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Article

Leaching of Herbicides Commonly Applied to Sugarcane in Five Agricultural Soils

Lixiviação de Herbicidas Comumente Aplicados na Cana-de-Açúcar em Cinco Solos Agricultáveis

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ABSTRACT - Leaching intensity depends on the physicochemical properties of soils and herbicides. Consequently, a good understanding of this process is essential to determine mitigation measures to reduce or eliminate the risk of water contamination around areas with sugarcane crops. Therefore, the objective of this study was to analyze the leaching of ametryn, diuron, hexazinone, and metribuzin by using columns in five soils with different physicochemical properties cultivated with sugarcane. The radiolabeled herbicides with ^{14}C were evaluated at six soil depths (0-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, and 0.25-0.30 m) and in the leachate after 200 mm rainfall simulation for 48 h. Herbicide leaching was mostly affected by soil type. Ametryn and diuron were reported in the highest amount (>87%) on the topsoil (0-0.05 m), which was indicative of the low leaching of these two herbicides in the soil profile. Thus, these herbicides can contaminate surface water by runoff. Leachate percentage was always <0.3% for ametryn, diuron, and metribuzin; this was also the case for hexazinone in two out of the five soils. Hexazinone proved to be a potential contaminant of groundwater and metribuzin presented high leaching in the soil profile. Previous knowledge of the physico-chemical properties of soils cultivated with sugarcane is essential to recommend the use of these herbicides in weed management.

Keywords: soil behavior, pre-emergent, leachate, mobility.

RESUMO - A intensidade da lixiviação depende das propriedades físico-químicas dos solos e dos herbicidas. Consequentemente, uma boa compreensão desse processo é essencial para a determinação de medidas de mitigação para reduzir ou eliminar o risco de contaminação de águas próximas às áreas cultivadas com cana-de-açúcar. Portanto, o objetivo deste estudo foi analisar a lixiviação de ametryn, diuron, hexazinone e metribuzin usando colunas de cinco solos cultivados com cana-de-açúcar. Os herbicidas radiomarcados com ^{14}C foram avaliados em seis profundidades do solo (0-0,05; 0,05-0,10; 0,10-0,15; 0,15-0,20; 0,20-0,25; e 0,25-0,30 m) e no lixiviado após uma simulação de 200 mm de chuva por 48 horas. A lixiviação dos herbicidas foi principalmente afetada pelo tipo de solo. Ametryn e diuron foram encontrados em maior quantidade (>87%) na camada superficial do solo (0-0,05 m), mostrando a baixa lixiviação desses dois herbicidas no perfil do solo; assim, esses herbicidas podem contaminar as águas superficiais por escoamento superficial. A porcentagem do lixiviado foi sempre <0,3% para ametryn, diuron e metribuzin, o que também ocorreu para o hexazinone em dois dos cinco solos. O hexazinone mostrou ser um potencial contaminante das águas subterrâneas, e o metribuzin apresentou alta lixiviação no perfil do solo. O conhecimento prévio das propriedades físico-químicas dos solos cultivados com cana-de-açúcar é essencial para recomendar o uso desses herbicidas no manejo das plantas daninhas.

Palavras-chave: comportamento no solo, pré-emergente, lixiviado, mobilidade.

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INTRODUCTION

Among the existing problems in the sugarcane industry that affect production is weed control, which may account for losses from 74.1 to 90.5% of production without control (Yirefu et al., 2012). Such negative effects caused by the presence of weeds can be minimized by control practices, such as mechanical, cultural and chemical methods. Under the current production conditions in Brazil, the chemical method, which involves the application of herbicides, is the most widely used (Carvalho et al., 2010; Kuva and Salgado, 2014) because of extensive cultivated areas, limited availability of manual labor, ease of application, cost and treatment efficacy.

Herbicides play a vital role in modern agriculture. However, concerns about food safety and the environmental impact of residues of these molecules have increased (Zhang et al., 2010; Kubo et al., 2012). Because of agricultural herbicide applications, surface and ground waters have been contaminated as a result of runoff and leaching into the soil (Rozemeijer and Broers, 2007). The leaching process is the main form of descending transport of non-volatile and water-soluble molecules into the soil. These molecules move through the soil profile, along with the water flow. The water potential difference between two points and leaching intensity depend on the physicochemical properties of soils and herbicides (Inoue et al., 2003). Consequently, a good understanding of this process is essential to determine mitigation measures to reduce or eliminate water contamination risk (Dores et al., 2013) in the areas surrounding sugarcane cultivation.

A wide variety of herbicides are used in Brazil, and they may have a strong environmental impact because of their high leaching potential in soils (Dores et al., 2013; Toniêto et al., 2016). Among these herbicides, ametryn [1,3,5-triazine-2,4-diamine, N-ethyl-N'-(1-methylethyl)-6-(methylthio)], diuron [3-(3,4-dichlorophenyl)-1,1-dimethylurea], hexazinone [3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4 (1*H*,3*H*) dione], and metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] are pre-emergent herbicides heavily used for weed control in sugarcane. Indeed, they have been frequently reported in groundwaters (Kubilius and Bushway, 1998; Kim and Feagley, 2002; Caracciolo et al., 2005; Santos et al., 2015).

Therefore, the objective of the study was to evaluate the leaching of ametryn, diuron, hexazinone, and metribuzin using soil columns in five classes of soils from areas cultivated with sugarcane.

MATERIAL AND METHODS

Four leaching experiments were conducted, using ^{14}C-labeled ametryn, diuron, hexazinone and metribuzin according to the method described in the guidelines "Leaching in Soil Columns" by the OECD (2004).

The five soils used in the experiments were collected in sugarcane fields in the region of Piracicaba, São Paulo, Brazil, on Iracema Farms, from the 0-0.10 m depth layer after a layer of vegetation covering the soil was removed. The soil samples were air dried, sieved on a 1.7-mm mesh and stored at room temperature in labeled plastic bags. The main physicochemical properties of soils are shown in Table 1.

The stock solutions were prepared by using non-radiolabeled analytical standards of ametryn (4,000 g ha^{+1}), diuron (4,000 g ha^{-1}), hexazinone (500 g ha^{-1}), and metribuzin (1,920 g ha^{-1}), with purities of 99.0, 98.7, 99.5, and 99.7%, respectively (Sigma Aldrich, Saint Louis, MO, USA), at a concentration of 2.0 μg μL^{-1} in acetone for ametryn, diuron, and hexazinone; and 10.0 μg μL^{-1} in acetronitrile for metribuzin prior to preparing the herbicides for the work solution. The analytical standards ^{14}C-ametryn, ^{14}C-diuron, ^{14}C-hexazinone, and ^{14}C-metribuzin (Izotop, Budapest, Hungary) showed 100.0, 98.7, 99.7, and 97.0% radiochemical purity and 1.4, 2.4, 3.1, and 2.3 MBq mg^{-1} of specific activity, respectively. Radiolabeled and non-radiolabeled standards were carefully mixed in 0.01 mol L^{-1} $CaCl_2$ to the work solution, and then 200.0 μL of each solution was added to each soil column, directly applied with an automatic pipette to the moist soil at the top of each column. Thus, 785.0, 785.0, 98.0, and 380.0 μg a.i. (active ingredient) of ametryn, diuron, hexazinone, and metribuzin, respectively, were added to the glass column. Herbicide rates

Table 1 **-** Physicochemical properties of sugarcane areas of soils used in the experiments in Piracicaba, São Paulo, Brazil

Attribute	Soil classification – symbols$^{(1)}$				
	Clay-1 (LVe)	Clay-2 (LVAd)	Loam-1 (NXe)	Loam-2 (PVAe)	Sand (RQo)
Texture	clay	clay	loamy sand	loamy sand	sandy loam
Sand (%)	18.2	12.2	58.2	56.1	88.6
Clay (%)	72.9	75.4	30.2	32.7	10.1
Silt (%)	8.9	12.4	11.6	11.2	1.3
pH ($CaCl_2$)	5.09	4.45	5.93	5.11	4.96
P (mg dm^{-3})	60	24	19	6	20
S (mg dm^{-3})	19	79	7	11	4
K (mmol$_c$ dm^{-3})	6.4	3.1	1.4	2.2	0.4
Ca (mmol$_c$ dm^{-3})	32	28	78	23	16
Mg (mmol$_c$ dm^{-3})	28	26	60	14	6
Al (mmol$_c$ dm^{-3})	0.01	1	0.01	0.01	1
H+Al (mmol$_c$ dm^{-3})	38	71	9	23	22
SB (mmol$_c$ dm^{-3})	66.4	57.1	139.4	39.2	22.4
CEC (mmol$_c$ dm^{-3})	104.4	127.8	148.3	62.6	44.4
V (%)	64	45	94	63	50
OC (%)	1.8	1.0	1.2	1.6	2.0

(1) According to Soil Taxonomy and Brazilian Soil Science Society (Embrapa, 2013). Latossolo Vermelho eutrófico (Clay-1) [Oxisol Typic Hapludox], Latossolo Vermelho Amarelo distrófico (Clay-2) [Oxisol Typic Hapludox], Nitossolo Háplico eutrófico (Loam-1) [Nitosol Eutrophic], Argissolo Vermelho Amarelo eutrófico (Loam-2) [Udult soil] and Neossolo Quartzarenico órtico (Sand) [Typic Quartzipsaments]. **Source:** Department of Soil Science – ESALQ/USP, Piracicaba, SP, Brazil.

were calculated in accordance with a gathering depth of 0.1 m and column area equal 19.625 x 10^{-4} m^2.

A 0.50 m tall glass column (two repetitions) packed with samples of five types of soils was used for the experiment. The soil columns were prepared by closing the tip with quartz wool, filling the conical part with washed quartz sand dried in an oven at 100 °C and packing the column to a height of 0.30 m, placing small dry soil air at the bottom portions, and vibrating the set to accommodate the soil sample to avoid the formation of air bubbles. The soil samples which were conditioned on the columns were weighed to check the performance of the packaging process and contained 637.9 g of Clay^{-1}; 696.1 g of Clay^{-2}; 917.17 g of Loam^{-1}; 853.3 g of Loam^{-2}, and 951.9 g of Sand.

Soil columns were placed inside a 2.0 L beaker and wetted slowly with upward flow of a 0.01 mol L^{-1} $CaCl_2$ solution so that the solution level was not greater than 0.10 m front wetting of the soil sample. The soil sample was flooded for approximately 30 min. After flooding of the column, when the $CaCl_2$ solution reached the top of the upward flow, the columns were removed from the beaker and installed on an iron support to hold the soil columns. After 1 to 2 h, the $CaCl_2$ solution was drained.

After application, the surface of the soil sample was covered with a quartz wool disk, fitting an inverted funnel connected to a tube by which the 0.01 mol L^{-1} $CaCl_2$ solution was passed. A flow of approximately 8 mL h^{-1} for 48 h was simulated while using the 0.01 mol L^{-1} $CaCl_2$ solution, resulting in a rain simulation of approximately 200 mm in 48 h.

Every 12 h, three aliquots of 10 ml of leachate were collected and added to 10 mL of Insta-Gel for measurement by liquid scintillation spectrometry (LSS), using a Tri-Carb 2910 TR counter (LSA PerkinElmer, Waltham, MA, USA). After 48 h of radiolabeled herbicide application, the glass columns were removed from the support, the soil samples were withdrawn from the columns, and air was injected at the tip of the column to force the soil outlet, which was cut into six sections of equal-size depths (0-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, and 0.25-0.30 m). The soil samples were air dried, weighed, homogenized and ground in a mechanical mill (Marconi MA330, Piracicaba, SP, Brazil). Three sub-samples (0.2 g) of each dried layer of soil were biologically oxidized (OX500, RJ Harvey Instrument Corporation, Tappan, NY, USA) for quantification of total radioactivity.

The results were expressed as the percentage of radioactivity found in the leachate and in each segment of the column relative to the radioactivity initially applied. The recovery of the studies (sum of the percentages of radiolabeled herbicide found in the soil depth and leachate) should range between 90 and 110% for the radiolabeled substances according to the OECD (2004). Additionally, to check the repeatability and sensitivity of the analytical method, the samples of oxidized soil and leachate were analyzed in triplicate.

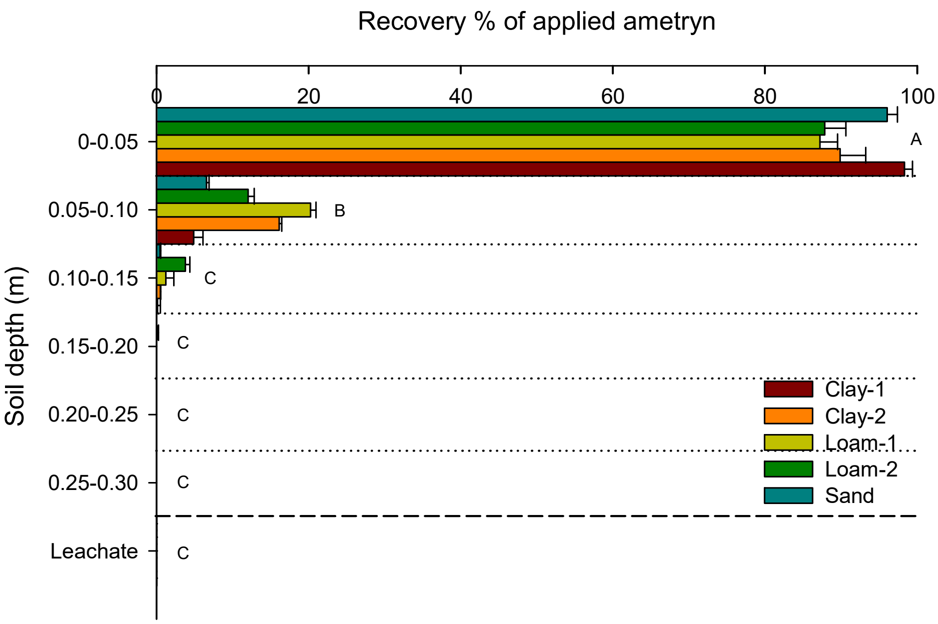
To analyze herbicide leaching along the soil column, an analysis was made of the effect of two factors, soil types and total leaching (herbicides found at six depths plus leachate), as well as their interactions. All measurements were performed in replicates, with arithmetic means and standard desviation of means (means ± SD) calculated from the repeated measurements. The entire data set was tested to ensure that the principles of the basic analysis of variance were met for each herbicide. In the case of significant effects, Tukey's test ($p<0.05$) for multiple comparisons of the means was used. Figures were plotted in Sigma Plot (version 10.0 for Windows, Systat Software Inc., Point Richmond, CA, USA).

RESULTS AND DISCUSSION

Mass balance was conducted to calculate the amount of ^{14}C found in the soil depth which was transformed into ^{14}C-CO$_2$ plus ^{14}C found in the leachate for all herbicides. Considering an efficiency of 98% of the biological oxidizer where determinations were performed, total recovery of ^{14}C ranged from 103.16 to 108.69%, 98.15 to 109.86%, 100.86 to 107.44%, 92.52 to 106.74%, of the initial applied dose of ametryn, diuron, hexazinone, and metribuzin, respectively, for all soil types, which indicates appropriate mass recoveries for the methods used in our studies.

The interaction between the five soils (Clay^{-1}, Clay^{-2}, Loam^{-1}, Loam$_{-2}$, and Sand) and total leaching (herbicides found in six depths plus leachate) was assessed for diuron ($F = 19.22$; $p<0.01$), hexazinone ($F = 23.09$; $p<0.01$), and metribuzin ($F = 4.02$; $p<0.01$) (Figures 2, 3, and 4, respectively), but not for ametryn ($F = 1.47$; $p>0.05$) (Figure 1).

Radioactivity of ametryn was reported only for superficial layers, and deeper layers (0.15-0.30 m) accounted for less than 0.2%; the highest percentage (>87%) of this herbicide was found



Means followed by the same uppercase letter for each soil depth plus leachate and lowercase letter for soil types do not differ by Tukey's test ($p<0.05$). The horizontal bars associated with each column represent the standard deviation (±SD) of each mean value ($n = 2$). LSD, least significance difference. LSD$_{\text{row (soil types)}}$ = 4.26; LSD$_{\text{column (soil depth and leachate)}}$ = 5.47. CV, coefficient of variation = 26.08%.

Figure 1 **-** Recovery percentage of ametryn applied in a glass column with different depths (0-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, and 0.25-0.30 m) of Clay^{-1} (Oxisol Typic Hapludox), Clay^{-2} (Oxisol Typic Hapludox), Loam^{-1} (Nitosol Eutrophic), Loam^{-2} (Udult soil), and Sand (Typic Quartzipsaments), with simulated rainfall of 200 mm for 48 h in the soil depth and leachate.

on the topsoil (0-0.05 m) (Figure 1), indicating limited leaching of this herbicide in the soil profile. This hypothesis was conformed, based on the fact that no ametryn was found in the leachate. Corroborating the data, Vivian et al. (2007) reported that most ametryn remained in the layer from 0 to 0.10 m depth in a Typic Haplufalf soil (pH = 6.6, organic carbon (OC) = 0.69-0.92%, and clay = 29-39%). Paula et al. (2016) also reported that, after the first rain simulation, 80% of the mass of applied ametryn remained at a depth of 0.05 m in a Red-Yellow Latosol (pH = 4.73, OC = 3.4%, and clay = 60%). Leaching of ametryn can be influenced by different physico-chemical soil properties; however, in our study, this influence was not found, probably because of the low number of study soils (*n* = 5). Leaching of ametryn was also influenced by rainfall intensity, OC content and pH of the Red-Yellow Ultisol (pH = 5.9, OC = 1.48%, and clay = 25%) and the Red-Yellow Latosol (pH = 4.9, OC = 0.98%, and clay = 44%) from pasture areas in Brazil (Andrade et al., 2010).

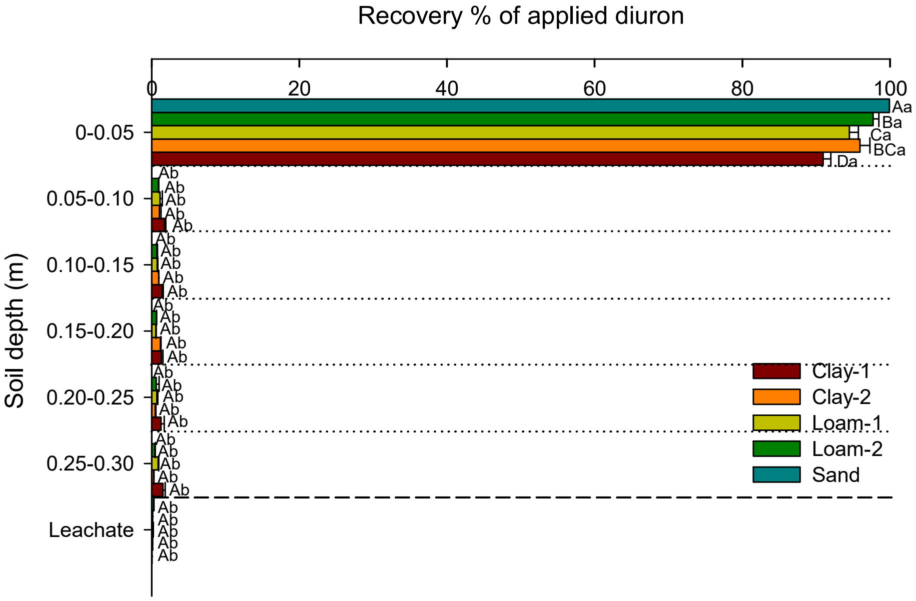
Ametryn is a very weak acid with 200 mg L^{-1} of water solubility at 20 °C, showing low leachability and dissociation coefficient (pK_a) of 10.07 (PPDB, 2017), although ametryn was present in a high amount in molecular (neutral) form within the pH range of soils (4.45-5.93) in this study (Table 1). On the other hand, Paula et al. (2016) reported that ametryn has a high leaching potential (1-7% detected in the leachate after 15 cm) in the long term because it is very persistent (over 60% of the herbicide remained in soil after 70 days of application). However, Mitchell et al. (2005) identified ametryn waste (0.3 μg L^{-1}) in river water in Australia, close to soils cultivated with sugarcane, probably carried with rainwater flow by runoff, which is usually inversely proportional to leaching.

Diuron was also concentrated on the topsoil (0-0.05 m), with more than 90% of the total amount of herbicided applied, but the highest diuron concentration was found in Sand soil (Figure 2). This fact can be justified by the higher OC content (2.0%) in Sand soil (Table 1). As well as ametryn, diuron also demonstrated less leaching (<2%) in the soil profile (0.05-0.30 m), and only about 0.3% of herbicide was reported in the leachate from all soils. This is similar to limited diuron leaching found in other studies (Caracciolo et al., 2005; Guzzella et al., 2006; Dores et al., 2013). The behavior of diuron in soil can be attributed to low water solubility (35.6 mg L^{-1} at 20 °C) (PPDB, 2017) and to high sorption coefficient, K_d = 14.3 mL g^{-1} in Brazilian soils (Dores et al., 2013) of this herbicide. Mendes et al. (2016) found that diuron was detected only in the superficial layer (0-0.05 m) of two soils, Alfisol – Paleudult (pH = 6.4, OC = 1.80%, and clay = 37.6%) and Ultisol - Typic Hapludalf (pH = 6.9, OC = 0.52%, and clay = 15.1%).

Several studies have indicated that diuron behavior is positively correlated with OC contents and cation exchange capacity (CEC) (Spurlock and Biggar, 1994; Troiano, 2001); thus, soils with low OC content exhibit high leaching of this herbicide. When studying leaching in soil columns of diuron in an Oxisol Typic Hapludox (OC = 0.34-0.72% and clay = 24-30%) and Typic Quartzipsaments (OC = 0.20-0.30% and clay = 6-11%) representative of the Guarani Aquifer recharge areas, Matallo et al. (2003) concluded that diuron leached through the 0.50 m layer, and the OC content of these soils determined the leaching capacity of this herbicide.

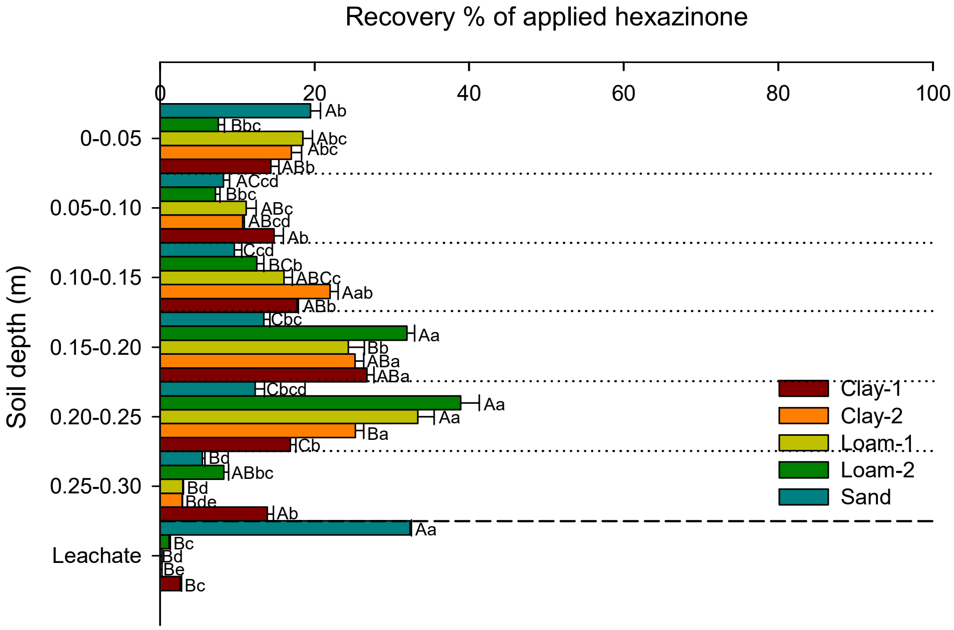
On the other hand, Chen and Young (2008) reported that diuron is a commonly used herbicide in California (USA) and it has been frequently detected in the drinking water of the state. They also found that diuron was probably carried with rainwater flow by runoff, as already described above. The study suggests that diuron may be a precursor to the formation of nitrosodimethylamine (NDMA). NDMA is a member of the N-nitrosamine family and a potentially strong carcinogen. The authors also report that increased concern about the occurrence of NDMA in drinking water has resulted from the reactions during chlorination or contamination with industrial effluents. In this study, the formation of diuron metabolites was not evaluated, but preventing this herbicide from going into the water sources is obviously of concern.

In general, radioactivity of hexazinone was found at different depths, with higher herbicide concentration (<39%) in the 0.15-0.25 m layer for all soils (Figure 3), indicating significant leaching of this herbicide in soil profile, as also reported by Mendes et al. (2016) and Reis et al. (2017). Roy et al. (1989), who studied the behavior of hexazinone in clay soils, also reported high herbicide concentrations in the first 0.15 m of soil (approximately 98%). Toniêto et al. (2016) reported that about 42% of the applied hexazinone was retained in the first 0.025 m of the straw layer of sugarcane and ~43% was leached (>0.30 m), with low sorption ($K_d \leq 1.74$ mL g^{-1}) in the



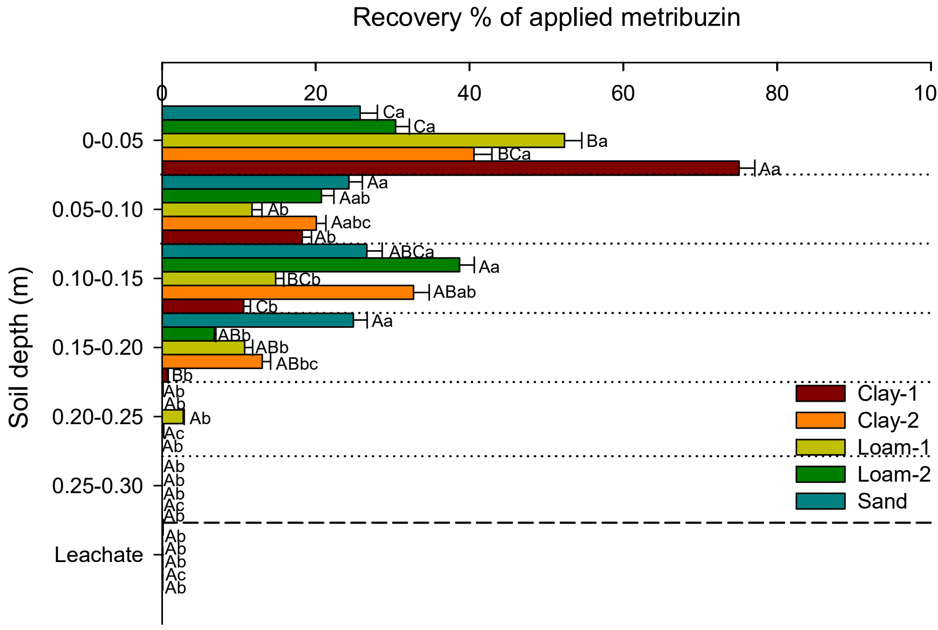
Means followed by the same uppercase letter for each soil depth plus leachate and lowercase letter for soil types do not differ by Tukey's test ($p<0.05$). The horizontal bars associated with each column represent the standard deviation (±SD) of each mean value (n = 2). $LSD_{row\ (soil\ types)}$ = 3.17; $LSD_{column\ (soil\ depth\ and\ leachate)}$ = 2.92. CV = 6.97%.

Figure 2 - Recovery percentage of diuron applied in a glass column with different depths (0-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, and 0.25-0.30 m) of Clay^{-1} (Oxisol Typic Hapludox), Clay^{-2} (Oxisol Typic Hapludox), Loam^{-1} (Nitosol Eutrophic), Loam^{-2} (Udult soil), and Sand (Typic Quartzipsaments), with simulated rainfall of 200 mm for 48 h in the soil depth and leachate.



Means followed by the same uppercase letter for each soil depth plus leachate and lowercase letter for soil types do not differ by Tukey's test ($p<0.05$). The horizontal bars associated with each column represent the standard deviation (±SD) of each mean value (n = 2). $LSD_{row\ (soil\ types)}$ = 7.88; $LSD_{column\ (soil\ depth\ and\ leachate)}$ = 7.26. CV = 16.83%.

Figure 3 - Recovery percentage of hexazinone applied in a glass column with different depths (0-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, and 0.25-0.30 m) of Clay^{-1} (Oxisol Typic Hapludox), Clay^{-2} (Oxisol Typic Hapludox), Loam^{-1} (Nitosol Eutrophic), Loam^{-2} (Udult soil), and Sand (Typic Quartzipsaments), with simulated rainfall of 200 mm for 48 h in the soil depth and leachate.



Means followed by the same uppercase letter for each soil depth plus leachate and lowercase letter for soil types do not differ by Tukey's test ($p<0.05$). The horizontal bars associated with each column represent the standard deviation (±SD) of each mean value (n = 2). $\text{LSD}_{\text{row (soil types)}} = 22.54$; $\text{LSD}_{\text{column (soil depth and leachate)}} = 20.75$. CV = 40.22%.

Figure 4 **-** Recovery percentage of metribuzin applied in a glass column with different depths (0-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, and 0.25-0.30 m) of Clay^{-1} (Oxisol Typic Hapludox), Clay^{-2} (Oxisol Typic Hapludox), Loam^{-1} (Nitosol Eutrophic), Loam^{-2} (Udult soil), and Sand (Typic Quartzipsaments), with simulated rainfall of 200 mm for 48 h in the soil depth and leachate.

clay Oxisol (pH = 4.3, OC = 2.3%, and clay = 59.3%). These authors also concluded that rainwater distribution is a crucial factor which dictates herbicide environmental fate because it is the vehicle by which the molecule is transferred from the straw to the soil in green-cane systems.

In this research, hexazinone leached <0.1% only for the Clay^{-2} and Loam^{-1} soils, following Clay^{-1} and Loam^{-2} (<3%), whch are not statistically different between soil types. However, higher leaching (~32%) was found in Sand soil as compared to other soils (Figure 3). According to Nicholls (1988), leaching is higher in sandy soils than in silty or clay soils. The data also agree with those found by Reis et al. (2017), who found that averages for hexazinone detected in the leachate were 0.03 and 5.01% for the clay soil (Dark-Red Latosol) and the sandy soil (Typic Quartzipsamments), respectively.

According to PPDB (2017), hexazinone is a weakly basic herbicide with $pK_b = 2.2$ and high solubility in water (33 g L^{-1} at 20 °C). The pH values of all soils used in this experiment are higher than this value (Table 1). This indicates that the molecules are predominantly in the molecular form and more available in the soil solution, hence they are more susceptible to leaching, which contributes to the increasing number of reports of contamination of surface water and groundwater sources (Queiroz et al., 2009).

In the case of metribuzin, radioactivity was found at different depths, except at a depth of 0.25-0.30 m, and higher amounts (<75%) of herbicide were retained in the first 0.05 m layer in Clay^{-1} soil, and only <0.2% of metribuzin was detected in the leachate from all soils (Figure 4). Kim and Feagley (2002) reported that the portion of metribuzin within the top 0.0-0.15 m soil depth was 75.4% of the portion found at the top 0-0.60 m soil depth about 30 days after application; as such, metribuzin was also mainly found at the top 0.15 m soil depth because of its high solubility in water (11.65 g L^{-1} to 20 °C), its weak sorption force (K_{foc} = 37.92 mL g^{-1}), its pK_b of 0.99 (PPDB, 2017), and its soil pH ranging from 4.45 to 5.93 (Table 1). Therefore, it is worth noting that the presence of OC in soils may also encourage increased sorption; hence, less leaching of metribuzin is found (López-Piñeiro et al., 2013). Triazine herbicides, such as metribuzin, are strongly acid in nature and their leaching is influenced by variation in soil pH

(Ladlie et al., 1976). However, in their studies, Savage (1976), Peter and Weber (1985) found that metribuzin leaching was also influenced by sand, clay and soil OC content.

Therefore, as previously described by Mendes et al. (2016), recommendations for the use of herbicides for weed management in areas cultivated with sugarcane without prior knowledge of the physico-chemical properties of the soil can result in inefficient control of weeds and possible contamination of groundwater and surface water.

With these findings, the following conclusions can be inferred about the potential leaching of ametryn, diuron, hexazinone, and metribuzin in soils cultivated with sugarcane. Leaching percentage was always <0.3% for ametryn, diuron, and metribuzin; for hexazinone, this was also the case in two out of the five soils. Hexazinone proved to be a potential contaminant of groundwater; metribuzin presents high leaching in soil profile whereas ametryn and diuron have low leaching in the short term and high intensity rainfall because of physicochemical properties; thus, these herbicides can contaminate surface water by runoff. For a more complete understanding about the bioavailability of these herbicides when applied in different soils, sorption-desorption and persistence studies should be performed.

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