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Modeling of imazethapyr dose and velvetleaf (*Abutilon theophrasti* medik) density interaction on red bean (*Phaseolus calcaratus* L.) and velvetleaf competition

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Abstract: Background: Red bean (*Phaseolus calcaratus* L.) is cultivated as an economic crop in the Mazandaran Province, Iran. Velvetleaf (*Abutilon theophrasti* Medik.) competes severely with red bean growth and reduces yield. Imazethapyr is a selective herbicide recommended for management of grasses and dicotyledonous weeds in different crops including beans.

Objectives: This research was conducted to develop an empirical model of red bean yield that incorporates the dose-responses of imazethapyr and velvetleaf densities.

Methods: Modeling of imazethapyr herbicide dose on red bean and velvetleaf competition was conducted using four levels of velvetleaf densities and five dosages of imazethapyr arranged in a factorial design.

Results: Velvetleaf competitiveness decreased with the increasing imazethapyr dose represented by the standard dose-response curve. A model was improved to composing the dose-response standard curve with the rectangular hyperbola equation. This model estimated red bean economic yield under velvetleaf-free conditions, weed competitivity with no-herbicide application, and the imazethapyr dosage needed to decrease velvetleaf competitiveness about 50%. Imazethapyr at the 0.66 L ha^{-1} dose was sufficient to control the highest density (12 plants m^{-2}) of velvetleaf.

Conclusions: Information gained from this study will be important in evaluating economic and environmental terms.

Keywords: combined model; competition; dose-response; weed competitivity; yield loss

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1. Introduction

Herbicides are essential inputs in agroecosystems while the increasing of herbicide-resistant weeds, environmental damages, and economic constrains have led to reduce chemical control in various cropping systems (Swanton, Murphy, 1996). Therefore, producers are acclaimed to less herbicide application and apply integrative weed management practices including tillage to effectively control weeds. Moreover, the practices that reduce herbicide dose (lower than recommended doses) is considered as an alternative approach to weed management. Fernandez-Quintanilla et al. (2000) and Talgre et al. (2004) showed that reduced dose may reduce weed population appropriately but obtain optimum yield. Effectiveness of herbicide reduced dose was reported by Melo et al. (2019) in onions (*Allium cepa* L.). However, if reduction in herbicide doses are applicable, the interaction between weed density and herbicide dose in crop–weed interference may be effective in achievement to the unexpected results and may led to incomplete weed control, resulting crop yield loss (Zhang et al., 2000; Richards, 1993). To avoid such a failure in weed control and crop yield reduction, it is important to understand the interactions between herbicide dosages and weed density when crop and weed interfere.

Red bean (*Phaseolus calcaratus* L.) grows in different regions of Iran and is cultivated as a grain legume by farmers. Weeds, which can markedly decrease dry bean yield, are a major constrain in red bean production (Amini, Ghanepour, 2013). Velvetleaf (*Abutilon theophrasti* Medik.), from the Malvaceae family, is a troublesome weed in red bean production in Northern Iran due to its tall growth habit and great competiveness ability. These growth characteristics can severely reduce red bean growth and affect yield (Amini, Ghanepour, 2013). Imazethapyr, formulated as Pursuit®, is a selective herbicide that recommended for control of grasses and dicotyledonous weeds in soybean (*Glycine max*), bean (*Phaseolus vulgaris*), peanut (*Arachis hypogaea*), alfalfa (*Medicago sativa*), and chickpea (*Cicer arietinum*) in Iran (Ghadiri, 2002). Noor-Ziarat et al. (2019) reported that imazethapyr effectively controlled smellmelon (*Cucumis melo* var. agrestis Naudin) in soybean.

The objective of the research was to develop an empirical model of crop yield that incorporates the dose-responses of a herbicide and weed densities. To parameterize the model, the impacts of a range of imazethapyr doses and velvetleaf densities were examined in red bean. As a result of this research, new combined models can be applied to velvetleaf management decisions in red bean production.

2. Materials and methods

2.1 Field experiment

This study was set up in Mahmoudabad (36°35´N, 52°20´E), Mazandaran Province, Iran. This region has an average annual precipitation of 977 mm. The soil at this location was a silty loam with a pH of 7.4, 1.7% organic matter, and 0.07% total nitrogen. Treatments consisted of a factorial arrangement of four velvetleaf densities (0, 4, 8 and 12 plants m^{-2}) and five imazethapyr doses (0, 0.25, 0.5, 0.75, and 1 L ha^{-1}) in a randomized complete block design (RCBD) with three replicates. Seeds of velvetleaf were collected from a field at Sari Agricultural Sciences and Natural Resources University. Imazethapyr (100 g a.i. lit^{-1}, Gyta shimi, Iran) was applied at 0, 25, 50, 75 and 100 g a.i. ha^{-1}. The recommended dose of the herbicide is 100 g a.i. ha^{-1}.

The red bean cultivar 'Derakhshan' was sown at a density of 20 plants m^{-2} in 2 m × 4 m plots. Velvetleaf seeds were sown by hand simultaneously with red bean between rows. Seedlings were thinned after establishment to reach the optimum density in the experiment. A weed free treatment was maintained by hand weeding during the growing season. Imazethapyr was sprayed at 4 leaf stage of velvetleaf growth using a Matabi 18 electric knapsack sprayer equipped with Teejet nozzle and regulated to spray a volume of 250 L ha^{-1} at a pressure of 2.5 bars.

Red bean economic yield was determined from an area of 1.0 m^2 at maturity by hand cutting of plants. Matured red beans pods were separated from the plants. Seeds were extracted from pods and then cleaned and used as economic yield calculation. Velvetleaf was harvested at maturity and oven-dried at 60°C for 72 h and then weighed.

2.1.1. *Model development*

A rectangular hyperbola model was applied to explain the relation between the red bean yield and velvetleaf density (Cousens, 1985; Wilson, Wright, 1990). The equation for the relationship was:

$$Y = \frac{Y_0}{1 + \beta x} \quad (1)$$

where Y, Y_o, x, and β, are crop yield, weed-free crop yield, weed density, and weed competitiveness (velvetleaf density of 1/β that decrease red bean yield to half), respectively.

When ranges of imazethapyr dosage are used, the parameters of the model are affected by herbicide dosage. Therefore, the effect of herbicide dosage imported to the model and equation 1 was rewritten to equation 2. The general reaction curve for the i^{th} imazethapyr rate is:

$$Y = \frac{Y_{0i}}{1 + \beta_i x} \quad (2)$$

Using equation 2, a high number of parameters (2 parameters at each imazethapyr dosage) are required to predict red bean economic yield. However, if the relationship between each of the parameters of red bean yield without presence of velvetleaf (Y_o) and velvetleaf competitiveness (β) obtained with herbicide doses are integrated into equation 2, the final mixed model can be applied to yield from a range of herbicide dosages and weed densities.

2.1.2. *Statistical analysis*

No data transformation was needed for crop yield. All data were imposed to the analysis of variance (ANOVA) and non-linear regression was used to fit the models. The fitness of the models was tested with the use of Root Mean Square Error (RMSE) (equation 3) and r^2 (Sigmaplot, ver. 11).

$$RMSE = \sqrt{\left(\frac{1}{n}\right)\sum (Y_{obs} - Y_{pred})^2} \quad (3)$$

where Y_{obs}, Y_{pred}, and n, are observed values, predicted parameters, and number of samples, respectively. RMSE values and r^2 closer to 1 value indicate a better fit of the model to the data.

The Akaike Information Criterion (AIC) index (equation 4) was applied to select the best function to describe each parameter associated with herbicide dosages. AIC represents the sum of squared error decrease when the degree of freedom error is reduced and the model complexity is not appropriate (Burnham, Anderson, 2002).

$$AIC = nLn\left(\frac{RSS}{n}\right) + 2k \quad (4)$$

where RSS, n, and k, are sum of square of residuals, number of samples, and number of model parameters, respectively. After determining the minimum AIC, calculating the ranking functions Δi (eqn 5) was performed.

$$\Delta i = \mathrm{AIC}_i - \min \mathrm{AIC} \quad (5)$$

where AIC_i, and min AIC, represent AIC value of the i^{th} function, and the minimum AIC value calculated from the functions, respectively. Models with Δi values greater than 10 (Δi > 10) have relatively little support. This difference in the fitted functions and function with larger AIC is not appropriate. However, Δi < 10 refers to the lack of difference in the fitted functions and functions with a greater AIC also offers an appropriate fit (Burnham, Anderson 2002).

3. Results and discussion

3.1 Red bean yield modeling

The effect of velvetleaf density, imazethapyr dosages and interaction of velvetleaf density and imazethapyr rate on red bean yield was significant (Table 1) and therefore, the interaction of imazethapyr dose and velvetleaf density on red bean yield is modeled.

The velvetleaf-free red bean yield (Y_o) and velvetleaf competitiveness (β) parameters were approximated for each dose of imazethapyr by fitting equation 2 to red bean production using a nonlinear regression. Estimated values of this equation are presented in Table 2. The hyperbola model (formula 2) represented a good description (r^2= 0.75-1) of the red bean yield with imazethapyr dosages (Table 2).

The relationship between weed-free red bean yield (Y_o) and weed competitivity (β) parameters were studied separately at imazethapyr dose levels. To explore these relationships, the values of the estimated parameters (Y_o and β) were plotted against the different imazethapyr dosages (Figure 1).

There was no evidence that yield of red bean without presence of velvetleaf (Y_o) was markedly affected by imazethapyr doses (Table 3). Low values of r^2 (0.11) show that Y_o was not affected by imazethapyr dose and the linear model could not describe parameter changes with imazethapyr doses. Although the quadratic model had a high r^2 value, some of the coefficients of this model were not significant (P_{value}> 0.05), and Δi value <10 shows no difference between linear and quadratic models of this parameter at different herbicide doses (Table 3). However, this was not unexpected, as red bean growth is unlikely imposed to imazethapyr dose (as a selective herbicide); also, red bean yield in the non presence of velvetleaf was not imposed to imazethapyr dose, so equation 2 can be simplified to equation 6. It was also described previously by Kim et al. (2006) and Brain et al. (1999).

$$Y = \frac{Y_0}{1 + \beta_i x} \tag{6}$$

Results showed that β parameter was reduced by enhancement in imazethapyr dosage (Figure 1). The combination of weed-crop competition and herbicide doses supplies a proper method to improve herbicide application. Christensen's (1993) equation for the interaction between crop-weed competition and herbicide efficiency applied a single weed density and evaluated weed dry matter in order to investigate competition ability of cereal crops. Brain et al. (1999) modeled the complex relationship between herbicide dosage and crop-weed competition, but their model used weed dry matter data instead of weed density. Their model uses weed dry matter, which is not applicable for large-scale studies.

Since weed dry matter and competitiveness depend on weed leaf area, these two factors are interrelated. Moreover, the weed dry matter and herbicide dose relationship is properly described by the standard dose-response curve (logistic form). Therefore, changes of β parameter with imazethapyr dose can be modeled by applying the standard dose-response curve (equation 7),

$$\beta_i = \frac{\beta_0}{1 + \left(\frac{Dose_i}{LD_{50}}\right)^C} \tag{7}$$

where β_o, LD_{50}, and C, represents competitiveness without imazethapyr application, the logarithm of the herbicide rate needed to decline weed competition ability about 50%, and the response dose or steepness of the curve, respectively. The β_i and $Dose_i$ parameters represent

Table 1 - ANOVA results of effect of velvetleaf density and herbicide doses and interaction on red bean economic yield

S.O.V.	MS	
	d.f.	Economic yield
R	3	15236.98
Velvetleaf density	3	2035656.18 **
Herbicide dose	4	3112358.82 **
Velvetleaf density × Herbicide dose	12	413491.89 **
Error	57	19779.68
Coefficient of Variation (%)		6.34

**: significant at p=0.01; ns: non-significant.

Table 2 - Estimated parameters obtained from fitting the red bean economic yield data by hyperbolic model (equation 2) at imazethapyr dose levels

Imazethapyr doses (L ha^{-1})	Estimated parameters		r^2
	Y_o (kg ha^{-1})	B	
0	2644.9 (10.4)	0.118 (0.002)	1
0.25	2643.4 (56.5)	0.11 (0.008)	0.99
0.50	2608.4 (51.9)	0.016 (0.003)	0.93
0.75	2623.8 (30.7)	0.001 (0.002)	0.75
1	2685.7 (28.2)	0.005 (0.002)	0.86

Y_o, weed-free red bean economic yield (kg ha^{-1}); B, weed competitivity (a weed density of $1/B$ will reduce the crop economic yield by 50%). The numbers in parentheses are standard errors.

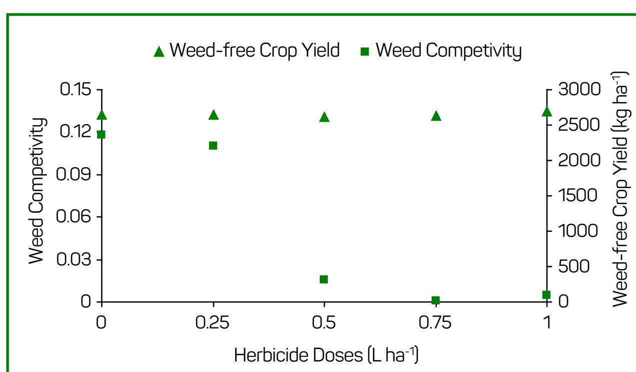

Figure 1 - Changes of the velvetleaf competitivity (β) and weed-free red bean economic yield (Y_o) parameters against imazethapyr doses

Table 3 - The relationship between weed-free red bean economic yield (Y_o) and velvetleaf competitivity (β) parameters with imazethapyr doses by different models

Parameter	Model		Estimated coefficient	P_{value}	r^2	RMSE	AIC	Δi
Y_o	Linear	a	2628.9 (24.4)	<0.0001	0.11	24.47	35.97	4.9
		b	24.7 (39.9)	0.5794				
	Quadratic	a	2654.2 (18.2)	<0.0001	0.77	12.24	31.05	-
		b	-177.8 (86.3)	0.1755				
		c	202.6 (82.7)	0.1341				
β	Linear	a	0.117 (0.023)	0.0142	0.81	0.022	-33.09	22.3
		b	-0.134 (0.037)	0.0365				
	Quadratic	a	0.1317 (0.028)	0.0436	0.86	0.019	-33.64	21.8
		b	-0.2517 (0.134)	0.2027				
		c	0.1177 (0.129)	0.4584				
	Standard dose-response	a	0.118 (0.003)	0.0008	0.99	0.002	-55.44	-
		b	0.375 (0.018)	0.0022				
		c	6.411 (0.9)	0.0192				

Linear, Quadratic, and Standard dose-response models are Y=a+bx, Y=a+bx+cx^2, and Y=a/(1+(x/b)^c), respectively. Where Y, and x, considered parameter, herbicide dose; and a, b, and c, coefficients are related to each model, respectively. RMSE and AIC, are Root Mean Square Error and Akaike Information Criterion, respectively. The numbers in parentheses are standard errors.

velvetleaf competitiveness and imazethapyr dose for the i^{th} imazethapyr dose, respectively.

Linear, quadratic, and standard dose-response (equation 7) models were fitted to the competitivity (β) parameter. Although linear and quadratic models had high value of r^2 (0.81, and 0.86, respectively), some of the coefficients of this model were not significant (P_{value} > 0.05) (Table 3). Smaller RMSE and AIC values for the standard dose-response model present an appropriate fit of the model to the β parameter. The Δi values for linear and quadratic models (> 10) show differences between the standard dose-response with linear and quadratic models in fitting of β at herbicide doses and this model (equation 7) which describe velvetleaf competitivity (β) against imazethapyr doses (r^2 = 0.99) (Table 3). Therefore, equation 6 can be rearranged to equation 8 by replacing β_i with equation 7.

$$Y = \frac{Y_0}{1 + \left(\frac{\beta_0 x}{1 + \left(\frac{dose}{LD_{50}} \right)^B} \right)} \quad (8)$$

Finally, equation 5 was fitted to red bean economic yield. The combined model (equation 8) presents a good description (r^2 = 0.94) of red bean yield. The estimated values for the model are indicated in Table 4.

Combined model estimated parameters of weed-free red bean economic yield (Y_o), velvetleaf competitiveness without imazethapyr application (β_o), the logarithm of the imazethapyr dose needed for 50% reduction of velvetleaf competitiveness (LD_{50}), and steepness of the dose-response curve (C) are 2622.5 kg ha^{-1}, 0.116, 0.376 L ha^{-1}, and 6.143, respectively (Table 4). The β_o value (0.116) indicates a density of 8.6 ($\frac{1}{0.116}$) plants m^{-2} will reduce red bean grain yield by 50%. Maximum red bean grain yield under weed-free conditions will be 2622.5 kg ha^{-1} (Table 4).

Table 4 - Parameter estimates for the simulation of red bean economic yield obtained from fitting the red bean economic yield data by combined model (equation 7) at different velvetleaf densities and imazethapyr doses.

Estimated coefficients		P_{value}	r^2
Y_o (kg ha^{-1})	2622.5 (21.3)	<0.0001	0.94
β_o	0.116 (0.007)	<0.0001	
LD_{50} (L ha^{-1})	0.376 (0.028)	<0.0001	
C	6.143 (1.41)	<0.0001	

Y_o, weed-free red bean yield (kg ha^{-1}); C, a response rate of the dose-response curve; β_o, weed competitivity at no-herbicide treatment; LD_{50} (L ha^{-1}), the log of the dose required to reduce weed competitivity by 50%. The numbers in parentheses are standard errors.

Weed dry matter is in a relationship with soil fertility and temperature which can change with external factors. Weed dry matter also varies during the crop life cycle, so the time during which it can be evaluated is not distinct. In comparison, the model presented in this study is according to the velvetleaf density early in the growing season, which stayed relatively fixed up to the last evaluation. Brain et al. (1999) modified the weed-crop competition model by supposing that weed competitiveness is linearly dependent on individual plant leaf area (Kropff, Spitters, 1991). Jolliffe et al. (1988) reported that the relationship between the total leaf area and the weed dry matter was allometric. Walsh et al. (2015) reported that imazethapyr dose needed for 80% control of velvetleaf was 18 g ha^{-1}.

3.2 Red bean economic yield prediction

Using equation 7 and predicted values (Table 4), red bean economic yield can be predicted in Figure 3. Red bean yield, with no imazethapyr application, decreased in a hyperbolic form in order of increasing velvetleaf density; whereas, at the recommended imazethapyr dose, no change in yield was observed. Also, the increase of herbicide dose under weed-free conditions had no effect on red bean yield. However, with increasing herbicide dose and velvetleaf densities, economic yield of red bean changed as S-shaped. When the imazethapyr dose was less than 0.25 L ha^{-1}, no change in red bean yield was noted at any weed density. At imazethapyr doses higher than 0.25 L ha^{-1}, yield quickly increased up to 0.75 L ha^{-1}. At doses higher than 0.75 L ha^{-1}, the effect of weed competition was absolutely eliminated (Figure 2).

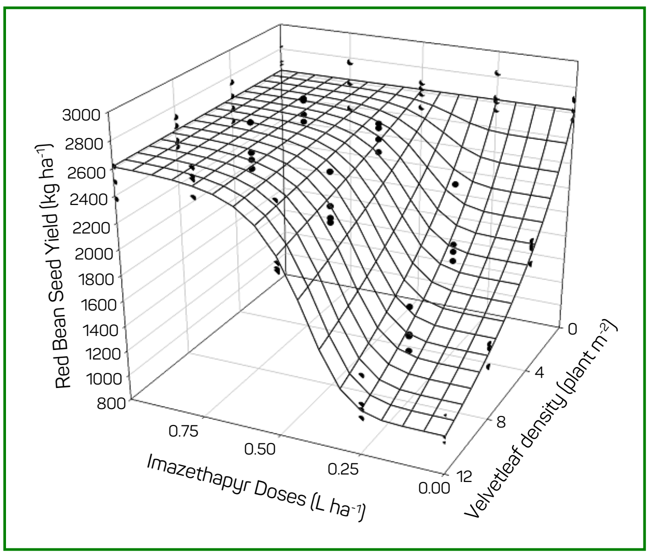

Figure 2 - Predicted red bean economic yield as affected by velvetleaf densities and imazethapyr doses

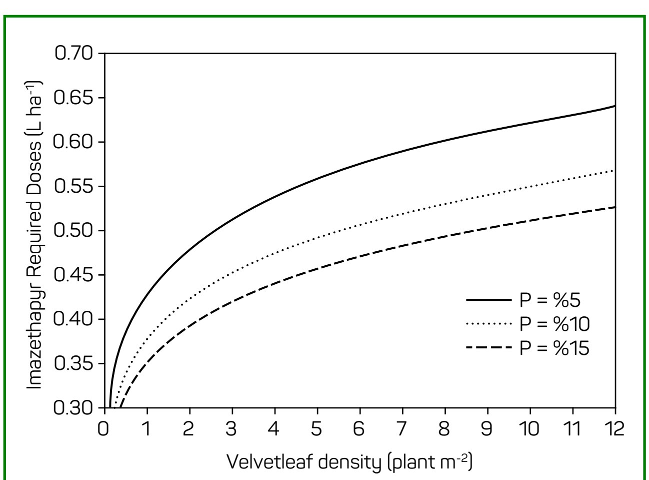

Figure 3 - Estimated imazethapyr doses required to restrict grain yield losses to less than p% for a range of velvetleaf densities

Equation 7 likely also supplies a response to the imazethapyr dose requirements. When a limitation of reasonable percent yields loss indicated by p%, and equation 7 readdressed to equation 9.

$$D_p = \exp(ED_{50}) \left(\frac{(100 - P)\, \beta_0 x_0}{P} - 1 \right)^{1/\beta} \tag{9}$$

where D_p, is the dose needed to decrease red bean yield reduction to lower than p%. For our study, D_p estimated by the values that denoted in Table 2 and equation 8 and the results indicated in Figure 3. For instance, if a reasonable yield loss was 5, 10, and 15%, and velvetleaf density was 12 plants m^{-2}, imazethapyr doses of 0.66, 0.58, and 0.54 L ha^{-1} can significantly influence weed control. Similarly, if p% was 5, 10, and 15%, and weed density was 4 plants m^{-2}, herbicide doses including 0.55, 0.49, and 0.45 L ha^{-1} can markedly reduce velvetleaf population (Fig. 3).

The goal of weed-crop relationship modeling is to forecast crop production. Incorporating factors such as herbicide dose mostly reduces the simplification of prediction process. However, the equation indicated in the research gives us an ability to predict the influence of herbicide dose. Since velvetleaf density and data from model 7 are known for a given site/year and equation 8 can estimate the suitable dose of imazethapyr; therefore, the risk of an unsuccessful weed control control can be reduced. Moreover, this equation also is appropriate for an economic analysis before using herbicides to improve economic yield.

4. Conclusions

The smaller number of parameters (four) in the model presented in this study compared with the equation of Brain et al. (1999) using weed dry matter (five parameters) is more suited to complicated and changeable situations, including multiple-weed species competition, fertilizer doses, and time of herbicide application studies. These findings gives us basic information to model the complicated relations between herbicides and weed competition. Our research was carried out in a field with an artificial velvetleaf infestation and in a one year/field; more research is necessary considering the effect of soil parameters and climatic information for validation and parameter adjustment of the model. Our results can be applied to rectangular hyperbolic equations according to leaf area that also has high applicability.

Authors' contributions

SH and RA: designed the study. SH: collected samples and carried out the measurements. SH, MR, and RA: analyzed and interpreted the data. MR and RA: wrote and edited the manuscript. JG: edited the quality of English writing of the manuscript as an English native language editor.

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