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Velvetleaf (*Abutilon theophrasti* Medik.) productivity in competitive conditions

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Abstract: Velvetleaf (*Abutilon theophrasti* Medik.) is an invasive alien species in many countries and one of the major weeds in summer row crops worldwide. Weed-management techniques that reduce weed production need to be investigated to provide new approaches. The first step in this process is the determination of weed productivity in different competitive conditions. Field experiments were conducted in 2006 and 2008 in an experimental field in Padinska Skela to quantify growth and seed production of velvetleaf in maize, as well as in a velvetleaf monoculture. A density of velvetleaf ranging from 1 to 8 plants m^{-1} was artificially created. In a mixture with maize, velvetleaf was sown in crop rows. The growth of velvetleaf was estimated based on plant height, fresh aboveground biomass and leaf area index (LAI). Velvetleaf fecundity was determined as seed mass $plant^{-1}$ and seed mass m^{-2}. Differences between years in plant production were very prominent. In general, velvetleaf productivity in maize depended on its density. Intraspecific competition had a major influence on growth and seed production when velvetleaf density was from 4 to 8 plants m^{-1} in maize rows. This information indicates that environmental conditions and weed density can promote/reduce inter- and intraspecific competition and help in the construction of population dynamics models to predict population density, seed bank and competitiveness of weeds and reduce inputs for weed management.

Key words: velvetleaf; density; vegetative parameters; fecundity.

INTRODUCTION

Herbicides are highly effective in reducing weed populations, but their continuous use is often offset by an increased abundance of more tolerant weed species [1], or by the development of herbicide resistance [2-4]. Moreover, if weed control is not aimed to achieve total weed eradication, then a proportion of the population present will survive to produce seeds that will then produce plants in crops in subsequent years [5]. An understanding of seed production and the seed soil bank is crucial for understanding the potential impact of such less intensive weed control. Thus, there is a growing need for the development of cost-effective, environmentally safe, integrated and alternative weed management strategies.

Competition between row crops and weeds has been a serious challenge to crop production in Serbia since the last century. Maize is one of the most important crops in Serbia, grown on an average of 1.2 million ha. Yields in intensive and extensive production areas amount to approximately 10-12 t ha^{-1} and 3-4 t ha^{-1}, respectively [6]. Excluding environmental variables, yield losses in maize are mainly caused by competition from weeds [7-10] and some of those problems were attributed to maize and *Abutilon theophrasti* [11-14]. Generally, the major goal of crop-weed competition studies has been focused on the effects of crop density on weed population size, growth and reproduction [11-13]. Few studies have focused on the effects of weed density on its

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own vegetative productivity and fecundity in row crops [15,16].

Abutilon theophrasti Medik. (syn. *A. avicennae* Gaertn. = velvetleaf) has been cultivated in China since the beginnings of civilization as a fiber plant. From China it spread through Asia Minor to the Balkan Peninsula as a potential fiber crop plant. Velvetleaf is a major weed in maize and other summer row crops in many European countries [17,18]. In Serbia, velvetleaf is the predominant weed species found in maize and other row crops, occupying more than 50% of arable fields [19]. It is also one of the most troublesome weeds in both maize and soybean in the USA [11].

The successful colonization by velvetleaf can be explained by its biological/ecological set of traits and inadequate weed management on arable and non-arable land. Velvetleaf is an erect summer annual species up to 2 m tall, with high seed production (up to 50000+ ha^{-1}) [20]. Velvetleaf seeds mature within 15 to 24 d [21]. Most seeds fall near the parent plant, but some disperse to greater distances via water, mud, soil movement, manure and especially agricultural operations. The seeds are hard-coated, survive ingestion by poultry and most livestock, and resist decomposition by soil microorganisms [22]. Some seeds remain dormant and viable even when the seed coat is broken. Most seeds germinate from mid-spring through early summer, with optimal germination temperatures ranging from 16 to 20°C. Seeds can survive for 50 years or more in the soil seed bank [23]. In an Iowa study, only 8% of the velvetleaf seed produced germinated the year after seed production, with an additional 15% emerging within a 4-year period [24]. In another study, under ideal conditions for velvetleaf germination and emergence, only 54% of the seed emerged the year after seed production [25]. These studies demonstrate that if left untreated, low densities of velvetleaf may produce sufficient seed to cause an economic problem for many years. Also, if velvetleaf emerges simultaneously with maize it is almost always able to grow taller than the maize. Velvetleaf height and leaf area increase rapidly in the vegetative phase, during which the major portion of plant biomass is produced [16,17]. In addition, the growth of weed species can also be influenced by intraspecific competition. Aguiar et al [26] reported that under relatively stable environmental conditions (i.e. when there is a lack of disturbance or stress), the coexistence of species with similar requirements occurs when intraspecific competition is more intense than interspecific competition.

Understanding weed-crop interactions is crucial in predicting crop yield loss, but it is also important to understand how these interactions affect weed productivity. Therefore, this research was conducted to characterize the vegetative productivity and fecundity of velvetleaf in a monoculture (without maize) and in a maize crop, according to weed density and environmental conditions during two experimental years. Furthermore, this research established a basis for constructing population dynamics models to predict the likely consequences of lower-input weed management that is being promoted to reduce the environmental impact of weed control.

MATERIALS AND METHODS

Field experiments

The experiments were conducted in 2006 and 2008 in an experimental field in the Institute "PKB Agroekonomik" Padinska Skela (7455462N, 4979442E, 78 m a.s.l.) near Belgrade (Republic of Serbia) in conventional maize tillage. The soil is an alluvial black marsh with 2.5% organic matter and pH 8.00. Soil preparation consisted of primary and secondary tillage. Cultural practices were conducted according to local practices for maize production. Fertilizer was applied at 92 kg N two weeks before planting. The maize hybrid "Dukat" was planted on May 06, 2006 and April 28, 2008. The experimental field was divided into two main plots: velvetleaf with maize (I) and velvetleaf without maize (II). Subplots in both main plots consisted of four velvetleaf plant densities: 1 (D_1), 2 (D_2), 4 (D_3), and 8 (D_4) plants m^{-1} in-row. Each experimental subplot was 4.2 m wide (equal to 6 rows at 0.7 m row spacing) by 5.0 m long. Each subplot was laid out in a randomized complete block design with four replications. Velvetleaf seeds were hydrated for 24 h prior to planting to facilitate uniform germination and seedling emergence. Six rows of each subplot (in both main plots) were overseeded with velvetleaf using a hand planter immediately after maize planting. Shortly after emergence, velvetleaf seedlings were manually thinned to defined densities. In main plot I, maize was planted at a standard density 0.70 x 0.25 m (57000 plants ha^{-1}). During both seasons all other weed species were controlled by hand weeding regularly.

Parameters of competitiveness

Plant height, fresh aboveground biomass per plant and leaf area index (LAI) were measured every two weeks beginning three weeks after planting in 2006 and four weeks after planting in 2008 (Table 1). Four total destructive harvests were taken per treatment (3 plants x 4 replications = 12 plants) from two lateral rows on either side of the plot (first, second, fifth and sixth rows) in both years. Plant height was measured from the soil surface to the highest point of the stem tissue. Aboveground shoots were clipped at the soil surface and weighed immediately in the field for fresh biomass. Leaves were removed from the shoots and leaf area measured using a Delta-T leaf area meter (Delta-T Devices, Burwell, Cambridge, UK). LAI per plant was calculated as the ratio of total leaf area divided by the area of the soil over which the plant grew. As velvetleaf seed capsules matured, samples were obtained by hand-harvesting the middle two rows (third and fourth rows), each of 5 m in length in every plot. Velvetleaf fecundity was calculated as seed mass $plant^{-1}$ and seed mass m^{-2}. Environmental conditions during two experimental years are shown in Table 2.

Data analyses

Statistical procedures were carried out using STATISTICA 5.0 software. Due to variations in averages for all parameters and variations in weather conditions (rainfall in the growing season was 309.4 mm and 235.6 mm in 2006 and 2008, respectively) from each year were analyzed separately. Data were subjected to one-way ANOVA (F-values) to evaluate the main effects of velvetleaf densities on velvetleaf vegetative productivity (plant height, fresh biomass $plant^{-1}$, LAI) and fecundity (seed mass $plant^{-1}$, seed mass m^{-2}) in the treatment without maize (intraspecific competition) and in the treatment with maize (interspecific competition). Plant height, fresh biomass, as well as LAI, were analyzed using a four-parameter log-logistic model, where the *C* term was fixed at 0 [27]:

Table 1. Time line and additional information about the trials.

	Years	
	2006	2008
Preceding crop	**soybean**	**Wheat**
Planting date	May 06	April 28
I-Date of first assessment	May 27	June 02
II-Date of second assessment	June 12	June 19
III-Date of third assessment	June 29	July 04
IV-Date of fourth assessment	July 14	July 16
Date of harvest	September 27	September 10
Duration of vegetation season	144 d	135 d

Table 2. Rainfall and GDD in 2006 and 2008 at the experimental field.

Month	Rainfall (mm) GDD			
	2006	2008	2006	2008
April		37.6		11.15
May	34.6	49.0	164.15	218.60
June	135.6	39.6	268.25	320.05
July	14.8	42.0	362.21	333.65
August	98.8	35.0	329.55	356.40
September	27.2	70.0	193.60	121.50
Total	**309.4**	**235.6**	**1317.76**	**1361.35**

$$Y = C + (D-C)/\{1+\exp[B(\log X - \log E)]\}$$

where *Y* is the response (e.g., plant height), *C* is the lower limit, *D* is the upper limit, *X* is GDD (growing degree days) calculated (see below) after crop planting, *E* is GDD giving a 50% response between the upper and lower limit (also known as inflection point, I_{50} or ED_{50}), and *B* is the slope of the line at the inflection point. The graphs were made with R program (R Development Core Team 2006) utilizing the dose-response curves (drc) statistical addition package.

Temperatures were converted to GDD using the following equation:

$$GDD = \Sigma\ [\{(T\text{max} + T\text{min})/2\} - T\text{base}]$$

where *T*max and *T*min are the daily maximum and minimum air temperatures (°C), respectively, and *T*base is the base temperature (10°C).

RESULTS

Velvetleaf seedling emergence began quickly after planting in 2006, but was delayed by approximately 7 d in 2008 (Table 1). Environmental conditions (rainfall and GDD) during the two years of this study were partially different (Table 2). In 2006, rainfall from planting to harvesting date was high (24% higher during the growing period than in 2008 for the same period), especially during June when the differences were the highest. On the other hand, GDD during the growing periods were similar in both years despite a 9-d shorter vegetation season in 2008. Because of environmental differences between years, velvetleaf vegetative and fecundity data could not be pooled because of the lack of homogeneity between variances. Therefore, the results are presented individually for each year.

Velvetleaf vegetative productivity

Regression parameters (±SE) for plant height, fresh biomass and leaf area index plant^{-1} production of velvetleaf at 1, 2, 4 and 8 plants m^{-1}, in treatments without and in a mixture with maize, are given in Tables 3 and 4 for 2006 and 2008, respectively. Velvetleaf density did not have a significant effect on its height in either of the treatments (with or without maize) in earlier growing periods, but the height was significantly affected by the density during the late season (F=5.6609; P≤0.01), except with maize in 2008 (Fig. 1). Furthermore, higher velvetleaf heights were measured in all treatments without maize.

The effect of velvetleaf density on fresh biomass plant^{-1} was significant (F=3.8355-278.2835; P≤0.01 or P≤0.05) during both years, except at the first assessment (Fig. 2; Tables 3 and 4). Starting from the second assessment, in both years at higher velvetleaf densities (4 and 8 plants m^{-1}) lower fresh biomass was obtained in both treatments, with and without maize. Contrary to this, at lower densities (1 and 2 plants m^{-1}) signifi-

Table 3. Regression parameters (±SE) for plant height, fresh biomass and leaf area index plant^{-1} production of *Abutilon theophrasti* at 1, 2, 4 and 8 plants m^{-1} in treatments without maize and in a mixture with maize, in 2006 (Fig. 1a, b; Fig. 2a, b; Fig. 3a, b).

	Response	Density (plant m^{-1})	Regression parameters (±SE)		
			B	*D*	*E*
A. theophrasti without maize	Plant height (cm)	1	-20.15 (1.64)	172.0 (4.71)	418.61 (30.91)
		2	-20.28 (4.41)	169.3 (4.50)	415.50 (31.45)
		4	-21.54 (4.81)	171.7 (4.32)	417.91 (32.15)
		8	-22.63 (1.63)	157.7 (6.11)	416.44 (56.22)
	Fresh biomass (g plants-1)	1	-19.87 (0.60)	678.4 (27.80)	408.22 (12.57)
		2	-20.18 (2.14)	644.5 (8.00)	408.31 (13.93)
		4	-17.11 (3.07)	468.0 (8.94)	408.30 (9.70)
		8	-18.13 (4.28)	402.2 (15.46)	407.95 (11.21)
	Leaf area index	1	-2.83 (0.35)	3.99 (0.14)	291.89 (18.94)
		2	-2.79 (0.36)	3.80 (0.21)	281.59 (19.25)
		4	-7.15 (0.76)	1.76 (0.06)	183.11 (2.45)
		8	-6.55 (1.03)	1.07 (0.05)	171.51 (4.42)
A. theophrasti with maize	Plant height (cm)	1	-20.50 (1.26)	164.5 (9.13)	419.78 (48.28)
		2	-20.41 (2.65)	159.3 (6.97)	415.88 (49.03)
		4	-20.97 (1.30)	154.2 (9.08)	417.26 (44.06)
		8	-19.85 (1.87)	140.2 (17.78)	416.22 (64.74)
	Fresh biomass (g plants-1)	1	-19.43 (1.43)	628.2 (38.83)	408.22 (12.57)
		2	-20.18 (2.14)	607.3 (30.64)	408.31 (13.93)
		4	-17.11 (3.07)	310.6 (18.83)	408.30 (9.70)
		8	-18.13 (0.28)	273.3 (13.77)	407.95 (11.21)
	Leaf area index	1	-2.87 (0.36)	3.80 (0.09)	300.82 (19.36)
		2	-2.68 (0.37)	3.41 (0.19)	287.59 (21.35)
		4	-6.35 (0.99)	1.44 (0.03)	178.78 (3.70)
		8	-5.79 (1.16)	0.98 (0.05)	172.16 (4.80)

Regression parameters are estimated by Eq. (1)

B – the slope of the line at the infection point, C – the lower limit, D – the upper limit, E – the growing degree days (GDD) giving a 50 % response between the upper and lower limit (also known as inflection point).

Table 4. Regression parameters (±SE) for plant height, fresh biomass and leaf area index plant^{-1} production of *Abutilon theophrasti* at 1, 2, 4 and 8 plants m^{-1} in treatments without maize and in a mixture with maize, in 2008 (Fig. 1c, d; Fig. 2c, d; Fig. 3c, d).

	Response	Density (plant m^{-1})	Regression parameters (±SE)		
			B	*D*	*E*
A. theophrasti without maize	Plant height (cm)	1	-36.28 (7.10)	176.1 (2.85)	604.98 (40.94)
		2	-36.06 (5.55)	175.3 (4.32)	605.49 (36.84)
		4	-32.92 (4.83)	165.7 (8.28)	610.19 (30.72)
		8	-35.77 (7.99)	159.0 (5.40)	606.83 (41.38)
	Fresh biomass (g plants-1)	1	-32.54 (4.13)	590.2 (16.21)	596.64 (11.86)
		2	-31.26 (3.78)	602.1 (14.78)	596.76 (10.22)
		4	-29.03 (3.36)	352.3 (2.16)	592.42 (5.04)
		8	-29.87 (4.41)	317.1 (5.32)	592.52 (6.01)
	Leaf area index	1	-4.50 (0.73)	3.92 (0.13)	498.15 (22.66)
		2	-4.57 (0.74)	3.77 (0.13)	500.90 (22.34)
		4	-5.57 (0.94)	1.51 (0.10)	354.02 (13.00)
		8	-3.61 (0.75)	0.97 (0.04)	333.21 (20.10)
A. theophrasti with maize	Plant height (cm)	1	-27.17 (2.19)	157.2 (7.76)	608.13 (22.25)
		2	-33.10 (2.88)	153.3 (9.06)	605.79 (44.89)
		4	-31.45 (4.07)	151.1 (6.13)	608.97 (29.82)
		8	-37.16 (2.83)	151.5 (8.10)	606.38 (63.10)
	Fresh biomass (g plants-1)	1	-30.05 (2.57)	528.2 (10.33)	595.06 (6.65)
		2	-30.99 (4.86)	463.4 (11.37)	593.42 (7.70)
		4	-26.37 (2.91)	252.0 (2.16)	588.67 (1.88)
		8	-28.51 (4.93)	238.1 (8.85)	589.37 (2.85)
	Leaf area index	1	-4.49 (0.71)	3.63 (0.09)	496.12 (21.83)
		2	-4.51 (0.54)	3.17 (0.11)	468.61 (15.91)
		4	-4.88 (0.49)	1.32 (0.08)	341.71 (8.69)
		8	-3.04 (0.60)	0.94 (0.07)	343.28 (23.26)

Regression parameters are estimated by Eq. (1)
Other details as in Table 3.

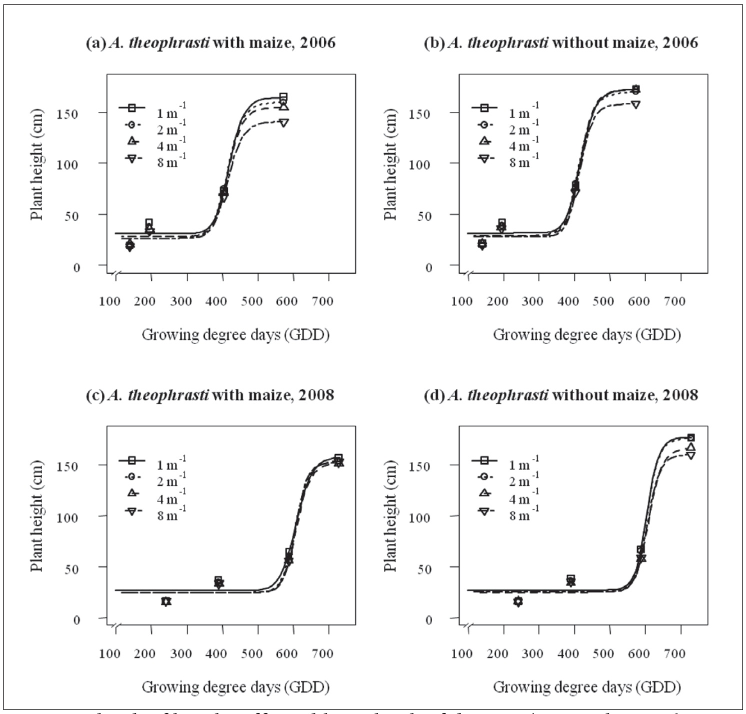

Fig. 1. Velvetleaf height affected by velvetleaf density (D_1- 1 plant m^{-1}, D_2- 2 plants m^{-1}, D_3- 4 plants m^{-1}, D_4- 8 plants m^{-1}) in treatments without and with maize. The regression lines were plotted using Eq. (1), and the parameter values are reported in Table 3 and 4.

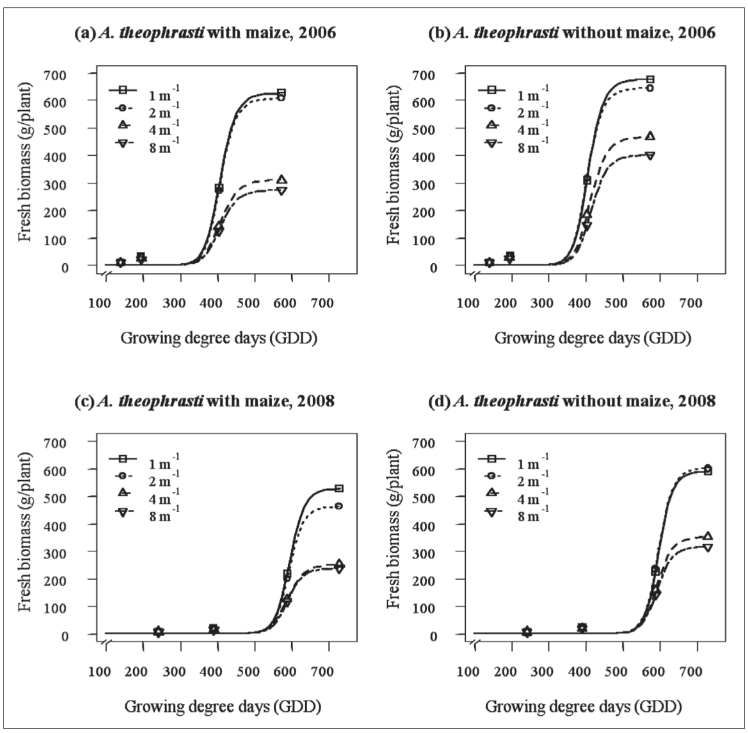

Fig. 2. Velvetleaf fresh biomass effected by velvetleaf density (D_1- 1 plant m^{-1}, D_2- 2 plants m^{-1}, D_3- 4 plants m^{-1}, D_4- 8 plants m^{-1}) in treatments without and with maize. The regression lines were plotted using Eq. (1), and the parameter values are reported in Table 3 and 4.

cantly higher fresh biomass was found in both years and both treatments. The greatest differences of density effects on the fresh biomass were confirmed at the last assessment, where the difference between the lower and higher density in 2006 were 40.7 and 56.5%, and in 2008 46.3 and 55.0% in the treatments without and with maize, respectively. Also, velvetleaf fresh biomass in both treatments was higher in the first than in the second year. The effects of velvetleaf density on LAI were similar to those on the fresh biomass. LAI was significantly ($P\leq 0.05$) affected by velvetleaf density at all times in the treatment without (F=8.8493-193.7320) and treatment with maize (F=25.3460-225.8788) in both years except in the first assessment (Fig. 3; Tables 3 and 4). Generally, LAI of velvetleaf in both treatments decreased with increasing plant densities. The largest difference in LAI was confirmed in the last assessment between the lower and higher density, which corresponded to 73.2 and 74.2% in 2006, and 75.3 and 74.1% in 2008, in treatments without and with maize, respectively. Also, velvetleaf LAI values were higher in the treatment without maize when compared to the treatment with maize. In addition, similarly to fresh biomass, the values of LAI in both treatments were higher in 2006 than in 2008.

Velvetleaf fecundity

Generally, in both years the seed mass plant^{-1} decreased as velvetleaf density increased, while seed mass m^{-2} increased as velvetleaf density increased in treatments without and with maize (Figs. 4 and 5; Table 5). The effect of velvetleaf density on seed mass plant^{-1} in treatments without and with maize was significant in both years (*$P\leq 0.05$*; F_{2006}=13.7383 and 10.6254, F_{2008}=10.6254 and 31.8309). Depending on the density (from D_4 to D_1), velvetleaf seed mass plant^{-1} ranged between 2.71 and 4.35 g, and 2.44 and 3.52 g in treatments without and with maize in 2006, respectively. A similar trend was found in 2008, were seed mass plant^{-1} ranged between 2.80 and 3.15 g,

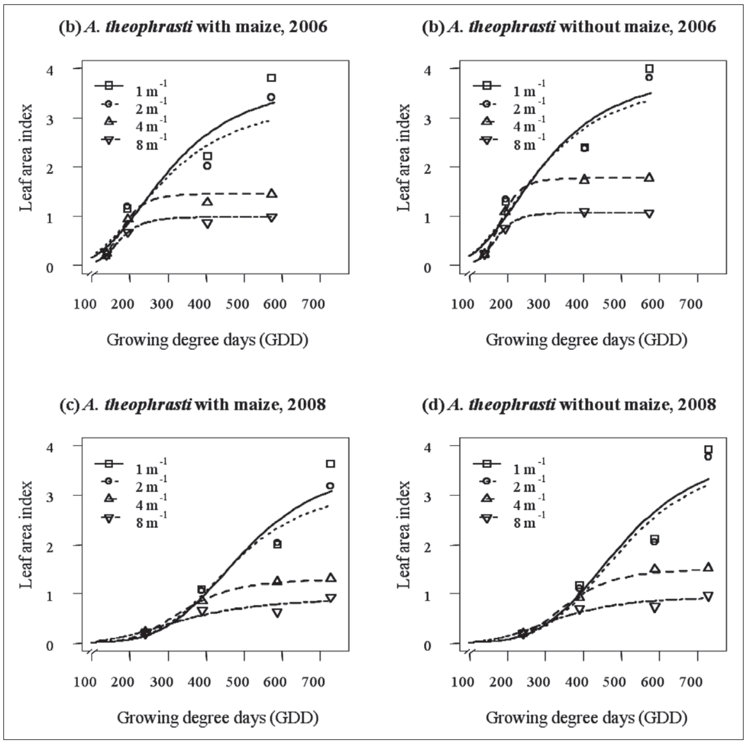

Fig. 3. Velvetleaf LAI affected by velvetleaf density (D1- 1 plant m-1, D2- 2 plants m-1, D3- 4 plants m-1, D4- 8 plants m-1) in treatments without and with maize. The regression lines were plotted using Eq. (1), and the parameter values are reported in Table 3 and 4.

Table 5. Velvetleaf seed production in different conditions.

Density	Treatments	2006		2008	
		seed mass plant^{-1}	seed mass m^{-2}	seed mass plant^{-1}	seed mass m^{-2}
D_1	monoculture	4.35±0.50	6.21±0.50	3.15±0.36	4.50±0.50
	mixture	3.52±0.12	5.03±0.46	2.84±0.06	4.05±0.40
D_2	monoculture	4.14±0.47	11.82±0.90	3.09±0.59	8.81±0.65
	mixture	3.72±0.04	10.64±0.96	2.78±0.03	7.93±0.60
D_3	monoculture	2.87±0.52	16.38±1.10	2.02±0.36	11.54±0.95
	mixture	2.58±0.06	14.74±1.00	1.82±0.03	10.38±0.95
D_4	monoculture	2.71±0.30	30.98±3.05	2.00±0.26	22.83±2.09
	mixture	2.44±0.06	27.88±2.10	1.80±0.02	20.55±2.00

and 1.80 and 2.84 g in treatments without and with maize, respectively. Quite the reverse, velvetleaf seed mass m^{-2} was significantly higher at the higher density (from D_1 to D_4) and ranged between 21 and 30.98 g, and 5.03 and 27.88 g in treatments without and with maize in the first year, respectively. The same trend was confirmed in the second year, were seed mass m^{-2} ranged between 4.50 and 22.83 g, and 4.05 and 20.55 g in treatments without and with maize, respectively.

DISCUSSION

Variable seed germination in 2006 and 2008 induced by environmental conditions in the pre-planting pe-

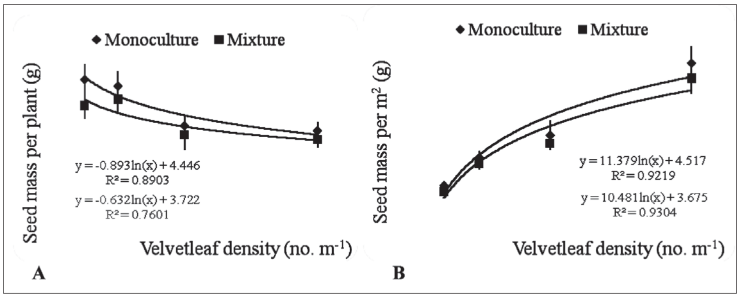

Fig. 4. Velvetleaf seed mass in 2006. **A** – velvetleaf seed mass plant^{-1}. Bars represent the standard error of the mean. The equation in the treatment without maize was y = -0.893 *ln*(x) + 4.446, R^2 = 0.890, and in the treatment with maize was y = -0.632 *ln*(x) + 3.722, R^2 = 0.670. **B** – velvetleaf seed mass m^{-2}. Bars represent the standard error of the mean. The equation in the treatment without maize was y = 11.379 *ln*(x) + 4.517, R^2 = 0.922, and in the treatment with maize was y = 10.481 *ln*(x) + 3.675, R^2 = 0.930.

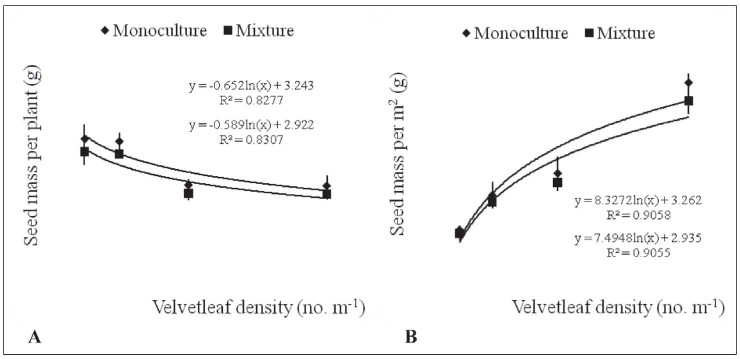

Fig. 5. Velvetleaf seed mass in 2008. **A** – velvetleaf seed mass plant^{-1}. Bars represent the standard error of the mean. The equation in treatments without maize was y = -0.652 *ln*(x) + 3.243, R^2 = 0.828, and in treatments with maize was y = -0.589 *ln*(x) + 2.922, R^2 = 0.831. **B** – velvetleaf seed mass per m^2. Bars represent the standard error of the mean. The equation in treatments without maize was y = 8.327 *ln*(x) + 3.262, R^2 = 0.906, and in treatments with maize was y = 7.495 *ln*(x) + 2.935, R^2 = 0.905.

riod (in a 30-d pre-planting period, 81.2 mm rainfall fell in 2006, compared with only 36.4 mm in 2008; data not shown) may explain the difference in emergence of velvetleaf. Differences in emergence time and environmental conditions during the growing period, as well as velvetleaf density, affected velvetleaf vegetative productivity (fresh biomass plant^{-1} and LAI) and fecundity in both treatments, without and with maize.

In our studies, increasing plant density often tended to decrease velvetleaf height but these results differ from those of Bailey et al. [16] and Werner et al. [28] where velvetleaf height was found to increase as plant density increased throughout the season. In addition, plant height differed between treatments and years. Depending on density, velvetleaf plants were taller in the treatment without maize compared with the treatment with maize by 4.4 to 11.1% and 4.7 to 12.8% in 2006 and 2008, respectively. Interspecific competition has shown a greater negative impact on velvetleaf height than intraspecific competition. The differences in velvetleaf height between years at all densities were not consistent when comparing treatments without and with maize. In the treatment without maize, velvetleaf plants were higher in relation to the treatment with maize in 2008 in all densities except at D_3; while in the treatment with maize velvetleaf was taller in 2006 in all densities except at D_4. Therefore, the impact of interspecific competition was prominent in the year with poor rainfall distribution (during June, the period of intensive velvetleaf growth, when cumulative rainfall was 135.6 and 39.6 mm in 2006 and 2008, respectively), which affected velvetleaf height in almost all densities.

Velvetleaf fresh biomass production decreased with increasing density and this decrease was proportional to density, which was the result of intra- and interspecific competition. In both years and all densities, interspecific competition was stronger than intraspecific. Our findings are in agreement with those of Scholes et al. [29] who reported a negative correlation between velvetleaf density and velvetleaf biomass production (at the lowest density the average plant weight was about 34 g, whereas at the highest density, the average plant weight was about 8.5 g). However, Werner et al. [28] reported a positive correlation between velvetleaf density and velvetleaf dry weight production m^{-2}. In addition, differences in plant fresh biomass between years were probably due to environmental conditions during the early-season growth (Table 2). Generally, velvetleaf produced a higher fresh biomass $plant^{-1}$ in all treatments in 2006 with favorable rainfall distribution. These results are in agreement with those of Conley et al. [30] based on weed density and cohort emergence time, where the maximum shoot biomass or fecundity m^{-2} differed between years. Also, Bailey et al. [16] found that velvetleaf density had no effect on the fresh weight, dry weight and stem diameter of velvetleaf plants in 1997. However, in 1998, all these parameters decreased significantly with increasing velvetleaf density. In our study, velvetleaf produced less fresh biomass $plant^{-1}$, depending on density, in the treatment with maize compared with the treatment without maize by 7.4-33.8% in 2006 and 10.6-33.1% in 2008, which was the result of interspecific competition. Lindquist et al. [11] also observed a substantially reduced velvetleaf biomass in a mixture with soybean. They explained that the reduction in velvetleaf survival in the mixture with soybean may have been due to competition for light because complete canopy closure occurred within 40 to 50 d after planting in the mixed stand plots.

In both treatments (velvetleaf with and without maize) and both years, velvetleaf LAI was negatively correlated with velvetleaf density. This demonstrates that the lack of space due to a denser plant population tended to hinder the growth and development of leaf area and *vice versa*. Our findings contrast with those of Scholes et al. [29] who reported a positive correlation between velvetleaf density and LAI. As with fresh biomass, LAI was higher in 2006 than in 2008. This suggests that velvetleaf that emerged later, due to poor rainfall distribution in the 2008 season, formed a smaller leaf area and was less competitive against maize than when it emerged early in 2006. Similar results were reported by Conley et al. [30] for relative leaf area of giant foxtail (*Setaria faberi* Herrm.), which depended on density in soybean.

Increased velvetleaf density tended to increase seed mass m^{-2} and decrease seed mass $plant^{-1}$ of velvetleaf in treatments with and without maize in both years. The reduction in fecundity in the treatment with maize may be due to competition for light because canopy closure occurred within 50 d after planting in the mixture with maize. A similar finding was reported by Cardina et al. [15], who measured maize yield and velvetleaf fecundity in response to density of early- and late-emerging velvetleaf. Our results coincided with past studies where seed production per plant decreased as velvetleaf density increased in rows of cotton [16]. Munger et al. [31] reported high velvetleaf seed production in a mixture with soybean in one year (770 seeds $plant^{-1}$), but low production in another year (17 seeds $plant^{-1}$). They attributed the low seed production to interspecific competition for water. Earlier, Zanin and Sattin [32] also observed a high velvetleaf seed production (3379 and 4520 seeds $plant^{-1}$) when grown in plots with maize. Seed production of this magnitude represents a substantial input to the seed bank, which is particularly important for velvetleaf seeds and which may survive for up to 50 years in soil [23].

Finally, velvetleaf height, fresh biomass $plant^{-1}$ and LAI were affected very significantly by velvetleaf density in treatments with and without maize. In addition, increased velvetleaf density tended to increase its fecundity (seed mass m^{-2}) in both treatments and in differing environmental conditions. Also, a larger number of plants per unit of area will leave more seeds, increase the seed bank and enable the increase in field weediness. These results indicate that when velvetleaf plants grow in relatively different environments, such as along field edges or in fields with poor crop stands, they are likely to produce a greater number of seeds. In addition, this result indicates that environmental conditions (distribution of rainfall throughout the season) and velvetleaf density can promote/reduce inter- and intraspecific competition. These data, with additional future experiments in similar environmental conditions and cropping systems, can help us construct population dynamic models to predict the population density, seed bank and competitiveness of velvetleaf and reduce input in weed management.

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