Early Postemergence Control of Woodland Bittercress (*Cardamine flexuosa* With.) and Yellow Woodsorrel (*Oxalis stricta* L.) with Dithiopyr and Isoxaben Combinations[1]

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Abstract

The objective of this research was to evaluate dithiopyr and isoxaben combinations and indaziflam (Marengo) for early postemergence control of woodland bittercress (*Cardamine flexuosa*) and yellow woodsorrel at 4 different early growth stages. Herbicides evaluated included sprayable formulations of isoxaben, dithiopyr + isoxaben, dithiopyr, indaziflam, and prodiamine + isoxaben without any surfactants. Woodland bittercress growth stages included seed production (extra-large), recently flowered (large), 6 to 9 leaf (medium) or in 2 to 5 leaf stage (small), while yellow woodsorrel growth stages included 8 to 12 leaf stage (extra-large), 4 to 6 leaf stage (large), 2 to 4 leaf stage (medium) and cotyledon to 1 leaf stage (small). Shoot fresh weight data showed all treatments provided ≤98% of woodland bittercress at the small stage. Dithiopyr + isoxaben (98%), isoxaben (90%), and indaziflam (93%) provided the highest level of woodland bittercress control at the medium stage and were the only treatments providing acceptable control (≥80%). In the large stage, dithiopyr + isoxaben provided acceptable control (80%) and outperformed other treatments. All treatments with the exception of isoxaben generally provided acceptable control of yellow woodsorrel up to the large growth stage. Only indaziflam (86% control) provided acceptable control at the extra-large stage.

Index words: herbicide, postemergence weed control, container-grown plants, phytotoxic damages.

Herbicides used in this study: isoxaben (Gallery® 4SC) N-[3-(1-ethyl-1-methylpropyl)- 5-isoxazolyl]-2,6-dimethoxybenzamide; dithiopyr (Dimension® 2EW) S,S'-dimethyl 2-(difluoromethyl)-4- (2-methylpropyl)-6-(trifluoromethyl)- 3,5-pyridinedicarbothioate; indaziflam (Specticle® FLO) N-[(1R,2S)-2,3-dihydro-2,6-dimethyl-1H-inden-1-yl]-6-(1-fluoroethyl)-1,3,5-triazine-2,4-diamine; prodiamine + isoxaben (Gemini® SC) 2,4-dinitro-N3,N3-dipropyl-6-(trifluoromethyl)-1,3-benzenediamine + N-[3-(1-ethyl-1-methylpropyl)- 5-isoxazolyl]-2,6-dimethoxybenzamide; dithiopyr + isoxaben (Dimension® + Gallery®) S,S'-dimethyl 2-(difluoromethyl)-4-(2-methylpropyl)-6-(trifluoromethyl)- 3,5-pyridinedicarbothioate + N-[3-(1-ethyl-1-methylpropyl)- 5-isoxazolyl]-2,6-dimethoxybenzamide.

Weed species evaluated: woodland bittercress (flexuous bittercress) (*Cardamine flexuosa* With.); yellow woodsorrel (*Oxalis stricta* L.).

Significance to the Horticulture Industry

Preemergence herbicide applications supplemented by handweeding are the current methods of controlling several bittercress (*Cardamine* spp.) and woodsorrel species (*Oxalis* spp.) that are problematic in container nurseries. In the southeastern United States, preemergence herbicides may dissipate rapidly from containers and reemergence of weeds can occur before sequential applications can be made. Utilizing preemergence herbicides that provide some early postemergence control can provide growers greater flexibility with preemergence applications. Previous research has shown that sprayable formulations of isoxaben and indaziflam provide early postemergence control of bittercress species and yellow woodsorrel, respectively. This research showed that sprayable formulations of dithiopyr and dithiopyr + isoxaben combinations can also provide early postemergence control of these weeds, but efficacy will be dependent upon growth stage. While growers should always strive to make preemergence applications to weed free pots, research presented here offers options for situations when this may not be possible.

Introduction

In many parts of the U.S., bittercress and woodsorrel species are problematic weed species in container nursery production, especially during cooler spring and fall months (Cross et al. 1992, Derr 1989, Gilliam et al. 1990). Several species of bittercress and woodsorrel are routinely ranked as top 10 common or troublesome weeds in ornamentals by the Weed Science Society of America weed surveys (Wychen 2015). Yellow woodsorrel is a perennial weed that spreads vegetatively via rhizomes and stolons, thus making it difficult to hand weed in container-grown ornamental plant production (Neal and Derr 2005). Yellow woodsorrel produce a large number of seeds which explosively dehiscence and germinate very quickly. Woodland bittercress is an annual weed species and may form dense understory root mats and flowers vigorously. Previous research has shown other bittercress species, such as hairy bittercress (*Cardamine hirsuta* L.), can produce five thousand seeds per plant (Bachman and Whitwell 1994) which have no dormancy requirement and can germinate quickly (Bachman and Whitwell 1994). Bittercress species seeds are small and sticky when wet,

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making them prone to being transported on shoes or clothing of nursery employees and can get stuck to the sides of empty nursery containers. Under favorable conditions, bittercress species can germinate, reach maturity and begin flowering and seeding within five to six weeks and is a host for common nursery pests including whiteflies, mites, and certain other diseases (Neal and Derr 2005).

Weed control in ornamentals is important for both marketability and to reduce competition (Berchielli-Robertson et al. 1990). Application of preemergence herbicides and supplemental hand weeding are the current weed control methods for nursery ornamental crop production. For handweeding, it is not only difficult to find labor (Kostandini et al. 2014, Taylor et al. 2012) but labor costs are also increasing (Martin and Calvin 2010). In the southeastern United States, herbicides often dissipate rapidly during nursery crop production (Judge et al. 2003), after which weeds may begin to reemerge. This requires additional hand weeding before reapplying the preemergence herbicides, an extremely laborious and expensive method (Darden and Neal 1999, Gilliam et al.1990). In many cases, it is not possible to completely remove weeds from the containers or to apply preemergence herbicides before new weed seedlings have emerged. Although applying preemergence herbicides to weed-free containers is the preferred and recommended weed control method in nurseries, identification of preemergence herbicides that some degree of early postemergence activity is highly beneficial to growers as many weeds are often missed while handweeding or begin to germinate before preemergence applications can be made.

Evaluating preemergence herbicides for early postemergence control has been investigated in many previous studies (Morse and Neal 1994, Brosnan et al. 2012, Simpson et al. 2004, Judge and Neal 2006, Marble et al. 2011). Altland et al. (2000) showed that isoxaben can provide 90 to 100% hairy bittercress control when applied at the labeled rate of 1.12 kg ai·ha^{-1} (1.0 lb ai·A^{-1}) to non-flowering small hairy bittercress [2 to 3 cm-tall (0.8 to 1.2 in)]. Research by Judge and Neal (2006) showed early postemergence applications of granular formulations of flumioxazin, oxyfluorfen + pendimethalin and isoxaben + trifluralin provided hairy bittercress control at the cotyledon to 1 leaf stage but were less effective at the 2 to 4 leaf stage.

In research evaluating yellow woodsorrel control, indaziflam has typically been shown to have a high degree of early postemergence activity. Indaziflam applied at 0.05 to 0.10 kg ai·ha^{-1} (0.04 and 0.09 lb ai·A^{-1}) provided 100% control of yellow woodsorrel up to the 2 to 4 leaf stage in previous trials (Marble et al. 2013). While indaziflam provided a high level of yellow woodsorrel control, the liquid formulation, which has been the most efficacious, cannot be applied over-the-top of nursery crops, reducing its utility in container production. The granular formulation of indaziflam can provide control up to the 2 to 4 leaf stage of growth but is generally not as effective as the liquid (SC) formulation (Marble et al. 2016). In two of the three experiments (Marble et al. 2013), isoxaben plus dithiopyr provided similar control to indaziflam at the cotyledon to 1-leaf stage and 2 to 4 leaf stage, albeit one of the dithiopyr treatments was applied at 2 times the labeled rate. Identifying additional preemergence herbicides that provide control of woodland bittercress and/or yellow woodsorrel would aid growers when trying to manage these two weeds, as early postemergence activity would allow them to control weeds that were missed during handweeding or that germinated prior to a sequential herbicide application.

Both dithiopyr and isoxaben are often applied to nursery crops as a component of a tank mix, such as dithiopyr + isoxaben or isoxaben + prodiamine, in order to broaden the spectrum of weed control. As dithiopyr has shown potential in previous trials, the objective of this research was to evaluate common dithiopyr and isoxaben combinations in comparison with indaziflam for early postemergence control of multiple growth stages of yellow woodsorrel and woodland bittercress.

Materials and Methods

The research was conducted at the Mid-Florida Research and Education Center, in Apopka, FL in 2017 and 2018. For all trials, square nursery pots 9 cm by 9 cm (3.5 in. by 3.5 in.) were filled with a pine bark:peat mix (Fafard® 52 growing mix, SunGro Horticulture, Agawam, MA) that had been previously amended with Osmocote® Pro 17-5-11 (N-P_2O_5-K_2O) (containing micronutrients) at a rate of 7.1 kg·m^{-3} (12 lb·yd^{-3}). Pots were filled at different dates and seeds of either woodland bittercress or yellow woodsorrel were sown into pots on the same day as filling to yield different stages of growth at the time of treatment (Table 1). This seeding schedule allowed for evaluating efficacy of herbicide treatments on woodland bittercress that had produced seed (extra-large, over 12 cm in height, Exp. 1 and 2), recently flowered (large, approximately 7 to 10 cm in height, Exp. 1-3), had 6 to 9 leaves (medium, approximately 5 to 8 cm in height, Exp. 1-3) or were in the 2 to 5 leaf stage (small, less than 5 cm in height, Exp. 2-3). Yellow woodsorrel growth stages evaluated included an 8 to 12 leaf stage (extra-large, over 10 cm in height, Exp. 1-2), 4 to 6 leaf stage (large, approximately 6 cm in height, Exp. 1-3), 2 to 4 leaf stage (medium, approximately 2 to 3 cm in height, Exp. 1-3) and cotyledon to 1 leaf stage (small, less than 2 cm in height, Exp. 2-3). Over-seeding was accomplished by surface applying approximately 30 seeds to each container. Pots were kept inside a shadehouse (approximately 40% shade) and irrigated 1.3 cm (0.5 in.) per day using overhead irrigation. Herbicide treatments (Table 1) were applied on April 27, 2017 in experiment 1 [28 C (83 F) 63% relative humidity, winds 11 km/h or 7 mph, clear skies], on June 28, 2017 in experiment 2 [27 C (80 F), 81% relative humidity, winds 5 mph, partly cloudy], and on April 13, 2018 in experiment 3 [29 C (84 F), 45% relative humidity, winds 7.4 mph, partly cloudy] using a CO_2 backpack sprayer calibrated to deliver 561 L·ha^{-1} (60 gal·A^{-1}) using a 8004 flat fan nozzle spray tip ((TeeJet Technologies, Wheaton, IL) at 207 kpa (30 psi). All foliage was dry at the time of application and plants remained dry until the following morning (approximately 18 hours after treatment) at which time overhead

Table 1. Seeding and treatment date for four different growth stages of yellow woodsorrel and woodland bittercress over three experimental replications.

Species growth stage: Woodland bittercress	Species growth stage: Yellow woodsorrel	Code:	Seeding date	Treatment date
Experiment 1 (2017)				
Seed development	8 to 12 leaf	extra large	31 Mar.	27 Apr. 2017
Recently flowered	4 to 6 leaf	large	7 Apr.	
6 to 9 leaf	2 to 4 leaf	medium	14 April.	
Experiment 2 (2017)				
Seed development	8 to 12 leaf	extra large	1 June	28 June 2017
Recently flowered	4 to 6 leaf	large	8 June	
6 to 9 leaf	2 to 4 leaf	medium	12 June	
2 to 5 leaf	cotyledon to 1 leaf	small	18 June	
Experiment 3 (2018)				
Recently flowered	4 to 6 leaf	large	15 Mar.	13 April 2018
6 to 9 leaf	2 to 4 leaf	medium	23 Mar.	
2 to 5 leaf	cotyledon to 1 leaf	small	3 April	

irrigation was applied as described above. Data collected included control ratings, done visually on a scale of 0 to 100 (0 = 0% control in comparison with non-treated plants, 100 = 100% control or no green tissues) at 1, 2, and 4 weeks after treatment (WAT). At 4 WAT, shoots were clipped at the soil line and shoot fresh weights were determined. Shoot fresh weight was converted to a percent control (percent fresh weight reduction) using the formula: [((fresh weight nontreated – fresh weight treated)/fresh weight nontreated))*100]. The trial was designed as a completely randomized block with minor growth differences in weed size or density serving as the blocking factor and 8 single pot replications per herbicide treatment in each weed species in each growth stage. Each species and growth stage were kept together during the experiment and thus were analyzed separately. Data were analyzed using a mixed model analysis of variance in SAS (Ver. 9.4, SAS, Cary, NC). All data were arcsin transformed to satisfy the assumptions of analysis of variance. Replication was considered a random factor while herbicide treatment was a fixed factor. Treatment means were separated using Fisher's protected least significance difference test at $p \leq 0.05$. As percent control ratings were similar among treatments on most evaluation dates, only data from 2 weeks after treatment (WAT) and shoot fresh weight reductions are presented and discussed for sake of brevity. As there were no experiment by treatment interactions, results were pooled over either 2 or 3 experimental runs (Table 1).

Results and Discussion

Woodland bittercress. At 2WAT, all treatments at the small growth stage provided acceptable control based on visual ratings (Table 2). The only treatment that provided less than 95% control at this time was dithiopyr alone (86%), but this was still considered acceptable. Shoot fresh weight reduction showed that all treatments provided ≥98% control of woodland bittercress at this growth stage and there were no treatment differences.

Ratings at the medium growth stage showed that dithiopyr + isoxaben gave greater control than all other herbicidal treatments by providing 91% control (Table 2). Based on shoot fresh weight reduction, dithiopyr + isoxaben (98% reduction) and indaziflam (93%) provided the highest level of control followed by isoxaben (90%) and dithiopyr (74%) and prodiamine + isoxaben (76%).

Once woodland bittercress reached the large stage, no herbicide provided over 80% control (Table 2). Dithiopyr + isoxaben was the most efficacious treatment, providing 49% control at 2WAT and an 80% reduction in shoot fresh weights. The next most efficacious treatment was isoxaben (62%), although dithiopyr (47%) provided similar control. Only 37 and 23% FW reduction was achieved by over the top applications of indaziflam and prodiamine + isoxaben,

Table 2. Percent control and shoot fresh weigh reduction (% F. W. reduction) of woodland bittercress (*Cardamine flexuosa*) with selected preemergence herbicides applied early postemergence[z].

Treatment		Growth stage[y]							
		Small growth stage: 2 to 5 leaf		Medium growth stage: 6 to 9 leaf		Large growth stage: recently flowered		Extra-large growth stage: seed head development	
Herbicide	Rate (kg a.i. ha^{-1})	% Control[x] 2WAT[v]	% F.W. reduction[w]	% Control 2WAT	% F.W. reduction	% Control 2WAT	% F.W. reduction	% Control 2WAT	% F.W. reduction
isoxaben	1.1	95 b	99 a	76 b	90 b	32 b	62 b	10 bc	10 bc
dithiopyr + isoxaben	0.56 + 1.1	99 a	100 a	91 a	98 a	49 a	80 a	24 a	27 a
dithiopyr	0.56	86 c	98 a	59 c	74 c	18 c	47 bc	1 c	5 c
indaziflam	0.04	99 a	99 a	76 b	93 ab	18 c	37 c	4 bc	21 a
prodiamine + isoxaben	1.3 + 0.85	97 ab	99 a	59 c	76 c	17 c	23 d	18 ab	18 ab

[z]Means followed by the same letter within a column are not significantly different according to Fisher's LSD ($p = 0.05$).

[y]Growth stage shows approximate size of plants at treatment based on leaf development and flowering. Data were pooled over 2 to 3 experimental runs for each growth stage.

[x]Percent control ratings (visual ratings) were taken on a scale of 0 to 100, 0 = no control, 100 = complete control based upon a non-treated control group.

[w]Fresh weight (F.W.) reduction was calculated 4 weeks after treatment using shoot fresh weights and the formula [((mean weight nontreated - weight of treated)/mean weight nontreated))*100].

[v]WAT = weeks after treatment.

Table 3. **Percent control and shoot fresh weigh reduction (% F. W. reduction) of yellow woodsorrel (*Oxalis stricta*) with selected preemergence herbicides applied early postemergence[z].**

Treatment		Growth stage[y]							
		Small growth stage: cotyledon to 1 leaf		Medium growth stage: 2 to 4 leaf		Large growth stage: 4 to 6 leaf		Extra-large growth stage: 8 to 12 leaf	
Herbicide	Rate (kg a.i. ha^{-1})	% Control[x] 2WAT[v]	% F.W. reduction[w]	% Control 2WAT	% F.W. reduction	% Control 2WAT	% F.W. reduction	% Control 2WAT	% F.W. reduction
isoxaben	1.1	89 b	89 b	63 d	76 c	47 d	62 d	23 d	5 d
dithiopyr + isoxaben	0.56 + 1.1	99 a	99 a	97 ab	98 ab	84 a	90 ab	38 c	45 b
dithiopyr	0.56	92 b	99 a	91 bc	99 a	72 b	85 bc	52 b	56 b
indaziflam	0.04	100 a	100 a	98 a	100 a	93 a	94 a	76 a	86 a
prodiamine + isoxaben	1.3 + 0.85	100 a	99 a	86 c	94 b	62 c	79 c	28 cd	21 c

[z]Means followed by the same letter are not significantly different according to Fisher's LSD ($p = 0.05$).

[y]Growth stage shows approximate size of plants at treatment based on leaf development and flowering. Data were pooled over 2 to 3 experimental runs for each growth stage.

[x]Percent control ratings (visual ratings) were taken on a scale of 0 to 100, 0 = no control, 100 = complete control based upon a non-treated control group.

[w]Fresh weight (F.W.) reduction was calculated at 4 weeks after treatment using shoot fresh weights and the formula [((mean weight nontreated - weight of treated)/mean weight nontreated))*100].

[v]WAT = weeks after treatment.

respectively, when applied to the recently flowered woodland bittercress.

Once seed heads began to develop, no treatment provided acceptable control (Table 2). Dithiopyr + isoxaben (27%) and indaziflam (21%) provided greater shoot weight reduction compared with isoxaben (10%). Prodiamine + isoxaben (18%) provided results similar to other isoxaben containing treatments. Overall, no treatment was considered acceptable based on shoot fresh weight reduction.

Yellow woodsorrel. Similar to results observed with woodland bittercress, almost all treatments provided close to or above 90% control of yellow woodsorrel at the small (cotyledon to 1 leaf) growth stage (Table 3). The effective treatments at 2WAT were dithiopyr + isoxaben (99%), indaziflam (100%) and prodiamine + isoxaben (100%), all of which provided greater control than dithiopyr (92%) and isoxaben (89%) applied alone. All treatments provided 99% control or greater with the exception of isoxaben (89%) which provided less control than other treatments based on shoot fresh weight reduction.

At the medium (2 to 4 leaf) growth stage, indaziflam (98%) provided higher control than any other treatment with the exception of dithiopyr + isoxaben (97%), which provided similar control at 2WAT (Table 3). Shoot fresh weights showed that indaziflam (100%) and dithiopyr (99%) provided greater control than prodiamine + isoxaben (94%) but were similar to dithiopyr + isoxaben (98%). Isoxaben provided only a 76% reduction in shoot fresh weights and was the least efficacious treatment. Once yellow woodsorrel reached the 4 to 6 leaf stage, the only treatments providing 90% or greater control were indaziflam (94%) and dithiopyr + isoxaben (90%). Dithiopyr applied alone provided an 85% reduction in shoot fresh weights, similar to results seen with prodiamine + isoxaben (79%). Once yellow woodsorrel reached the extra-large (8 to 12 leaf stage), the only treatment providing over 80% reduction in shoot fresh weight was indaziflam (86%). The next most effective treatments were dithiopyr (56%) and dithiopyr + isoxaben (45%).

Data from these studies show that for small (2 to 5 leaf) woodland bittercress, sprayable formulations of dithiopyr, isoxaben, indaziflam and combinations of these herbicides will provide a high degree of early postemergence control. At the medium growth stage, dithiopyr + isoxaben provided greater control than any other treatment except indaziflam, and less control was observed with dithiopyr alone or prodiamine + isoxaben when compared to the dithiopyr + isoxaben combination. It is important to note that in the prodiamine + isoxaben combination, only 0.85 kg ai·ha^{-1} (0.76 lb ai·A^{-1}) of isoxaben was applied while 1.1 kg ai.ha^{-1} (1 lb ai·A^{-1}) was applied in other isoxaben treatments.

Dithiopyr + isoxaben provided the highest level of woodland bittercress control at the large growth stage (recently flowered) and gave greater control than isoxaben alone and isoxaben + prodiamine. This experiment was not designed to evaluate synergism between dithiopyr and isoxaben, but it appears there is a possibility that dithiopyr could potentially have some synergistic effect with isoxaben when used for early postemergence woodland bittercress control. Once woodland bittercress reached the seed head development stage, dithiopyr + isoxaben and indaziflam provided better control than isoxaben or dithiopyr alone, but no treatment would be considered commercially acceptable. Dithiopyr + isoxaben provided the same level of control as indaziflam for yellow woodsorrel up to the large (4 to 6 leaf) growth stage. Dithiopyr alone was also comparable to indaziflam at the small and medium growth stages, similar to results reported by Marble et al. (2013).

Results from this study indicate that a tank-mix of dithiopyr + isoxaben will provide effective control of woodland bittercress up to the large (recently flowered) growth stage of woodland bittercress and will provide greater control of woodland bittercress than isoxaben applied alone. The dithiopyr + isoxaben combination also provided better control than prodiamine + isoxaben at all growth stages with the exception of the small growth stage, but a higher isoxaben rate was used in the dithiopyr tank mix, and isoxaben has been shown to be highly effective on small hairy bittercress seedlings (Altland et al. 2000). When yellow woodsorrel is the primary weed of concern, growers may be able to achieve some early postemergence control with dithiopyr + isoxaben up to the 4 to 6 leaf stage. The highest level of control was typically seen with indaziflam at larger growth stages, but this treatment could only be used as a directed application in container-grown ornamentals.

Growers have several preemergence options for different weed species that may also provide some early postemergence control, including isoxaben for bittercress (Altland et al. 2000), dimethenamid-P for spurge (Marble et al. 2011), indaziflam for annual bluegrass or yellow woodsorrel (Brosnan et al. 2012, Marble et al. 2013), dithiopyr for crabgrass species (Morse and Neal 1994) and oxyfluorfen combinations for multiple other weed species (Judge and Neal 2006), similar to yellow woodsorrel and woodland bittercress as reported in the present study. Using a dithiopyr + isoxaben tank mix may also provide a greater level of control of both species compared to using isoxaben applied alone. Isoxaben and dithiopyr are both labeled for hundreds of different ornamental crops as an over the top application (Anonymous 2014, Anonymous 2016), and thus would be more useful to container growers trying to manage these weeds early postemergence than indaziflam even though indaziflam was more effective on larger yellow woodsorrel. Future research should focus on not only control, determined visually, or biomass reduction in these species following an early postemergence application but should also determine if early postemergence applications reduce or delay flowering or seed set of surviving weed seedlings.

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