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Poison Ivy (*Toxicodendron radican*) Control with Dicamba and 2,4-D Applied Alone and in Tank Mixture

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Poison ivy is a virulent weed that is frequently treated with herbicides. Dicamba, 2,4-D, and two fixed-ratio tank mixtures of dicamba plus 2,4-D were evaluated across a series of rates for poison ivy control. Objective was to test whether tank mixtures were more effective than either herbicide applied alone. Dicamba alone, 2,4-D alone, a 1 : 3, and a 3 : 1 ratio (by weight) mixture of dicamba plus 2,4-D, respectively, were applied at eight rates to 2-yr-old, container-grown poison ivy plants. The eight rates ranged from 0.036 to 1.79 kg ae ha^{-1}, which, in terms of phytotoxicity, generally ranged from none to death. Percentage of control was determined from plant fresh-weight reduction relative to a nontreated control and was determined at 1 and 4 mo after treatment (MAT). Rates required for 95% control at 1 MAT and for control of regrowth at 4 MAT and the cost of those treatments were determined for the dicamba and 2,4-D applied alone and in the two mixtures. At the 1-MAT evaluation, 2,4-D alone was more cost effective than either dicamba alone or the two mixtures. By the 4-MAT evaluation, however, which followed clipping at 3 MAT, dicamba alone was more cost effective than either mixture. The 2,4-D alone failed to provide 95% control at the 4 MAT evaluation, even at the highest rate evaluated (1.79 kg ha^{-1}). Response curves for the two mixtures were equivalent to the response curves of the components applied alone at the 1 MAT evaluation and fell between the response curves of the components at the 4 MAT evaluation. Hence, 2,4-D plus dicamba mixtures were neither antagonistic nor synergistic. Results indicate that dicamba applied alone is far more effective than 2,4-D is for control of established and perennial poison ivy, assuming the intent is to obtain control with a single, one-time application.

Nomenclature: 2,4-D; dicamba; poison ivy, *Toxicodendron radican* (L.) Kuntze.
Key words: Herbicide interactions, nonlinear regression, virulent weeds, weed control.

Toxicodendron radican es una maleza virulenta que es tratada frecuentemente con herbicidas. Se evaluó dicamba, 2,4-D, y dos mezclas en tanque con proporciones fijas de dicamba más 2,4-D con una serie de dosis para el control de *T. radican*. El objetivo fue evaluar si las mezclas en tanque fueron más efectivas que cualquiera de dichos herbicidas aplicado solo. Dicamba solo, 2,4-D solo, y mezclas de dicamba más 2,4-D en proporciones (por peso) 1:3 y 3:1, respectivamente, fueron aplicados a ocho dosis a plantas de 2 años de edad crecidas en potes. Las ocho dosis variaron entre 0.036 a 1.79 kg ae ha^{-1}, las cuales en términos de fitotoxicidad, generalmente variaron de ningún daño a muerte. El porcentaje de control fue determinado a partir de la reducción en el peso fresco en relación al testigo no-tratado y se este se determinó a 1 y 4 meses después del tratamiento (MAT). Las dosis requeridas para 95% de control a 1 MAT y para el control del rebrote a 4 MAR además del costo de esos tratamientos fueron determinados para dicamba y 2,4-D aplicados solos y en las dos mezclas. En la evaluación a 1 MAT, 2,4-D rindió un mayor beneficio/costo que dicamba solo o las mezclas. Sin embargo, en la evaluación a 4 MAT, la cual se dio después de una poda 3 MAT, dicamba solo tuvo el mayor beneficio/costo el cual fue superior a cualquiera de las mezclas. El 2,4-D solo falló en brindar 95% de control en la evaluación a 4 MAT, inclusive con la dosis evaluada más alta (1.79 kg ha^{-1}). Las curvas de respuesta para las dos mezclas fueron equivalentes a las curvas de respuesta de los componentes aplicados solos en la evaluación a 1 MAT y se localizaron entre las curvas de respuesta de los componentes en la evaluación a 4 MAT. Así, mezclas de 2,4-D más dicamba no fueron antagónicas ni sinérgicas. Los resultados indican que dicamba aplicado solo es mucho más efectivo que 2,4-D para el control de plantas perennes establecidas de *T. radican*, cuando se realiza una sola aplicación.

Poison ivy is a high-climbing, woody vine native to North America and prevalent in nearly all forested areas of the United States and southern Canada (Miller and Miller 1999). It is also problematic in the landscape and forested sites in urban areas. Poison ivy produces clusters of flowers,

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the mature fruits are eaten, and the seeds are spread by birds (Miller and Miller 1999). Poison ivy sap contains urushiol, a yellowish, slightly volatile, oily allergen (Epstein and Byers 1981; Mitich 1995). Crushing or bruising of the foliage releases the sap, and when that sap contacts skin, it can result in skin dermatitis, a blistering and painful rash.

A survey of extension publications from across the United States revealed that collectively all of the following herbicides are recommended for poison ivy control: 2,4-D, mecoprop, dicamba, triclopyr, picloram, sulfometuron, and glyphosate, with glyphosate being the most commonly recommended. The very limited published research on poison ivy control has been reviewed in our previous publications (Wehtje and Gilliam 2012; Wehtje et al. 2013). In our first reported study (Wehtje and Gilliam 2012), both 2,4-D and triclopyr applied alone were more cost effective than glyphosate alone, glyphosate plus 2,4-D tank mixtures, or glyphosate plus triclopyr tank mixtures. We subsequently reported (Wehtje et al. 2013) that triclopyr alone was more cost effective than either metsulfuron alone or metsulfuron plus triclopyr tank mixtures.

Products containing only 2,4-D (both amine and low volatile ester formulations) and dicamba, as well as prepackaged mixtures of 2,4-D and dicamba are labeled for poison ivy control. Both 2,4-D and dicamba are synthetic, auxin-mimicking herbicides (Cobb and Reade 2010). However, dicamba is considered more effective on perennial species than 2,4-D is (Zimdahl 1999). The enhanced activity of dicamba against sensitive perennials has been attributed to comparatively excellent absorption and translocation and minimal degradation (Chang and Vanden Born 1971a,b).

Frequently, the intent of combining 2,4-D and dicamba into a tank mixture is to have a treatment that effectively controls more species than either herbicide applied alone (Jagschits and Skogley 1966; Martin 1987). However, on some weed species the interaction of 2,4-D and dicamba may not be simply additive. Skaptason (1971) evaluated 2,4-D, mecoprop, and 2,4-D plus mecoprop, with and without dicamba, for the control of Pennsylvania smartweed (*Polygonum pensylvanicum* L.) in corn (*Zea mays* L.). That author concluded that certain dicamba-containing mixtures were synergistic in that "levels of dicamba as low as 0.033 kg ha^{-1} while producing no visible effect on a weed, can cause that species to become extremely susceptible to 2,4-D and MCPP (mecoprop)." Colby (1967) published a procedure in which the performance of a mixture could be compared with the performance of the components applied alone through a relatively simple formula. Through that procedure, mixtures can be classified as *synergistic*, *antagonistic*, or *noninteractive*, i.e., additive. Using that procedure, Colby concluded that three of the four dicamba plus 2,4-D mixtures evaluated were synergistic for mouseear chickweed (Cerastium Vulgatum L.) control; the fourth mixture was classified as additive, but for dandelion (*Taraxacum* officinale Weber.) control, three of the four mixtures were classified as antagonistic and the fourth as synergistic.

Although the concept of synergism and antagonism is easy to comprehend, experimental procedures to establish and prove those interactions are controversial. Consequently, no consensus exists among researchers as to the best method to evaluate herbicide mixtures. An excellent review of this topic has been published by Streibig and Jensen (2000). They suggested that an effective and logical method would be to evaluate the components alone and in mixture over a series of rates that progress from minimal phytotoxicity to death. The mixture is held to a predetermined and constant ratio of the components. Through linear or nonlinear regression or both, an equally effective rate (e.g., the rate required for 95% control) for the components alone and the mixture can be then determined and its cost calculated. This approach was successfully used in our previous research on poison ivy control with mixtures and their components (Wehtje and Gilliam 2012; Wehtje et al. 2013). Hence, the objective of this research was to evaluate and compare the cost efficacy of 2,4-D, dicamba, and tank mixtures for poison ivy control. More specifically, the objective was to test the hypothesis that mixtures may be more effective than either 2,4-D or dicamba applied alone.

Materials and Methods

Test Plant Production. Poison ivy was propagated and grown in a manner comparable to that used to commercially propagate container-grown landscape plants. Plants were propagated 2 yr before the growing season in which the experiment was conducted. Poison ivy vines were collected from forested sites near the campus of Auburn University in late June through early July. Cuttings with aerial rootlets and two to four leaves were prepared from those vines. Cuttings were placed in 10-cm, square, plastic pots; filled with a 6 : 1 (v/v) ratio of pine bark–sand substrate. That substrate was amended with a controlled-release granular fertilizer (Polyon® 17N-6P-12K, available from Harrell's Fertilizer, Inc., 203 West 4th Street, Sylacauga, AL 35105), dolomitic limestone, and a micronutrient fertilizer (Micromax®, O.M. Scott Corp., 14111 Scottslawn Road, Marysville, OH 43401) at 8.3, 3.0, and 0.9 kg m^{-3}, respectively. Cuttings were maintained in a mist propagation bed for 8 wk. Cuttings with new growth were planted in 2.5-L plastic pots using soil (surface horizon, Pacolet sandy clay loam; 55% sand, 20% silt, and 18% clay) supplemented with composted hardwood sawdust at approximately 20% v/v. Poison ivy is a relatively slow-growing species, thus this pot size was considered adequate for 2 yr of growth before use in experimentation. Plants were maintained in an outdoor area with natural shade. Plants were irrigated approximately 0.6 cm three times a week. Plants went dormant in the fall and were covered with polyethylene film during periods of extreme cold during the following winter. Plants resumed growth the following spring. Plants were pruned twice in the growing season before the experimental year to encourage lateral branching and minimize runner length.

Experimental Procedures. Four treatment series were included: (1) 2,4-D (2,4-D amine, 456 g ae L^{-1} 2,4-D dimethyl amine, Universal Crop Protection Alliance LLC, 1300 Corporate Center Curve, Eagan MN 55121) applied alone; (2) dicamba (Banvel®, 480 g ae L^{-1} dicamba dimethyl amine, Arysta LifeScience North America LLC, 15401 Weston Parkway, Suite 150, Cary, NC 27513) alone; (3) a 1 : 3 mixture, by ae weight, of 2,4-D plus dicamba; and (4) the reverse ratio, i.e., a 3 : 1 mixture of 2,4-D plus dicamba. All four treatment series were applied at eight rates ranging from 0.036 to 1.79 kg ae ha^{-1}. A nontreated control was also included, resulting in a 33-treatment experiment. All herbicide-containing treatments also included a crop oil concentrate adjuvant (Agri-Dex®, Helena Chemical Company, 225 Schilling Blvd., Suite 300, Collierville, TN 38017) at 0.25% v/v. The experiment was conducted three times; i.e., in 2011, 2012, and 2013.

Treatments were applied during the first week of June using an enclosed-cabinet sprayer, calibrated to deliver 280 L ha^{-1} at 193 kPa. Plants were returned to the outdoor growing area immediately following treatment. Average daily high and low temperature in the 5 d immediately following application was 33 C and 22 C, respectively. Average daily relative humidity was 66%. Treated plants were not irrigated and were protected from rainfall for 72 h after treatment application. Treatments were applied to four, single-pot replicates in 2011 and 2012, and five replicates in 2013. A completely randomized design was used.

Data Collection and Statistical Aspects. At 1 mo after treatment (MAT), plants were clipped at approximately 5 cm above the soil line, and the fresh weight of any remaining nondesiccated foliage was determined. Plants were then allowed to regrow for the remainder of the growing season. At 4 MAT (or 3 mo after clipping [MAC]) plants were again clipped and the fresh weight of any regrowth determined. The second evaluation occurred during the second week of October, immediately before the first expected frost. Treated-plant weights were expressed as a percentage of the nontreated control; and subtracting this value from 100 resulted in a percentage of control value. Thus, a treatment that had foliage weight equal to the nontreated control at both 1 MAT and 4 MAT had 0% control at both 1 and 4 MAT. Conversely, a treatment that resulted in complete foliage desiccation and subsequently prevented any regrowth had 100% control at both 1 and 4 MAT.

Data were first subjected to ANOVA using the PROC MIXED procedure in SAS software (Statistical Analysis System Software®, Release 8.3, SAS Institute, Inc., Box 8000, SAS Circle, Cary, NC 27513). Years were treated as a random effect. No treatment-by-year interactions were detected ($P > 0.05$); consequently, data were pooled for further analysis. Specifically, data for each herbicide and herbicide mixture were subjected to nonlinear regression and fitted to the following four-parameter, log-logistic model, which has been previously described (Seefeldt et al. 1995; Wehtje and Gilliam 2012; Wehtje, et al. 2013) using Prism® software (GraphPad Software, Inc., 2236 Avenida de la Playa, La Jolla CA 92037).

Table 1. Nonlinear regression parameters from log-logistic analysis, and estimated rates-associated cost for 95% control of 2-y-old, container-grown poison ivy with 2,4-D, dicamba, and two fixed-ratio mixtures. Experiment were conducted in 2011, 2012, and 2013, and data pooled over those 3 y.[a]

Herbicide or herbicide mixture	Coefficient of determination	Parameter estimates Slope near I_{50}	 I_{50}	LD_{95} Rate	 Cost of rate[b]
	R^2		kg ha^{-1}	kg ha^{-1}	U.S.\$ ha^{-1}
Control, 1 MAT					
2,4-D	0.67	1.59	0.31	1.95	47.78
Dicamba	0.74	1.81	0.24	1.33	87.91
2,4-D + dicamba (1 : 3)	0.62	1.42	0.27	1.19	66.28
2,4-D + dicamba (3 : 1)	0.74	2.25 NS	0.29 NS	2.15	75.04
Control, 4 MAT and 3 mo after clipping[c]					
Dicamba	0.72	1.89	0.08 a[d]	0.39	25.78
2,4-D + dicamba (1 : 3)	0.64	1.68	0.11 c	0.68	37.88
2,4-D + dicamba (3 : 1)	0.67	1.77 NS	0.16 b	1.07	37.34

[a] Abbreviations: LD_{50}, half lethal dose; MAT, months after treatment; NS, not significant.

[b] Cost based on U.S.\$24.50 kg ae for 2,4-D, and \$66.10 kg^{-1} ae for dicamba, which equates to \$55.70 kg^{-1} ae for the 1 : 3 mixture and \$34.90 kg^{-1} ae for the 3 : 1 mixture.

[c] 2,4-D was excluded from this regression because the highest rate evaluated did not control ~100% (see Figure 1).

[d] Half-maximal inhibitory concentration (I_{50}) estimates with different letters are statistically different according to the goodness-of-fit test as described by Seefeldt (1995) at the 0.05 probability level.

The selected rates of dicamba and the two mixtures were sufficiently low and high so as to result in zero and complete control, respectively (data not shown). Consequently, in these cases, the lower and upper limits were constrained to 0 and 100, respectively. This allows for more accurate estimations of the half maximal inhibitory concentration (I_{50}) value and the slope (Motulsky and Christopoulos 2004). The highest rate of 2,4-D alone (1.79 kg ha^{-1}) did not provide 100% control at 4 MAT nor did the response fit the log-logistic model. Consequently, this treatment series was excluded from nonlinear regression. Individual rate-response curves were compared using the goodness-of-fit procedure, as described by Seefeldt et al. (1995). Through this procedure, it is possible to determine whether two rate-response curves are equivalent or not, and if not equivalent, which of the two calculated parameters (i.e., I_{50} or the slope) are different.

The rates necessary to provide 95% control (i.e., the 95% lethal dose [LD_{95}] value) were calculated for all four treatment series using the log-logistic model and the parameter estimates as generated by Prism®. Prism® was also used for graphic data presentation. Cost per hectare for the estimated LD_{95} rate for 2,4-D alone (1MAT evaluation only), dicamba alone, and the two mixtures were also determined. Herbicide costs were based on an Internet search for suppliers from which individual 3.8-L containers of 2,4-D and dicamba could be purchased.

Results and Discussion

Poison ivy control at the 1MAT evaluation for all four treatment series could be accurately described by the four-parameter, log-logistic model; R^2 values were at least 0.62 (Table 1; Figure 1). The rate response for all four treatment series was statistically equivalent because both the I_{50} values and the slopes were equivalent for all four treatment series (Table 1). However the LD_{95} rate estimates were numerically different. The rate required for 95% control ranged from 1.19 kg ha^{-1} for the 1 : 3 mixture, to 2.15 kg ha^{-1} for the 3 : 1 mixture. This estimated rate is above the maximum rate evaluated, i.e., 1.79 kg ha^{-1}. The cost required for 95% control was lowest with 2,4-D alone (1.95 kg ha^{-1} at a cost of U.S.\$47.78 ha^{-1}), and highest with dicamba alone (1.33 kg ha^{-1} at a cost of \$87.91 ha^{-1}). Both of the two mixtures were intermediate to these extremes.

At 4 MAT (which was also 3 MAC), the highest rate of 2,4-D applied alone (1.79 kg ha^{-1}) controlled poison ivy approximately 80% (Figure 1). Consequently, the 2,4-D-alone treatment series

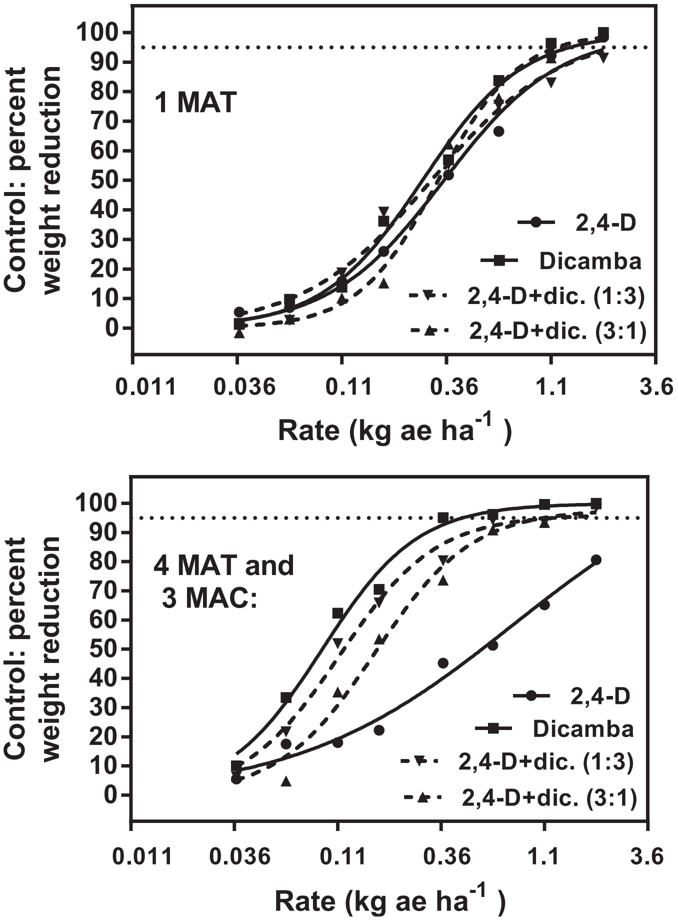

Figure 1. Response of 2-yr-old, container-grown poison ivy to 2,4-D, dicamba, a 1 : 3 mixture, and a 3 : 1 mixture of 2,4-D plus dicamba, respectively. Top is control at 1 mo after treatment (MAT); bottom is control at 4 MAT, which is also 3 mo after the clipping (MAC), which was required for the first evaluation.

was excluded from nonlinear regression. The inability of 2,4-D alone to prevent regrowth is in conflict with our previous study (Wehtje et al. 2012), in which the rate of 2,4-D applied alone required for 95% regrowth control was estimated to be 0.57 kg ha^{-1}. However, the previous study used 1-yr-old poison ivy plants vs. 2-yr-old plants in the current study. In contrast to the 1-yr-old plants, 2-yr old plants had a root mass that had reached to, and was beginning to encompass, the edge of the pot. The 1-yr plants typically had one to two runners at the time of treatment; 2-yr-old plants had two to four runners. Only dicamba and the two dicamba-containing mixtures were able to provide 100% regrowth control (Figure 1). Furthermore, regrowth control for the three dicamba-containing treatment series could be adequately described by the four-parameter log-logistic model; R^2 values were at least 0.64 (Table 1; Figure 1). The rate response for the three, dicamba-containing treatment series was statistically different. Although the slope values were equivalent, the I_{50} values were significantly different (Table 1). Dicamba alone had the lowest I_{50} value, i.e., 0.08 kg ha^{-1}; followed progressively by the 1 : 3 mixture (0.11 kg ha^{-1}), and then by the 3 : 1 mixture (0.16 kg ha^{-1}). Thus, progressively greater dilution of dicamba with 2,4-D resulted in a progressively less-effective treatment. This trend was also evident with the rate and cost of the rate required for 95% control. The rate of dicamba required for 95% control, applied alone was estimated to be 0.39 kg ha^{-1}, at a cost of \$25.78 ha^{-1}. Both of the two mixtures were less effective than dicamba alone, both in terms of the required rate and the cost of that rate. Chang and Vanden Born (1971a,b) reported that the ED_{50} values for dicamba on wheat (*Triticum vulgare* L.), barley (*Hordeum vulgare* L.), wild mustard (*Sinapis arvensis* L.), and Tartary buckwheat [*Fagopyrum tataricum* (L.) Gaertn.] were 2.1 kg ha^{-1}, 1.4 kg ha^{-1}, 35 g ha^{-1}, and 35 g ha^{-1}, respectively. The sensitivity of the two weed species, i.e., wild buckwheat (*Polygonum convolvulus* L.) and Tartary buckwheat, was attributed to comparatively greater absorption and translocation, combined with minimal metabolism to inactive, nonphytotoxic metabolites. Metabolism was very slow in sensitive species. Using radiolabeled dicamba, it was determined that 86.5% of the absorbed dicamba remained unaltered and, therefore, phytotoxic 40 d after treatment (Chang and Vanden Born 1971a). We speculate that comparable extensive absorption and translocation, combined with minimal metabolism is likely the basis of the sensitivity of poison ivy to dicamba.

When limited to a relatively short evaluation period, i.e., 1 mo after application, 2,4-D alone was more cost effective than either dicamba alone or any dicamba-containing mixture. However, the greater efficacy of dicamba became apparent only after a longer evaluation period (4 MAT). Dicamba applied alone was the most effective treatment for the control of 2-yr-old, perennial poison ivy, both in terms of having the lowest application rate and the lowest cost. Combining dicamba with 2,4-D offered no benefit. Therefore, our hypothesis that mixtures may be more effective than either 2,4-D or dicamba applied alone was proven false. The response curves of the two mixtures were equivalent to the response curves of the components applied alone at the 1 MAT evaluation. At the 4 MAT evaluation, response curves of the mixtures fell between the response curves of the components applied alone. Therefore, it can be concluded that 2,4-D plus dicamba mixtures are noninteractive, or additive, with respect to poison ivy control.

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