation *i*. *D* and *C* denote the upper and lower limit of aboveground dry matter at zero and large doses. $ED_{90(i)}$ denotes the dose of herbicides preparation *i* required to reduce aboveground dry matter 90% between the upper and lower limit, *D* and *C*; and b_i is proportional to the slope around $ED_{90(i)}$. In most experiments, the assumption that $C = 0$ was not rejected by a test for lack of fit; hence, a three parameter model was used:

$$U_{ij} = \frac{D}{1 + \exp[b_i(\log(z_{ij}) + 1.099/b_i - \log(ED_{90(i)}))]} \quad (2)$$

A Box–Cox transform-both-sides approach was performed to achieve variance homogeneity. The goodness of fit was assessed by graphical analyses of residuals and *F*-test for lack of fit (Ritz & Streibig, 2005).

Joint action model

Assuming that Z_A and Z_B are the doses of herbicide A (2,4-D + MCPA) and B (foramsulfuron or nicosulfuron) producing for example a 90% effect, i.e. the ED_{90} doses when applied singly, the relative potency between the herbicides is

Table 1. Control percentages of redroot pigweed based on visual control ratings in fixed-ratio binary mixtures of foramsulfuron or nicosulfuron + 2,4-D + MCPA at the 4–6-true leaf stage in the greenhouse experiments.

	Foramsulfuron + 2,4-D + MCPA				Nicosulfuron + 2,4-D + MCPA		
		14 DAT	28 DAT			14 DAT	28 DAT
Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)		Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)	
Weedy check	–	0	0	Weedy check	–	0	0
66:34	5.28 + 2.72	19	31	69:31	9.1 + 4.07	51	63
	11.22 + 5.78	44	69		18.13 + 8.15	55	64
	16.5 + 8.5	78	89		27.2 + 12.22	59	69
	21.78 + 11.22	89	96		36.27 + 16.29	63	78
	27.72 + 14.28	73	89		45.33 + 20.37	74	80
	33 + 17	84	98		54.4 + 24.44	74	86
	38.94 + 20.06	79	96		63.51 + 28.53	75	84
43:57	5.59 + 7.41	24	40	47:53	8.71 + 9.82	28	43
	10.75 + 14.25	34	58		17.41 + 19.63	56	63
	16.34 + 21.66	39	79		26.11 + 29.45	59	65
	21.5 + 28.5	45	88		34.82 + 39.26	66	80
	27.09 + 35.91	65	93		43.52 + 49.1	73	90
	32.25 + 42.75	90	99		52.23 + 58.89	75	94
	37.84 + 50.16	91	99		60.93 + 68.71	75	89
17:83	4.76 + 23.24	30	64	21:79	7.72 + 29.07	34	58
	9.69 + 47.31	38	75		15.46 + 58.14	45	66
	14.45 + 70.55	63	95		23.18 + 87.22	58	70
	19.38 + 94.62	75	96		30.91 + 116.29	66	79
	24.14 + 117.86	89	96		38.64 + 145.36	76	88
	28.9 + 141.1	84	91		46.37 + 174.43	74	89
	33.83 + 165.17	91	100		54.11 + 203.53	83	98
6:94	3.84 + 60.16	25	45	7:93	5.11 + 67.94	49	63
	7.74 + 121.26	49	86		10.23 + 135.87	60	73
	11.58 + 181.42	84	95		15.34 + 203.81	60	75
	15.42 + 241.58	88	100		20.45 + 271.75	71	86
	19.26 + 301.74	90	98		25.57 + 339.68	73	85
	23.16 + 362.84	95	100		30.68 + 407.62	79	91
	27 + 423	98	99		35.79 + 475.56	86	99
3:97	2.88 + 93.12	49	84	3:97	3.08 + 99.50	64	71
	5.79 + 187.21	78	95		6.15 + 199.01	65	78
	8.67 + 280.33	94	100		9.23 + 298.51	74	84
	11.58 + 374.42	85	98		12.31 + 398.01	76	88
	14.46 + 467.54	99	100		15.39 + 497.51	81	91
	17.37 + 561.63	95	100		18.46 + 597.02	86	91
	20.25 + 654.75	98	100		21.54 + 696.54	88	96
LSD (1%)	–	13.73	12.44	LSD (1%)	–	7.66	8.88

Note: Visual control ratings of redroot pigweed were made 14 and 28 days after treatment (DAT).

$$R = \frac{Z_A}{Z_B} \quad (3)$$

Because of expected ED_{90} doses of the sulfonylurea herbicides are several times lower (in g a.i. ha^{-1}) than 2,4-D + MCPA, then we calculated the adjusting ratios by using the following equation:

$$P = \frac{(R - R^{\theta})}{(R - 1)} \quad (4)$$

where θ is the ratio of the herbicides in binary mixtures and R is relative potency. Therefore, the expected potency of each mixture can be calculated using the following equation:

$$R_m = P + R(1 - P) \quad (5)$$

If e.g. R_m was 10, then we considered the maximum dose in mixture 10 times lower than the maximum dose of 2,4-D + MCPA.

The ADM graphs were constructed by plotting the ED_{90} doses of each of herbicides of the binary mixture on the *x*- and *y*-axes and connecting them with a straight line. The straight line represents the ADM isoboles of predicted responses. The observed ED_{90} doses were plotted on the graph and compared to the ADM isoboles. Points above the isoboles indicate that the joint action of a mixture is lower than predicted by ADM, while points below the isoboles indicate a joint action higher than predicted by ADM (Kudsk & Mathiassen, 2004).

No generally accepted procedure exists for testing statistically significant deviations from ADM. In the present study, we examined whether the predicted ED_{90} doses of the herbicide mixture were contained in the 95% confidence interval of the estimated ED_{90} doses. This approach inevitably overestimates the number of significant deviations because it does not incorporate a variation around the isobole. Significant deviations were termed antagonism if higher and synergism if lower than the corresponding estimated ED_{90} doses. As the results

Table 2. Control percentages of common lambsquarters based on visual control ratings in fixed-ratio binary mixtures of foramsulfuron + 2,4-D + MCPA at the 4–6-true leaf stage in the greenhouse experiments.

	Foramsulfuron + 2,4-D + MCPA		
		14 DAT	28 DAT
Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)	
Weedy check	–	0	0
66:34	6.16 + 3.17	14	20
	12.32 + 6.34	38	39
	18.47 + 9.52	44	53
	24.63 + 12.69	46	56
	30.79 + 15.86	50	68
	36.95 + 19.03	46	76
	43.11 + 22.21	58	85
43:57	5.93 + 7.87	35	40
	11.87 + 15.73	43	59
	17.8 + 23.6	48	60
	23.74 + 31.46	53	61
	29.67 + 39.33	51	63
	35.61 + 47.2	55	68
	41.54 + 55.07	54	79
17:83	5.13 + 25.06	40	43
	10.26 + 50.12	50	55
	15.4 + 75.17	51	58
	20.53 + 100.23	50	59
	25.66 + 125.29	54	66
	30.79 + 150.35	58	71
	35.93 + 175.44	58	83
6:94	3.98 + 62.36	44	53
	7.96 + 124.72	50	55
	11.94 + 187.1	56	68
	15.92 + 249.44	53	64
	19.9 + 311.8	60	87
	23.88 + 374.16	65	89
	27.87 + 436.57	75	91
2:98	1.96 + 95.78	51	59
	3.91 + 191.55	55	66
	5.86 + 287.33	53	68
	7.82 + 383.1	60	74
	9.77 + 478.88	61	85
	11.73 + 574.63	71	93
	13.68 + 670.44	81	98
LSD (1%)	–	5.88	8.9

Note: Visual control ratings of common lambsquarters were made 14 and 28 days after treatment (DAT).

with the herbicide mixtures originate from up to seven separate experiments, it was necessary to standardize the *x*- and *y*-axes so that the ED_{90} doses of the herbicides applied separately were always fixed to 1 (Kudsk & Mathiassen, 2004).

Results

In total, 35 different binary mixtures of foramsulfuron or nicosulfuron with 2,4-D + MCPA in 7 separate experiments were studied on redroot pigweed (2 experiments), common lambsquarters (1 experiment), common purslane (2 experiments) and black nightshade (2 experiments).

Visual control ratings (%)

Sulfonylurea herbicides mixture with 2,4-D + MCPA leads to chlorosis and epinasty of the leaves and petioles, bending and twisting, tissue swelling and bursting of weed stems, especially in mixtures where the 2,4-D + MCPA mixture ratio was a much more higher than sulfonylurea herbicides. Plant stem internodes were shortened by increasing herbicide doses, which resulted in reduced plant height. In addition, lignifications were observed at the base of stems, especially in mixtures where the sulfonylurea herbicides mixture ratio was higher in a mixture with 2,4-D + MCPA. Black nightshade also indicated purple spots at the leaf surface.

Redroot pigweed was the most susceptible to foramsulfuron + 2,4-D + MCPA between the weed species tested. Results indicated that the weed was controlled up to 90% at lower doses in the fixed-ratio binary mixtures. Tank mixing nicosulfuron with 2,4-D + MCPA was not as great as foramsulfuron + 2,4-D + MCPA. However, nicosulfuron + 2,4-D + MCPA adequately controlled redroot pigweed up to 90% at maximum doses 28 DATs (Table 1). Foramsulfuron + 2,4-D + MCPA did not adequately control (up to 90%) the growth of common lambsquarters where the foramsulfuron mixture ratio was higher in a mixture based on visual control ratings (Table 2). Based on visual control ratings, we could not find any preference of the foramsulfuron or nicosulfuron in mixture with 2,4-D + MCPA on common purslane and could not conclude that one is better than the other (Table 3). Finally, tank mixing nicosulfuron with 2,4-D + MCPA by the 5:95, 10:90 and 27:73 mixture ratios controlled black nightshade better than foramsulfuron + 2,4-D + MCPA by the 3:97, 8:92 and 22:78 mixture ratios, while tank mixing foramsulfuron with 2,4-D + MCPA by the 49:51 and 70:30 mixture ratios controlled black nightshade better than nicosulfuron + 2,4-D MCPA by the 54:46 and 74:26 mixture ratios (Table 4).

Foramsulfuron: 2,4-D + MCPA mixtures

Mixture ratios were well distributed along the isobole using redroot pigweed as test plant and all observations were located below the isobole indicating that the estimated doses of mixtures were significantly lower than the ones predicted according to ADM. Three of the five mixture ratios (6:94, 17:83 and 43:57) were significantly more effective than predicted by ADM and two mixture ratios (3:97 and 66:34) did not deviate from ADM. Overall, the results suggest that the mixture of foramsulfuron and 2,4-D + MCPA responded synergistically on redroot pigweed (Table 5 and Figure 1(A)).

Similar to redroot pigweed, foramsulfuron + 2,4-D + MCPA mixture ratios were also well distributed along the isobole using common lambsquarters as test plant. However, mixture ratios tended to be

Table 3. Control percentages of common purslane based on visual control ratings in fixed-ratio binary mixtures of foramsulfuron or nicosulfuron + 2,4-D + MCPA at the 4–6-true leaf stage in the greenhouse experiments.

	Foramsulfuron + 2,4-D + MCPA				Nicosulfuron + 2,4-D + MCPA		
		14 DAT	28 DAT			14 DAT	28 DAT
Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)		Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)	
Weedy check	–	0	0	Weedy check	–	0	0
73:27	14.1 + 5.21	60	64	73:27	15.45 + 5.72	40	41
	28.19 + 10.43	68	70		30.91 + 11.43	46	48
	42.29 + 15.64	66	71		46.36 + 17.15	44	44
	56.39 + 20.85	66	70		61.82 + 22.86	56	56
	70.48 + 26.07	69	76		77.27 + 28.58	60	71
	84.58 + 31.28	76	84		92.72 + 34.3	61	80
	98.68 + 36.5	69	85		108.22 + 40.03	65	79
52:48	13.38 + 12.35	58	71	53:47	14.77 + 13.09	56	55
	26.76 + 24.7	55	65		29.53 + 26.19	63	63
	40.14 + 37.1	55	70		44.3 + 39.28	64	70
	53.52 + 49.4	60	74		59.06 + 52.38	63	74
	66.9 + 61.75	79	85		73.83 + 65.47	60	75
	80.28 + 74.1	81	86		88.59 + 78.57	64	75
	93.68 + 86.48	86	90		103.39 + 91.69	73	91
25:75	11.44 + 34.33	54	64	25:75	12.1 + 36.16	63	65
	22.89 + 68.66	49	63		24.11 + 72.32	68	73
	34.33 + 102.98	66	78		36.16 + 108.47	69	75
	45.77 + 137.31	75	90		48.21 + 144.63	71	71
	57.21 + 171.64	75	95		60.26 + 180.79	73	84
	68.66 + 205.97	86	100		72.32 + 216.95	83	95
	80.1 + 240.31	90	99		84.38 + 253.13	79	98
9:91	7.36 + 74.39	60	79	10:90	8.36 + 75.24	69	69
	14.71 + 148.71	61	86		16.72 + 150.48	68	79
	22.06 + 223.07	75	99		25.08 + 225.72	63	95
	29.42 + 297.42	91	100		33.44 + 300.96	75	98
	36.77 + 371.78	94	100		41.8 + 376.2	79	98
	44.12 + 446.14	91	100		50.16 + 451.44	83	100
	51.48 + 520.55	94	100		58.53 + 526.73	86	100
4:96	4.35 + 104.4	59	80	4:96	4.42 + 105.99	65	65
	8.7 + 208.8	83	98		8.83 + 211.99	61	65
	13.05 + 313.2	88	100		13.25 + 317.98	70	83
	17.4 + 417.6	98	100		17.67 + 423.97	70	95
	21.75 + 522	100	100		22.08 + 529.97	80	100
	26.1 + 626.4	96	100		26.5 + 635.96	89	100
	30.45 + 730.82	100	100		30.92 + 741.98	93	100
LSD (1%)	–	12.33	12.04	LSD (1%)	–	11.1	13.75

Note: Visual control ratings of common purslane were made 14 and 28 days after treatment (DAT).

located along the upper part of the isobole. A better distribution of the responses would have been obtained if mixtures with a higher ratio of 2,4-D + MCPA to foramsulfuron had been included in the experiment. At the ED_{90} response level, all mixtures except one (2:98 mixture ratio) were located above the isobole indicating that the responses of the mixtures were less than predicted by ADM. Overall, the estimated ED_{90} doses of two of the five mixture ratios (2:98 and 6:94) did not deviate significantly from the assumption of additivity of doses, while three of the five mixture ratios (17:83, 43:57 and 66:34) were significantly higher than predicted by ADM (Table 5 and Figure 1(B)).

Foramsulfuron and 2,4-D + MCPA mixture ratios were not evenly distributed along the isobole using common purslane as test plant. At the ED_{90} response level, three of the five observations (25:75, 52:48 and 73:27) were located along the upper part of the isobole. In total, mixture ratios all performed according to the assumption of additivity (Table 6 and Figure 2(A)). This indicates that mixture of foramsulfuron + 2,4-D + MCPA on common purslane followed ADM. Mixtures with higher foramsulfuron ratios predominantly tended to be located outside the isobole using black nightshade as test plant. However, estimated ED_{90} doses tended to be closer to the isobole by lower ratios of foramsulfuron. At the ED_{90} response level, three of five mixture ratios (8:92, 49:51 and 70:30) were located significantly outside the isobole, whereas the remaining two observations (3:97 and 22:78) did not deviate from ADM based on 95% confidence interval. In general, foramsulfuron in mixture with 2,4-D + MCPA indicated slightly antagonism when foramsulfuron mixture ratios were higher than that of 2,4-D + MCPA (Table 7 and Figure 2(B)).

Nicosulfuron: 2,4-D + MCPA mixtures

At the ED_{90} response level, three of five observations (3:97, 21:79 and 69:31) were located outside

Table 4. Control percentages of black nightshade based on visual control ratings in fixed-ratio binary mixtures of foramsulfuron or nicosulfuron + 2,4-D + MCPA at the 4–6-true leaf stage in the greenhouse experiments.

	Foramsulfuron + 2,4-D + MCPA				Nicosulfuron + 2,4-D + MCPA		
		14 DAT	28 DAT			14 DAT	28 DAT
Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)		Mixture ratios	Total herbicide dose (g a.i. ha^{-1})	Control (%)	
Weedy check	–	0	0	Weedy check	–	0	0
70:30	10.6 + 4.54	11	15	74:26	17.46 + 6.13	6	6
	21.2 + 9.08	24	43		34.91 + 12.27	7	9
	31.8 + 13.63	40	51		52.37 + 18.4	18	19
	42.4 + 18.17	38	53		69.83 + 24.53	23	26
	52.99 + 22.71	40	60		87.28 + 30.67	30	31
	63.59 + 27.3	55	74		104.74 + 36.8	50	63
	74.21 + 31.81	56	74		122.23 + 42.94	45	65
49:51	10.24 + 10.66	13	18	54:46	16.5 + 14.06	8	9
	20.48 + 21.32	19	31		33.02 + 28.12	6	7
	30.72 + 31.98	49	51		49.52 + 42.19	24	26
	40.96 + 42.64	59	65		66.03 + 56.25	36	38
	51.21 + 53.3	56	60		82.54 + 70.31	49	61
	61.45 + 63.96	61	71		99.05 + 84.37	45	63
	71.69 + 74.61	64	80		115.59 + 98.46	61	73
22:78	8.76 + 31.08	19	31	27:73	13.9 + 37.57	10	10
	17.53 + 62.15	31	40		27.79 + 75.15	26	26
	26.29 + 93.23	43	49		41.69 + 112.72	40	40
	35.06 + 124.3	51	60		55.59 + 150.29	59	76
	43.82 + 155.38	65	70		69.48 + 187.87	68	94
	52.59 + 186.45	64	75		83.38 + 225.44	80	98
	61.36 + 217.56	75	90		97.29 + 263.03	88	100
8:92	6.09 + 70.03	16	21	10:90	8.66 + 77.95	14	16
	12.18 + 140.06	39	41		17.32 + 155.9	36	38
	18.27 + 210.09	63	84		25.98 + 233.85	59	75
	24.36 + 280.12	60	83		34.64 + 311.8	71	100
	30.45 + 350.15	63	85		43.31 + 389.75	69	98
	36.54 + 420.18	83	95		51.97 + 467.7	76	100
	42.63 + 490.26	86	95		60.63 + 545.65	79	100
3:97	3.14 + 101.67	19	26	5:95	5.61 + 106.51	28	29
	6.29 + 203.33	40	50		11.21 + 213.03	48	48
	9.43 + 304.99	53	68		16.82 + 319.54	75	93
	12.58 + 406.66	68	79		22.42 + 426.06	81	100
	15.72 + 508.33	61	79		28.03 + 532.57	79	100
	18.87 + 609.99	66	81		33.64 + 639.08	81	100
	22.01 + 711.68	70	84		39.24 + 745.64	84	100
LSD (1%)	–	11.35	14.6	LSD (1%)	–	7.64	10.32

Note: Visual control ratings of black nightshade were made 14 and 28 days after treatment (DAT).

the isobole of the nicosulfuron + 2,4-D + MCPA using redroot pigweed as test plant, whereas the remaining two mixtures (7:93 and 47:53) were located lower than the isobole. Overall, none of the mixture ratios did deviate from ADM (Table 5 and Figure 3(A)). In summary, foramsulfuron + 2,4-D + MCPA was more synergistic than that of nicosulfuron + 2,4-D + MCPA on redroot pigweed. All observations were distributed more evenly along the isobole when nicosulfuron applied in tank-mix with 2,4-D + MCPA compared to foramsulfuron + 2,4-D + MCPA using common purslane as test plant (Table 6 and Figure 3(B)). At the ED_{90} response level, four of five mixture ratios (4:96, 25:75, 53:47 and 73:27) were located outside the isobole and one (10:90 mixture ratio) was located on the isobole, but none of observations did deviate significantly from ADM suggesting that nicosulfuron + 2,4-D + MCPA on common purslane followed ADM. Finally, the mixture ratios were all well distributed along the isobole when nicosulfuron applied in tank-mix with 2,4-D + MCPA on black nightshade, but all mixture ratios had ED_{90} doses that were significantly higher than predicted by ADM, and in this light, the results clearly indicate that nicosulfuron in mixture with 2,4-D + MCPA responded antagonistically on black nightshade (Table 7 and Figure 3(C)).

Discussion

Redroot pigweed control increased when sulfonylurea herbicides tank-mixed with 2,4-D+ MCPA compared to these herbicides applied alone. Similarly, Brown, Al-Khatib, Regehr, Stahlman and Loughin (2004) reported that metsulfuron-methyl applied alone provided 45–60% and 68–79% control of ivyleaf morningglory and velvetleaf, respectively, but the control improved when metsulfuron was tank-mixed with 2,4-D, fluroxypyr and dicamba. In

Table 5. Dose–response parameters of the log-logistic model for either the herbicides applied alone or fixed-ratio binary mixtures of foramsulfuron or nicosulfuron with 2,4-D plus MCPA on redroot pigweed and common lambsquarters at the 4–6-true leaf stage.

Herbicide	Mixture ratio	Upper limit (d)	Curve slope (b)	ED_{90}
Redroot pigweed				
Foramsulfuron	100:0	2.58[1] (0.1)[2]	0.92 (0.12)	23.51[3] (3.5)
Foramsulfuron + 2,4-D plus MCPA	66:34	2.54 (0.16)	0.64 (0.06)	20.76 + 10.69 (2.92 + 1.51)
Foramsulfuron + 2,4-D plus MCPA	43:57	2.53 (0.16)	0.74 (0.06)	17.47 + 23.15 (2.13 + 2.83)
Foramsulfuron + 2,4-D plus MCPA	17:83	2.55 (0.16)	0.70 (0.05)	12.66 + 61.80 (1.61 + 7.87)
Foramsulfuron + 2,4-D plus MCPA	6:94	2.58 (0.15)	0.71 (0.04)	7.77 + 121.75 (0.94 + 14.76)
Foramsulfuron + 2,4-D plus MCPA	3:97	2.55 (0.16)	0.79 (0.05)	6.84 + 221.25 (0.78 + 25.17)
Nicosulfuron	100:0	2.59 (0.1)	0.76 (0.08)	63.81 (8.59)
Nicosulfuron + 2,4-D plus MCPA	69:31	2.58 (0.1)	1.08 (0.06)	65.21 + 29.30 (5.18 + 2.33)
Nicosulfuron + 2,4-D plus MCPA	47:53	2.56 (0.14)	1.28 (0.06)	48.29 + 54.46 (3.04 + 3.43)
Nicosulfuron + 2,4-D plus MCPA	21:79	2.56 (0.15)	0.48 (0.05)	56.63 + 213.02 (10.75 + 40.45)
Nicosulfuron + 2,4-D plus MCPA	7:93	2.59 (0.12)	0.67 (0.04)	19.29 + 256.24 (1.96 + 26.04)
Nicosulfuron + 2,4-D plus MCPA	3:97	2.58 (0.12)	0.59 (0.06)	11.64 + 376.54 (1.57 + 50.91)
2,4-D plus MCPA	0:100	2.57 (0.10)	0.63 (0.1)	375.26 (82.04)
Common lambsquarters				
Foramsulfuron	100:0	2.64 (0.11)	0.67 (0.07)	38.26 (5.31)
Foramsulfuron + 2,4-D plus MCPA	66:34	2.71 (0.1)	0.82 (0.05)	46.58 + 23.99 (3.61 + 1.86)
Foramsulfuron + 2,4-D plus MCPA	43:57	2.70 (0.1)	0.52 (0.04)	49.91 + 66.16 (6.56 + 8.69)
Foramsulfuron + 2,4-D plus MCPA	17:83	2.70 (0.1)	0.44 (0.04)	43.96 + 214.64 (6.68 + 32.63)
Foramsulfuron + 2,4-D plus MCPA	6:94	2.70 (0.1)	0.41 (0.04)	19.67 + 308.17 (2.64 + 41.39)
Foramsulfuron + 2,4-D plus MCPA	2:98	2.70 (0.1)	0.56 (0.04)	8.58 + 420.38 (0.83 + 40.40)
2,4-D plus MCPA	0:100	2.62 (0.1)	0.86 (0.09)	573.26 (70.67)

[1]The units for upper limit are g dry matter at harvest.
[2]Standard errors are in parentheses.
[3]For ED parameter, the unit is g a.i. ha^{-1}.

contrast, efficacy of sulfonylurea herbicides in mixture with 2,4-D + MCPA was decreased on common lambsquarters and black nightshade compared to both herbicides applied alone especially in the nicosulfuron + 2,4-D + MCPA. Antagonistic interaction may be more likely to occur when the interacting herbicides enter the target plant via same plant parts, and if one herbicide reduces the rate of penetration and translocation of the other herbicide into the plant and target sites (Richard & Baker, 1979; Sundaru, Baba, Tanabe, Tamoi, & Motoda, 1983). The amount of herbicide reaching the site of action may be reduced by translocation with another herbicide, especially when both translocate through the phloem or xylem (Sundaru et al., 1983). Weed species has a greater effect on herbicide absorption into the plant organs and finally translocation in effective dose to the target site of action. Weed species responded differently to herbicide used in mixture in our experiments. It is expected that common lambsquarters and black nightshade due to thickness and lipophilic nature of cuticle layer or other structural characteristics including stomatal conductance, stomata number or trichomes existence at the leaf surface have prevented penetration of herbicides in better form. These weed species may have shown certain physiological properties in response to herbicide interactions, too. Devine and Vandenborn (1985) reported that the amount of herbicide absorbed and translocated would vary by weed species. They stated that after 114 h, 29% of applied ^{14}C-clopyralid and 5% of applied ^{14}C-chlorsulfuron were translocated to the roots and root buds of Canada thistle (*Cirsium arvense* (L.) Scop.), but only about 3% of either herbicide applied to perennial sowthistle (*Sonchus arvensis* L.) was found in the roots. In another research, Sorensen, Meggitt and Penner (1987) observed that a mixture of acifluorfen and bentazon had a synergistic effect on common lambsquarters and velvetleaf, but an antagonistic effect on jimsonweed (*Datura stramonium* L.) and redroot pigweed. Therefore, these results suggest that interference in the absorption and translocation of one herbicide by another may be the major causes of antagonism in these weed species.

Besides, herbicide formulation can lead to increasing or decreasing efficacy of herbicides in a mixture rather than predicted by ADM. For example, Streibig, Kudsk and Jensen (1998) showed that mixing mecoprop-P potassium salt with MCPA dimethylamine salt made the mixture additive under the ADM, while mixing the same herbicides as esters made the mixtures synergistic under ADM. In another experiment, Hollaway, Hallam and Flynn (1996) found synergistic effects with MCPA isooctyl ester and metsulfuron-methyl at ED_{75} and ED_{90} response levels on oilseed rape [*Brassica*

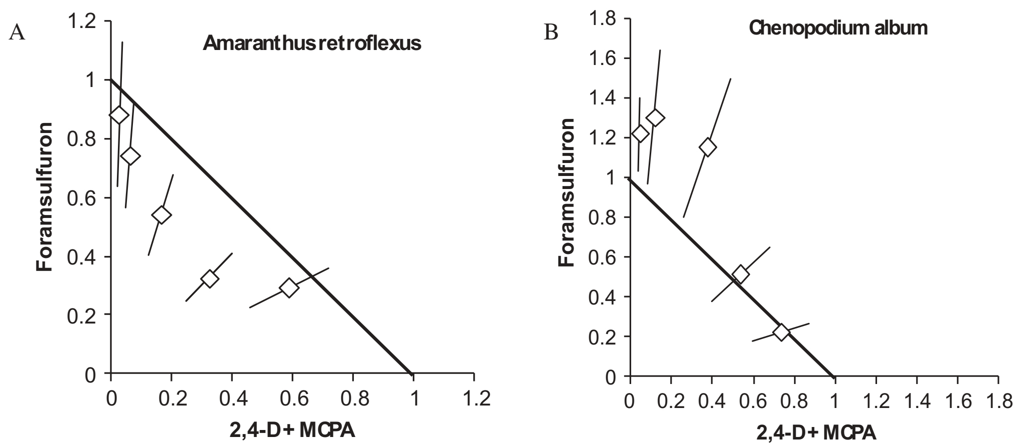

Figure 1. Isoboles and data for fixed-ratio binary mixtures of 2,4-D + MCPA and foramsulfuron at the ED_{90} (◇) response levels. All experiments were done with commercial formulations using (A) redroot pigweed and (B) common lambsquarters as test plants. Bars indicate 95% confidence intervals for the estimated ED_{90} doses. The doses have been scaled so that the doses of the herbicides applied separately are 1.0.

Table 6. Dose–response parameters of the log-logistic model for either the herbicides applied alone or fixed-ratio binary mixtures of foramsulfuron or nicosulfuron with 2,4-D plus MCPA on common purslane at the 4–6-true leaf stage.

Herbicide	Mixture ratio	Upper limit (d)	Curve slope (b)	ED_{90}
Foramsulfuron	100:0	1.35[1] (0.07)[2]	0.37 (0.07)	60.26[3] (22.42)
Foramsulfuron + 2,4-D plus MCPA	73:27	1.35 (0.16)	0.70 (0.07)	67.51 + 24.97 (14.05 + 5.19)
Foramsulfuron + 2,4-D plus MCPA	52:48	1.35 (0.16)	0.65 (0.07)	64.02 + 59.09 (14.25 + 13.15)
Foramsulfuron + 2,4-D plus MCPA	25:75	1.35 (0.16)	0.85 (0.09)	58.21 + 174.64 (10.95 + 32.85)
Foramsulfuron + 2,4-D plus MCPA	9:91	1.35 (0.16)	0.55 (0.06)	26.78 + 270.82 (6.97 + 70.46)
Foramsulfuron + 2,4-D plus MCPA	4:96	1.35 (0.16)	0.52 (0.05)	13.79 + 330.96 (3.81 + 91.43)
Nicosulfuron	100:0	1.30 (0.07)	0.53 (0.08)	66.70 (16.47)
Nicosulfuron + 2,4-D plus MCPA	73:27	1.30 (0.07)	1.33 (0.26)	55.92 + 20.68 (16.43 + 6.08)
Nicosulfuron + 2,4-D plus MCPA	53:47	1.30 (0.07)	0.86 (0.19)	78.41 + 69.53 (30.71 + 27.23)
Nicosulfuron + 2,4-D plus MCPA	25:75	1.30 (0.07)	0.72 (0.18)	85.76 + 257.27 (41.92 + 125.75)
Nicosulfuron + 2,4-D plus MCPA	10:90	1.30 (0.07)	0.77 (0.23)	34.27 + 308.42 (15.96 + 143.62)
Nicosulfuron + 2,4-D plus MCPA	4:96	1.30 (0.07)	0.66 (0.24)	19.41 + 465.70 (9.99 + 239.68)
2,4-D plus MCPA	0:100	1.28 (0.07)	0.66 (0.1)	605 (128.85)

[1]The units for upper limit are g dry matter at harvest.
[2]Standard errors are in parentheses.
[3]For ED parameter the unit is g a.i. ha^{-1}.

napus (L.) Koch]. In contrast, Mathiassen and Kudsk (1993) found extreme antagonism at the ED_{50} and ED_{90} levels for foliar applied mixtures of chlorsulfuron or metsulfuron-methyl and MCPA, as a dimethylamine salt. Comparing the herbicide mixture responses revealed that formulation of foramsulfuron may have a positive effect on joint action of two herbicides in a mixture and therefore how to weed control for best effect than nicosulfuron + 2,4-D + MCPA. Pannacci, Mathiassen and Kudsk (2010) reported that adjuvants are of crucial importance in improving the performance of tribenuron-methyl and in obtaining high efficacy especially against the difficult-to-wet weed species likes common lambsquarters. Nandula, Curran, Roth and Hartwig (1995) stated that the addition of methylated seed oil (MSO) to sulfonylurea herbicides like nicosulfuron and primisulfuron has enhanced control of wirestem muhly (*Muhlenbergia frondosa* (Poir) Fern.). Bunting, Sprague and Riechers (2004) stated that foramsulfuron control of common lambsquarters, giant ragweed (*Ambrosia trifida* L.) and common ragweed were improved significantly when adjuvants system contained MSO.

Absorption and translocation of herbicides can be significantly increased or decreased when another herbicide is added to foliar applied spray mixtures. The current analysis based on ADM graphs does not provide evidence for absorption or translocation, but the addition of 2,4-D + MCPA had virtually no effect on the effects of sulfonylurea herbicides, regardless of the application rate of sulfonylurea herbicides especially about common lambsquarters and black nightshade. Isaacs, Hatzios, Wilson and

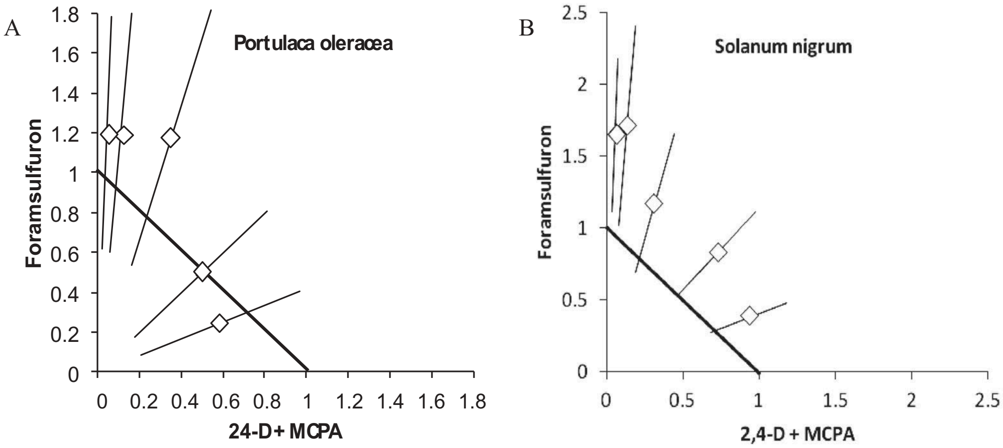

Figure 2. Isoboles and data for fixed-ratio binary mixtures of 2,4-D plus MCPA and foramsulfuron at the ED_{90} (¯) response levels. All experiments were done with commercial formulations using (A) common purslane and (B) black nightshade as test plants. Bars indicate 95% confidence intervals for the estimated ED_{90} doses. The doses have been scaled so that the doses of the herbicides applied separately are 1.0.

Table 7. Dose–response parameters of the log-logistic model for either the herbicides applied alone or fixed-ratio binary mixtures of foramsulfuron or nicosulfuron with 2,4-D plus MCPA on black nightshade at the 4–6-true leaf stage.

Herbicide	Mixture ratio	Upper limit (d)	Curve slope (b)	ED_{90}
Foramsulfuron	100:0	1.82[1] (0.08)[2]	0.41 (0.04)	52.42[3] (13.5)
Foramsulfuron + 2.4-D plus MCPA	70:30	1.73 (0.08)	0.75 (0.09)	86.43 + 37.04 (14.18 + 6.08)
Foramsulfuron + 2.4-D plus MCPA	49:51	1.72 (0.08)	0.62 (0.09)	89.73 + 93.39 (18.51 + 19.26)
Foramsulfuron + 2.4-D plus MCPA	22:78	1.72 (0.08)	0.56 (0.09)	61.59 + 218.39 (12.76 + 45.24)
Foramsulfuron + 2.4-D plus MCPA	8:92	1.72 (0.08)	0.66 (0.09)	43.45 + 499.72 (7.66 + 88.09)
Foramsulfuron + 2.4-D plus MCPA	3:97	1.73 (0.08)	0.81 (0.09)	19.86 + 642.02 (2.72 + 88.01)
Nicosulfuron	100:0	1.80 (0.08)	0.38 (0.05)	86.91 (23.38)
Nicosulfuron + 2.4-D plus MCPA	74:26	1.71 (0.07)	0.36 (0.04)	244.13 + 85.77 (39.19 + 13.77)
Nicosulfuron + 2.4-D plus MCPA	54:46	1.70 (0.07)	0.36 (0.04)	213.19 + 181.61 (32.14 + 27.38)
Nicosulfuron + 2.4-D plus MCPA	27:73	1.71 (0.07)	0.36 (0.03)	89.56 + 242.13 (8.56 + 23.15)
Nicosulfuron + 2.4-D plus MCPA	10:90	1.73 (0.07)	0.31 (0.03)	57.91 + 521.21 (6.52 + 58.70)
Nicosulfuron + 2.4-D plus MCPA	5:95	1.71 (0.07)	0.25 (0.03)	42.56 + 808.57 (6.21 + 118.09)
2.4-D plus MCPA	0:100	1.77† (0.08)*	0.65 (0.08)	691.14 (120.63)

[1]The units for upper limit are g dry matter at harvest.
[2]Standard errors are in parentheses.
[3]For ED parameter the unit is g a.i. ha^{-1}.

Toler (2006) reported that the addition of 2,4-D had no effect on the translocation pattern of ^{14}C-halosulfuron, regardless of the application rate of halosulfuron. Hart (1997) reported similar translocation results with the mixture of dicamba and halosulfuron in velvetleaf. The current results and previous findings suggest a limited absorption or translocation of 2,4-D + MCPA, but bioassay experiments with radiolabeled herbicides can confirm the interaction of sulfonylurea herbicides and 2,4-D + MCPA to determine absorbed and translocated herbicides to the target site of action.

In conclusion, the present study revealed that foramsulfuron or nicosulfuron tank mixture with 2,4-D + MCPA on redroot pigweed and common purslane either followed ADM or performed better than predicted by ADM. In contrast, foramsulfuron + 2,4-D + MCPA showed slight antagonism especially by increasing foramsulfuron mixture ratios using common lambsquarters and black nightshade as test plant, while, nicosulfuron + 2,4-D + MCPA was strongly antagonistic on black nightshade. These data indicated that only redroot pigweed has the potential for control at reduced rates of herbicides in mixture. Hence, to control a wide range of broadleaf weed species in fields, sulfonylurea herbicides must be applied at equals or higher rates in mixture with 2,4-D + MCPA compared to herbicides applied alone based on 90% reduction in aboveground dry matter mentioned in this research. However, growers should carefully choose appropriate mixtures so that they do not impose herbicides into environment.

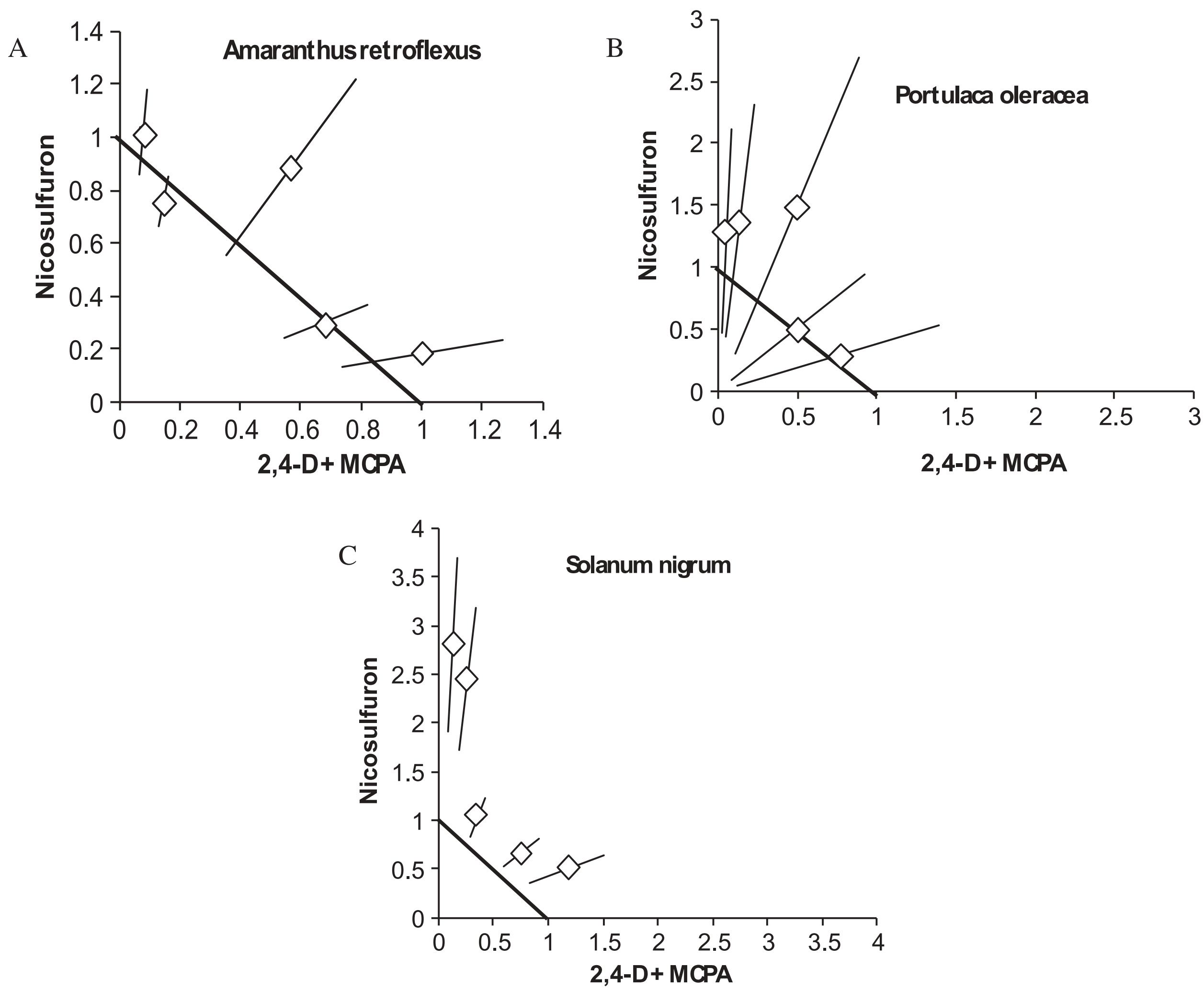

Figure 3. Isoboles and data for fixed-ratio binary mixtures of 2,4-D + MCPA and nicosulfuron at the ED_{90} (¯) response levels. All experiments were done with commercial formulations using (A) redroot pigweed, (B) common purslane and (C) black nightshade as test plants. Bars indicate 95% confidence intervals for the estimated ED_{90} doses. The doses have been scaled so that the doses of the herbicides applied separately are 1.0.

Nomenclature

2,4-D + MCPA; foramsulfuron; nicosulfuron; black nightshade, [*Solanum nigrum* (L.)]; common lambsquarters, [*Chenopodium album* (L.)]; common purslane, [*Portulaca oleracea* (L.)]; redroot pigweed, [*Amaranthus retroflexus* (L.)].

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Disclosure statement

No potential conflict of interest was reported by the authors.

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