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ORIGINAL ARTICLE

Evaluating percolation of the herbicide S-metolachlor with bioindicator plants

Estudo da lixiviação do herbicida S-metolachlor com plantas bioindicadoras

Antonio Carlos da Silva Junior[1*]
Maria Renata Rocha Pereira[2]
Dagoberto Martins[1]

[1]Universidade Estadual Paulista "Júlio de Mesquita Filho" – UNESP, Jaboticabal, SP, Brasil
[2]Faculdade de Tecnologia do Estado de São Paulo – FATEC, Capão Bonito, SP, Brasil

***Corresponding Author:**
E-mail: acsjr_agro@hotmail.com

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ABSTRACT: Leaching can be influenced by the physical characteristics of soil and precipitation when the herbicide S-metolachlor is used intensively in sugarcane areas. The objective of this study was to use bioindicator plants to evaluate the percolation potential of S-metolachlor when submitted to natural pluviometric precipitation in two soils of contrasting textures: clayish (Entisols) and medium sandy (Oxisols). Samples were collected using PVC columns that were introduced in both soil types after the herbicide had been applied at the doses of 1,960 and 1,440 g ha^{-1} a.i of S-metolachlor, recommended for the clayish and sandy soils, respectively. The columns were carefully extracted from the soil by excavating around them, thus keeping soil physical integrity. The samples were taken after the soils had been submitted to 30 – 40, 60 – 80, and 100 – 120 mm of rainfall. The columns were divided by a longitudinal cut to permit the sowing of seeds of the bioindicator plants, allowing sufficient space for 25 plants per species in the columns (cucumber and lettuce). The bioindicator plants were evaluated with respect to their degree of toxicity by a degree scale ranging from 0 to 100%; these evaluations occurred at 5, 7, 10, and 12 days after sowing. We verified that herbicide percolation depended on soil texture and accumulated rain. Under high precipitation conditions, the herbicide percolates to deeper depths in sandy soils. Cucumber was the most appropriate bioindicator plant in soils of clayish texture. In sandy soils, both cucumber and lettuce showed suitability as bioindicator plants.

RESUMO: *Pelo intenso uso do herbicida S-metolachlor em áreas de cana-de-açúcar, a lixiviação pode ser influenciada pelas características físicas do solo, além da precipitação. O objetivo deste trabalho foi avaliar o potencial de lixiviação do S-metolachlor com precipitações pluviométricas naturais, em dois solos com texturas contrastantes, argiloso (Latossolo Vermelho-Amarelo) e médio arenoso (Neossolos Litólicos), em condições de campo através de plantas bioindicadoras. As amostras foram coletadas em colunas de PVC introduzidas nos diferentes solos. As colunas foram retiradas mantendo a integridade original do solo após a aplicação do herbicida nas doses recomendadas (1.960 e 1.440 g ha^{-1} de S-metolachlor para o solo argiloso e médio arenoso, respectivamente) e posterior acúmulo das precipitações em um intervalo estipulado ao ambiente (30-40, 60-80 e 100-120 mm de chuva). As colunas foram separadas com corte longitudinal para a semeadura das espécies bioindicadoras, de maneira que pudessem emergir 25 plantas por espécie nas colunas (pepino e alface). Depois da semeadura, adotou-se a escala de notas de 0 a 100% de fitotoxicidade, aos 5, 7, 10 e 12 dias após a semeadura. A lixiviação do herbicida S-metolachlor foi dependente da textura do solo e da precipitação acumulada de chuvas. Em condições de altas precipitações, o S-metolachlor pode atingir maiores profundidades no solo de textura arenosa. Por demonstrar a presença do S-metolachlor em maiores profundidades, o pepino mostrou-se mais apropriado como planta bioindicadora para estudos de lixiviação em solos argilosos, sendo que, para solos arenosos, tanto o pepino como a alface mostraram-se adequados.*

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1 Introduction

The herbicide S-metolachlor belongs to the chloracetamide chemical group and is applied to cotton, bean, corn, and sugarcane crops in Brazil (Fontes et al., 2006; Rodrigues & Almeida, 2011; Brasil, 2014). S-metolachlor consists of two R-isomers and two S-isomers that are present in similar proportions in the commercial product. The S-isomers have a more pronounced herbicidal action and this has resulted in the commercial development of the S-metolachlor herbicide. The most important attribute of this product is that it can be applied at lower doses, which results in less environmental damage than other products (Procópio et al., 2003).

S-metolachlor is a preemergence herbicide that is used to control certain weed species. When absorbed by weed seeds, this herbicide acts as a growth inhibitor through the suppression of chlorophyll, protein, fatty acid, lipid, isoprenoid, and flavonoid synthesis (EXTOXNET, 2000). S-metolachlor is absorbed mainly by the seedling coleoptile and hypocotyl when these tissues come into contact with the herbicide during seed germination. Roots and leaves absorb very low amounts of this herbicide (Karam et al., 2003).

An efficient method to reduce S-metolachlor losses from soil is to increase the sorption capacity of the soil organic matter (Singh, 2003). S-metolachlor has lower mobility in organic soils with an organic matter content of approximately 2.0% (EXTOXNET, 2000). In addition, the percolation of this herbicide may be inhibited in clay- or silt-rich soils (Rivard, 2003). This occurs because S-metolachlor exhibits a certain level of mobility in light-textured soils due to its slight solubility in water (530 mg L^{-1}), low Koc value (200 mL g^{-1}) and dissociation constant (pKa) of 0.0 (Worthing, 1983).

The vapor pressure of S-metalochlor is relatively low (1.3×10^{-5} mm Hg at 20 °C) and consequently, this product is not found in the air. However, S-metalochlor is potentially capable of contaminating underground water due to its moderate persistence in soil and water; the average field dissipation half-life is 114 days and the hydrolysis half-life exceeds 200 days (Rivard, 2003). The soil persistence of S-metolachlor is highly variable, e.g., its average half-life varied between 6 and 100 days under field conditions and 8 and 85 days under laboratory conditions and was completely dependent on the conditions under which the experiments were conducted (Nunes & Vidal, 2008).

S-metolachlor is used intensively in sugarcane crops, where its percolation may be influenced by soils that contain large pores and are poor in organic C. In addition, precipitation and/or artificial irrigation may influence the rate of S-metolachlor percolation into underground water. Southwick et al. (2009) verified that during periods of reduced precipitation, the volume of water flowing above the surface was reduced by 79%, which resulted in a mean reduction of 93% in the movement of S-metolachlor.

Because S-metolachlor is relatively soluble in water and is moderately absorbed by soil particles, this herbicide may be transported in superficial and subterranean water in a dissolved phase, resulting in its common presence in environmental water. This indicates the need to better understand the role played by sediments on the degradation and availability of agricultural contaminants in aquatic systems (Rice et al., 2004).

Therefore, we wanted to determine how soils with different textures affect the leaching of S-metolachlor under different water regimes. Consequently, the objective of this study was to evaluate the percolation potential of S-metolachlor under conditions of natural precipitation using bioindicator plants growing in two soil types.

2 Materials and Methods

The first phase of this study was established and conducted under field conditions and the second phase was completed in a greenhouse. Two experiments were conducted, one in a medium sandy soil and the other in a clayish soil, classified as an Oxisol and Entisol, respectively (Sergio et al., 2005). Chemical and granulometric analyses were performed on samples collected from the 0 – 10, 10 – 20, and 20 – 30 cm depths of both soil types (Tables 1 and 2).

In the field, PVC columns (30 cm in length, 15 cm in diameter) were inserted into the soil. Herbicide was applied and daily precipitation monitoring was initiated. The following cumulative precipitation values were recorded: 31 and 36 mm in the clayish and sandy soil, respectively, 4 days after herbicide application; 62 and 66 mm in the clayish and sandy soil, respectively, 11 days after herbicide application, and 114 and 116 mm in the clayish and sandy soil, respectively, 16 days after herbicide

Table 1. Chemical analysis results of the soil samples collected from different depths in both experiments (Exp) after the application of S-metolachlor.

Tabela 1. Resultado da análise química de amostras de solos de ambos os experimentos de diferentes profundidades que receberam os tratamentos com S-metolachlor.

Exp	depth (cm)	pH ($CaCl_2$)	OM[3] (g dm^{-3})	P_{resine} (mg dm^{-3})	K	Ca	Mg	H+Al	SC[4]	CEC[5]	BS[6] (%)
					-------------mmol$_c$ dm^{-3}------------						
Entisols[1]	0-10	4.8	22	11	1.6	33	14	46	48	94	51
	10-20	4.7	21	10	1.8	29	14	50	44	94	47
	20-30	4.7	25	9	2.1	30	15	51	47	98	48
Oxisols[2]	0-10	4.1	14	17	0.9	4	2	39	7	46	15
	10-20	4.1	13	19	0.4	4	2	34	7	40	16
	20-30	4.1	12	18	0.6	5	3	38	8	46	18

[1]clayish soil. [2]medium sandy soil. [3]Organic Matter. [4]Sum of Cations. [5]Cation Exchange Capacity. [6]Base Saturation.

Table 2. Granulometric analysis of two soils sampled at different depths after treatment with S-metolachlor.
Tabela 2. Análise granulométrica de amostras de solos em diferentes profundidades, nas quais recebeu o tratamento com S-metolachlor.

particle size (g kg^{-1})	Entisols[1] - depth (cm)			Oxisols[2] - depth (cm)		
	0-10	10-20	20-30	0-10	10-20	20-30
Clay	436	449	460	193	189	186
Silt	163	163	152	37	36	35
Coarse sand	100	100	100	315	693	303
Fine sand	301	288	288	455	482	477
Total sand	401	388	388	770	775	780
Soil Texture	clayish	clayish	clayish	medium	medium	medium

[1]clayish soil. [2]medium sandy soil.

application. These values are within the pre-established ranges of 30 – 40, 60 – 80, and 100 – 120 mm of rain.

Soil samples were carefully removed by excavating around the PVC column to maintain the original soil integrity. The lower part of each column was covered with a thin screen to maintain the soil integrity. A pluviometer was set up in each experimental area to measure cumulative precipitation.

The PVC columns were separated into two halves along a longitudinal cut made using a metal thread. The halves were separated using a galvanized metal lamina. Then, seeds of both bioindicator species [cucumber (*Cucumis sativus*) and lettuce (*Lactuca sativa*)] were seeded in the columns at 25 seedlings per species. The selection of these bioindicators was based on a literature review that indicated the sensitivity of these species to S-metolachlor (Oliveira et al., 1999; Deuber et al., 2004).

The S-metolachlor doses were based on the technical recommendations for each soil type, i.e., 1,960 g ha^{-1} a.i. for the clayish soil and 1,440 g ha^{-1} a.i. for the sandy soil. The herbicide was applied to the top of each column maintaining a distance of 50 cm between the upper side of the column and the spray boom. The tractor moved at a speed of 1 m s^{-1}. The sprayer was CO_2 pressurized with flat spray nozzles at a work pressure of 2 kgf cm^{-2}, which resulted in a product volume of 200 L ha^{-1}.

Herbicide toxicity in the bioindicators plants was evaluated 5, 7, 10, and 12 days after sowing (DAS) using values between 0 and 100%, where 0 indicated a plantlet with no signs of injury and 100% indicated a dead seedling (SBCPD, 1995).

The experiment was established using a completely randomized design with the treatments arranged in a 3 8 factorial; 3 represented the verified precipitation indices prior to sample collection (i.e., 31, 62, and 114 mm for the clayish soil and 36, 65, and 116 mm for the sandy soil) and 8 referred to the number of evaluated soil depths (0 – 3, 3 – 6, 6 - 9, 9 – 12, 12 – 15, 15 – 20, 20 – 25, and 25 – 30 cm). The results were subjected to an analysis of variance and the means were compared using Tukey's test at a 5% probability level using the SISVAR 5.3 program (Ferreira, 2011).

3 Results and Discussion

There was an interaction between soil depth and rainfall on the phytotoxicity measured in cucumber plants (Table 3 and Table 4). Five DAS, these plants in the clayish soil exhibited signs of toxicity to a depth of 6 cm at all precipitation levels (31, 62, and 114 mm). However, at 7, 10, and 12 DAS, toxicity was measured in the 6 – 9-cm depth under the 62- and 114-mm precipitation levels. This indicates that at the end of the evaluation period (12 DAS), S-metolachlor percolated to a depth of 6 cm in the clayish soil under 31 mm precipitation and a depth of 9 cm when the precipitation increased to 62 or 114 mm.

A comparison of the herbicide effects at the same depths (i.e., 0 – 3, 3 – 6, and 6 – 9 cm) under different precipitation levels indicated greater toxicity with higher levels of precipitation, i.e., 62 and 114 mm. Therefore, the herbicide tends to remain in soil solution under heavy precipitation.

The percolation of S-metolachlor under 114 cm precipitation was restricted to the 0 – 9-cm layer of the clayish textured soil. However, a higher herbicide concentration was measured in the 0 – 3-cm layer independent of the amount of accumulated precipitation. This is shown by the higher percentage of cucumber plants that exhibited toxicity (72.5, 99.5, and 99.5% under 31, 62 and 114 mm precipitation, respectively) in the 0 – 3-cm layer 12 DAS.

In a study conducted in Minnesota, USA in spring, low S-metolachlor concentrations were detected up to a depth of 60 cm but similar to the current study, the highest herbicide concentrations were detected at the soil surface (0 – 10 cm) (Papiernik et al., 2009). In a Brazilian study, researchers measured the percolation of S-metolachlor in five soil types and observed that the herbicide was concentrated in the superficial (0 – 5 cm) layer. However, when the soil organic matter content was low, deeper percolation occurred, which contaminated the underground water.

There was an interaction between soil depth and rainfall on the phytotoxicity measured in lettuce plants (Tables 5 and 6). When the evaluation was made 5 DAS, only the plants that received 31 mm precipitation exhibited toxicity at the 0 - 3 and 3 – 6 cm depths. These plants showed increased signs of toxicity 7 DAS. At a precipitation of 114 mm, toxicity was evident to a depth of 6 cm. Evaluations made 10 and 12 DAS indicated that S-metolachlor remained in the soil profile to a depth of 6 cm independent of precipitation.

S-metolachlor was retained in the superficial layers of the clayish soil and the concentration of this herbicide decreased with an increase in soil depth. The degradation and dissociation of non-ionic herbicides such as S-metolachlor are related to the organic matter and clay content of the soil (Oliveira Junior, 2007). For example, the percolation of S-metolachlor is low

Table 3. Phytotoxicity percentage in *Cucumis sativus* plants after the application of S-metolachlor (1,960 g ha^{-1} a.i.) to a clayish-textured soil under different rainfall amounts.

Tabela 3. Porcentagem de fitotoxicidade em plantas de pepino após aplicação do herbicida S-metolachlor (1.960 g ha^{-1} i.a.) em solo de textura argilosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall																	
	5 DAS[1]									7 DAS								
		31 mm			62 mm			114 mm			31 mm			62 mm			114 mm	
0-3	A	10.0 (0.31)[2]	b	A	23.7 (0.50)	a	A	17.5 (0.42)	a		42.0 (0.70)	b	A	57.5 (0.86)	a	A	46.2 (0.74)	b
3-6	B	2.5 (0.11)	b	B	6.2 (0.25)	a	B	10.0 (0.27)	a		12.5 (0.36)	c	B	36.2 (0.64)	a	B	23.2 (0.48)	b
6-9	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a		0.0 (0.00)	c	C	7.0 (0.26)	a	C	4.2 (0.14)	b
9-12	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a		0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
12-15	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a		0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
15-20	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a		0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
20-25	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a		0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
25-30	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a		0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
F Rainfall (R)					4.357*									13.407**				
F Profile (P)					84.382**									222.743**				
F (R) X (P)					2.075*									3.511**				
C.V. (%)					74.4									39.1				
d.m.s. (R)					0.09									0.11				
d.m.s. (P)					0.12									0.15				

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). *significant at level (p<0,05). **significant at level (p<0,01).

Table 4. Phytotoxicity percentage in *Cucumis sativus* plants after the application of S-metolachlor (1,960 g ha^{-1} a.i.) to a clayish-textured soil under different rainfall amounts.

Tabela 4. Porcentagem de fitotoxicidade em plantas de pepino após aplicação do herbicida S-metolachlor (1.960 g ha^{-1} i.a.) em solo de textura argilosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall																	
	10 DAS[1]									12 DAS								
		31 mm			62 mm			114 mm			31 mm			62 mm			114 mm	
0-3	A	43.7 (0.72)[2]	c	A	58.7 (0.87)	b	A	85.7 (1.23)	a	A	72.5 (1.02)	b	A	99.5 (1.53)	a	A	99.5 (1.53)	a
3-6	B	12.0 (0,35)	b	B	36.2 (0.64)	a	B	37.5 (0.65)	a	B	23.7 (0.50)	c	B	55.0 (0.84)	a	B	43.7 (0.72)	b
6-9	C	0.0 (0.00)	b	C	7.5 (0.27)	a	C	3.7 (0.13)	ab	C	0.0 (0.00)	b	C	10.0 (0.31)	a	C	9.2 (0.26)	a
9-12	C	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	D	0.0 (0.00)	a
12-15	C	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	D	0.0 (0.00)	a
15-20	C	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	D	0.0 (0.00)	a
20-25	C	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	D	0.0 (0.00)	a
25-30	C	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	D	0.0 (0.00)	a
F Rainfall (R)					17.322**									51.223**				
F Profile (P)					215.516**									769.140**				
F (R) X (P)					6.965**									14.192**				
C.V. (%)					41.0									22.2				
d.m.s. (R)					0.14									0.10				
d.m.s. (P)					0.18									0.13				

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). **significant at level (p<0,01).

Table 5. Phytotoxicity percentage in *Lactuca sativa* plants after the application of S-metolachlor (1,960 g ha^{-1} a.i.) to a clayish-textured soil under different rainfall amounts.

Tabela 5. Porcentagem de fitotoxicidade em plantas de alface após aplicação do herbicida S-metolachlor (1.960 g ha^{-1} i.a.) em solo de textura argilosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall					
	5 DAS[1]			7 DAS		
	31 mm	62 mm	114 mm	31 mm	62 mm	114 mm
0-3	A 16.2 (0.34)[2] a	A 0.0 (0.00) b	A 0.0 (0.00) b	A 35.0 (0.61) a	A 0.0 (0.00) b	A 35.0 (0.62) a
3-6	A 11.2 (0.22) a	A 0.0 (0.00) b	A 0.0 (0.00) b	A 29.2 (0.52) a	A 0.0 (0.00) b	B 2.5 (0.11) b
6-9	B 0.0 (0.00) a	A 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a
9-12	B 0.0 (0.00) a	A 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a
12-15	B 0.0 (0.00) a	A 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a
15-20	B 0.0 (0.00) a	A 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a
20-25	B 0.0 (0.00) a	A 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a
25-30	B 0.0 (0.00) a	A 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a	A 0.0 (0.00) a	B 0.0 (0.00) a
F Rainfall (R)		6.503**			8.888**	
F Profile (P)		2.938**			13.739**	
F (R) X (P)		2.938**			4.456**	
C.V. (%)		384.2			177.4	
d.m.s. (R)		0.15			0.24	
d.m.s. (P)		0.20			0.31	

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). **significant at level (p<0,01).

Table 6. Phytotoxicity percentage in *Lactuca sativa* plants after the application of S-metolachlor (1,960 g ha^{-1} a.i.) to a clayish-textured soil under different rainfall amounts.

Tabela 6. Porcentagem de fitotoxicidade em plantas de alface após aplicação do herbicida S-metolachlor (1.960 g ha^{-1} i.a.) em solo de textura argilosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall					
	10 DAS[1]			12 DAS		
	31 mm	62 mm	114 mm	31 mm	62 mm	114 mm
0-3	A 51 (0.80)[2] b	A 20.0 (0.46) c	A 73.7 (1.05) a	A 100.0 (1.57) a	A 78.7 (1.09) b	A 100.0 (1.57) a
3-6	A 33.7 (0.60) a	B 2.5 (0.08) c	B 10.0 (0.32) b	B 46.2 (0.80) a	B 3.7 (0.10) c	B 15.0 (0.39) b
6-9	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a
9-12	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a
12-15	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a
15-20	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a
20-25	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a
25-30	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a
F Rainfall (R)		8.502**			14.198**	
F Profile (P)		61.423**			217.174**	
F (R) X (P)		4.686**			6.379**	
C.V. (%)		87.9			50.4	
d.m.s. (R)		0.20			0.19	
d.m.s. (P)		0.27			0.25	

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). **significant at level (p<0,01).

in organic soils, which was observed in this study. In another study that examined percolation through soil, Fontes et al. (2004) detected S-metolachlor in the 0- to 5-cm soil layer in conventional seeding area. The soil used in their experiment contained more than 20 g kg^{-1} of organic matter and between 430 and 490 g kg^{-1} of clay in the 0 – 15-cm layer, which reduced percolation and restricted the herbicide to the 0 – 5-cm soil layer, similar to our results.

Cucumber plants growing in the sandy soil examined 5 DAS indicated that S-metolachlor remained at the 0 – 6-cm layer under 36 and 116 mm precipitation and in the 6 – 9-cm layer under 65 mm precipitation (Table 7). There was no interaction between soil depth and rainfall 7 DAS, but the percolation of S-metolachlor reached a depth of 6 – 9 cm when precipitation was 116 mm. At 10 DAS, the percolation depth of S-metolachlor was restricted to the 0 – 6-cm layer when precipitation was 31 mm; at 65 mm precipitation, S-metolachlor percolated into the 0 – 9-cm layer, reaching a depth of 12 cm when precipitation was 116 cm (Table 8). At 12 DAS, S-metolachlor was detected at a depth of 6 cm in the sandy soil following precipitation of 36 mm, and a depth of 12 cm at precipitation levels of 65 and 116 mm.

These results indicate that herbicide percolation was linked to the highest precipitation levels (65 and 116 mm), which improved the ease with which the herbicide moved down the sandy soil profile due to the pressure exerted by the infiltrated water. Similar results were reported by Inoue et al. (2010). According to these authors, S-metolachlor was transported to depths greater than 5 cm in sandy soils where water laminas 80 mm thick or more caused the herbicide to percolate to depths between 15 and 20 cm. This result confirms that the thicker the water lamina, the greater the vertical movement of herbicide in sandy soils.

Rain or artificial irrigation interferes with the action of herbicides, especially with respect to their intensity and movement in the soil profile, because herbicides are not effective if applied to dry soils. It is necessary to emphasize that water molecules have high polarity and may thus compete with the herbicide molecules for soil particle adsorption sites. In dry soils, herbicides are strongly adsorbed whereas in wet soils, herbicide molecules are dissolved in solution (Procópio et al., 2001) and can easily percolate into the soil.

There was an interaction between soil depth and rainfall on the phytotoxicity of lettuce plants growing in the sandy soil (Table 9 and Table 10). An evaluation performed 5 DAS indicated herbicide percolation to depths between 3 and 6 cm under 36 mm precipitation. At 7 DAS, S-metolachlor percolated into the 9 – 12-cm layer under 65 and 116 mm precipitation but remained in the 3 – 6-cm layer when the precipitation was 36 mm. In evaluations performed 10 and 12 DAS, the herbicide was detected at a depth of 9 – 12 cm under the highest precipitation levels (65 and 116 mm) but at shallower depths (6 – 9 cm) under lower precipitation (36 mm) (Table 10).

These results indicate that the S-metolachlor molecule is more mobile in sandy soils based on the injuries caused to lettuce plants in the 9 – 12-cm layer. Reported that S-metolachlor percolation through a soil with organic residue was strongly delayed in comparison with the same soil without the organic

Table 7. Phytotoxicity percentage in *Cucumis sativus* plants after the application of S-metolachlor (1,440 g ha^{-1} a.i.) to a medium sandy-textured soil under different rainfall amounts.

Tabela 7. Porcentagem de fitotoxicidade em plantas de pepino após aplicação do herbicida S-metolachlor (1.440 g ha^{-1} i.a.) em solo de textura médio arenosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall																	
	5 DAS[1]									7 DAS								
	36 mm			65 mm			116 mm			36 mm			65 mm			116 mm		
0-3	A	26.2 (0.53)[2]	a	A	12.5 (0.36)	b	A	10.0 (0.31)	b	A	46.2 (0.74)	a	A	33.7 (0.61)	ab	A	20.0 (0.45)	b
3-6	B	7.5 (0.19)	a	A	7.5 (0.27)	a	A	7.5 (0.27)	a	B	22.5 (0.42)	a	A	21.2 (0.47)	a	A	16.2 (0.40)	a
6-9	C	0.0 (0.00)	a	B	1.2 (0.05)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	b	B	6.7 (0.22)	a	B	5.0 (0.16)	ab
9-12	C	0.0 (0.00)	a	B	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a
12-15	C	0.0 (0.00)	a	B	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a
15-20	C	0.0 (0.00)	a	B	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a
20-25	C	0.0 (0.00)	a	B	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a
25-30	C	0.0 (0.00)	a	B	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a
F Rainfall (R)	0,651^{ns}									1.065^{ns}								
F Profile (P)	71,623**									65.281**								
F (R) X (P)	2,234*									1.822ns								
C.V. (%)	75.7									69.7								
d.m.s. (R)	0.10									0.17								
d.m.s. (P)	0.13									0.22								

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). ^{ns}not significant. *significant at level (p<0,05). **significant at level (p<0,01).

Table 8. Phytotoxicity percentage in *Cucumis sativus* plants after the application of S-metolachlor (1,440 g ha^{-1} a.i.) to a medium sandy-textured soil under different rainfall amounts.

Tabela 8. Porcentagem de fitotoxicidade em plantas de pepino após aplicação do herbicida S-metolachlor (1.440 g ha^{-1} i.a.) em solo de textura médio arenosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall																	
	10 DAS[1]									12 DAS								
	36 mm			65 mm			116 mm			36 mm			65 mm			116 mm		
0-3	A	51.2 (0.79)[2]	b	A	72.5 (1.02)	a	A	33.7 (0.61)	c	A	78.5 (1.09)	a	A	78.7 (1.09)	a	A	53.7 (0.82)	b
3-6	A	37.5 (0.65)	b	A	55.0 (0.84)	a	A	42.5 (0.70)	ab	B	58.7 (0.87)	a	B	58.7 (0.87)	a	A	50.7 (0.79)	a
6-9	B	0.0 (0.00)	b	B	22.5 (0.48)	a	A	25.0 (0.50)	a	C	0.0 (0.00)	b	C	37.5 (0.65)	a	A	38.7 (0.67)	a
9-12	B	0.0 (0.00)	a	C	0.0 (0.00)	a	B	5.0 (0.11)	a	C	0.0 (0.00)	b	D	8.7 (0.21)	a	B	6.2 (0.13)	ab
12-15	B	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	B	0.0 (0.00)	a
15-20	B	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	B	0.0 (0.00)	a
20-25	B	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	B	0.0 (0.00)	a
25-30	B	0.0 (0.00)	a	C	0.0 (0.00)	a	B	0.0 (0.00)	a	C	0.0 (0.00)	a	D	0.0 (0.00)	a	B	0.0 (0.00)	a
F Rainfall (R)					9.564**									10.018**				
F Profile (P)					137.528**									221.864**				
F (R) X (P)					6.004**									9.776**				
C.V. (%)					43.0									32.1				
d.m.s. (R)					0.17									0.16				
d.m.s. (P)					0.22									0.21				

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). **significant at level (p<0,01).

Table 9. Phytotoxicity percentage in *Lactuca sativa* plants after the application of S-metolachlor (1,440 g ha^{-1} a.i.) to a medium sandy-textured soil under different rainfall amounts.

Tabela 9. Porcentagem de fitotoxicidade em plantas de alface após aplicação do herbicida S-metolachlor (1.440 g ha^{-1} i.a.) em solo de textura médio arenosa, sob diferentes precipitações.

Soil profile (cm)	Accumulated rainfall																	
	5 DAS[1]									7 DAS								
	36 mm			65 mm			116 mm			36 mm			65 mm			116 mm		
0-3	A	38.7 (0.67)[2]	a	A	0.0 (0.00)	b	A	0.0 (0.00)	b	A	100.0 (1.57)	a	A	40.0 (0.68)	b	A	41.2 (0.69)	b
3-6	B	1.2 (0.05)	a	A	0.0 (0.00)	b	A	0.0 (0.00)	b	B	5.0 (0.11)	b	A	40.0 (0.68)	a	A	37.5 (0.65)	a
6-9	B	0.0 (0.00)	a	A	0.0 (0.00)	a	A	0.0 (0.00)	a	B	0.0 (0.00)	b	B	15.0 (0.39)	a	B	17.5 (0.42)	a
9-12	B	0.0 (0.00)	a	A	0.0 (0.00)	a	A	0.0 (0.00)	a	B	0.0 (0.00)	b	C	5.0 (0.19)	a	C	5.0 (0.11)	ab
12-15	B	0.0 (0.00)	a	A	0.0 (0.00)	a	A	0.0 (0.00)	a	B	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
15-20	B	0.0 (0.00)	a	A	0.0 (0.00)	a	A	0.0 (0.00)	a	B	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
20-25	B	0.0 (0.00)	a	A	0.0 (0.00)	a	A	0.0 (0.00)	a	B	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
25-30	B	0.0 (0.00)	a	A	0.0 (0.00)	a	A	0.0 (0.00)	a	B	0.0 (0.00)	a	D	0.0 (0.00)	a	C	0.0 (0.00)	a
F Rainfall (R)					120.115**									1.247[ns]				
F Profile (P)					100.130**									191.712**				
F (R) X (P)					100.130**									31.476**				
C.V. (%)					89.4									38.1				
d.m.s. (R)					0.04									0.14				
d.m.s. (P)					0.05									0.19				

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). [ns]not significant. **significant at level (p<0,01).

Table 10. Phytotoxicity percentage in *Lactuca sativa* plants after the application of S-metolachlor (1,440 g ha^{-1} a.i.) to a medium sandy-textured soil under different rainfall amounts.

Tabela 10. Porcentagem de fitotoxicidade em plantas de alface (*Lactuca sativa*) após aplicação do herbicida S-metolachlor (1.440 g ha^{-1} i.a.) em solo de textura médio arenosa, sob precipitações.

Soil profile (cm)	Accumulated rainfall					
	10 DAS[1]			12 DAS		
	36 mm	65 mm	116 mm	36 mm	65 mm	116 mm
0-3	A 100.0 (1.57)[2] a	A 95.2 (1.36) a	A 72.5 (1.03) b	A 100.0 (1.57) a	A 100.0 (1.57) a	A 83.5 (1.25) a
3-6	B 82.5 (1.16) ab	A 91.2 (1.28) a	A 65.0 (0.94) b	A 100.0 (1.57) a	A 99.2 (1.51) a	A 82.0 (1.19) a
6-9	C 12.5 (0.26) b	A 72.5 (1.04) a	A 47.5 (0.75) a	B 28.7 (0.43) b	A 84.5 (1.29) a	A 74.7 (1.15) a
9-12	C 0.0 (0.00) b	B 20.0 (0.39) a	B 20.0 (0.27) ab	B 0.0 (0.00) b	B 40.0 (0.61) a	B 24.5 (0.35) ab
12-15	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a
15-20	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a
20-25	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a
25-30	C 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a	B 0.0 (0.00) a	C 0.0 (0.00) a	B 0.0 (0.00) a
F Rainfall (R)		6.173**			4.036*	
F Profile (P)		115.498**			78.434**	
F (R) X (P)		4.554**			2.728**	
C.V. (%)		42.3			49.3	
d.m.s. (R)		0.30			0.43	
d.m.s. (P)		0.39			0.56	

Means within a column followed by the same upper case letter and within a line followed by the same small case letter are not significantly different at the 5% probability level according to Tukey's test. [1]DAS - days after sowing. [2]Data in parentheses were transformed using the equation y = arc sin (root(x/x/100)). *significant at level ($p<0,05$). **significant at level ($p<0,01$).

residue, which they ascribed to the presence of the organic matter. Similarly, we concluded that the low organic matter content in the soil used in the current experiment resulted in S-metolachlor percolation to depths of 12 cm. These results may be used to determine the potential mobility of agrochemicals and the likelihood of ground water contamination, as well as to supply governmental institutions with subsidies for implementing public policies (Lourencetti et al., 2007).

4 Conclusions

The percolation of S-metolachlor depended on soil texture and cumulative precipitation. S-metolachlor can percolate deeply in sandy soils under conditions of high precipitation. Cucumber was more sensitive than lettuce as a bioindicator plant in clayish soils because it was capable of detecting the presence of the herbicide at deeper soil layers. Cucumber and lettuce were equally sensitive in the sandy soil.

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