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CROP PROTECTION

Carryover of tembotrione and atrazine affects yield and quality of potato tubers

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ABSTRACT. Crop rotation improves potato (*Solanum tuberosum* L.) crops; however, in some cases, it can have some negative effects due to the herbicides previously used in crops under rotation. These effects are the decline in the yield and the appearance of physiological disorders, including cracked tubers, which impair the quality and economic value of the potato. Two field experiments were performed with applications of tembotrione and atrazine, alone or in combination. In the Rio Paranaiba (Minas Gerais State) area, in clay soil, the herbicides were applied at post-emergence in corn (*Zea mays* L.). After corn harvest and soil preparation, the potatoes were planted. In the Serra do Salitre (Minas Gerais State) area, in the medium texture soil, the herbicides were applied and incorporated into the soil, and the potatoes were planted the day after. No injuries were found in the shoots. Decline in the potato yield was found only in the medium texture soil (Serra do Salitre). Atrazine did not affect the quality of potato tubers. In the two areas, tembotrione promoted cracks in "Atlantic" potato tubers.

Keywords: Atlantic; herbicide; physiological disorder; *Solanum tuberosum*.

Carryover de tembotrione e atrazine afeta a produtividade e a qualidade de tubérculos de batata

RESUMO. A cultura da batata (*Solanum tuberosum* L.) é favorecida pela rotação de culturas e, em alguns casos, desfavorecida pelos efeitos adversos dos herbicidas utilizados anteriormente nas culturas em rotação. Esses efeitos são redução de produtividade e desordens fisiológicas como, por exemplo, rachaduras de tubérculos, que reduzem a qualidade e valor comercial da batata para consumo *in natura* ou processamento industrial. Em dois experimentos de campo foram realizadas aplicações de tembotrione e atrazine, isolados ou em mistura. Na área de Rio Paranaíba (Estado de Minas Gerais) em solo de textura argilosa, os herbicidas foram aplicados na cultura do milho (*Zea mays* L.) em pós-emergência e na área de Serra do Salitre (Estado de Minas Gerais) em solo de textura média, foram aplicados e incorporados um dia antes do plantio da batata. Não foram observadas injúrias na parte aérea das plantas. A produtividade de batata foi reduzida somente no solo de textura média (Serra do Salitre). O atrazine não influenciou a qualidade dos tubérculos de batata. Nas duas áreas o tembotrione causou rachaduras em tubérculos de batata "Atlantic".

Palavras-chave: Atlantic; herbicida; desordem fisiológica; *Solanum tuberosum*.

Introduction

On the world stage, potato stands out among vegetables due to having the highest consumption and the largest quantity produced - 381 million metric tons in 2014 (FAO, 2017). Crop rotation is paramount for achieving the largest production and best quality of the potato (Campiglia, Paolini, Colla, & Mancinelli, 2009), mainly for interrupting life cycles of pests and diseases (Keiser Häberli & Stamp, 2012) and improving soil quality (Askari & Holden, 2015). However, the herbicides used in rotation crops such as corn and wheat can persist in the soil and impair growth and development of the potato plant.

Soils contaminated with herbicide residues reduce the yield of potato crops according to the cultivar used (Novo & Miranda Filho, 2006) due to the phenomenon known as herbicide carryover. Physiological disorders and the decline in the yield were observed due to sulfonylureas and imidazolinones (Eberlein & Guttieri, 1994; Eberlein, Westra, Harderlie, Withmore, & Guttieri, 1997; Novo & Miranda Filho, 2006), to auxin mimics

(Wall, 1994) and to glyphosate (Hutchinson, Felix, & Boydston, 2014), even at very low concentrations in the soil (for example, nicosulfuron 0.15 mg ha^{-1}) or due to treatment drift of areas adjacent to the potato crops.

Overall, the injuries caused by herbicide carryover are several patterns of chlorosis according to the herbicide, reductions in the growth and in the yield. In addition, these injuries can occur in tubers, causing physiological disorders such as multiple and deep cracks, tuber folding, tuber spiral, numerous side tubers connected to a single tuber or tuber chain (Eberlein et al., 1997; Thornton & Eberlein, 2001). The quality of tubers for fresh consumption or for industrial processing is reduced by the occurrence of any such physiological disorders.

Some Brazilian potato growers have reported that the tembotrione (2- {2-chloro-4-mesyl-3-[(2, 2, 2-trifluoroethoxy) methyl] benzoyl} cyclohexane-1, 3-dione) used in corn promotes physiological disorders in potatoes grown in succession, such as cracks in the tubers (personal communication). Those reports are substantiated by the 10-month restriction period information for the cultivation of potatoes after application of the product. Such information is included in the label for tembotrione (Laudis®), which is used in the United States of America (Bayer CropScience, 2015a). However, on the label of the tembotrione used in Brazil (Soberan®), Spain and Belgium (Laudis®), there is no information about a restriction period for the potato crop after using the product (Bayer CropScience, 2015 b; 2015c; 2015d).

Tembotrione is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) - inhibitor herbicide that belongs to the class of triketones, first registered in 2007. This herbicide is highly mobile in the soil (PPDB, 2017a), pKa = 3.17, weak acid characteristic, $t_{1/2}$ soil = 10 -14 days under laboratory conditions and tends to remain more stable in soils with higher pH (Barchanska, Kluza, Krajczewska, & Maj, 2016). Little is known about the behaviour of tembotrione in soil under field conditions and its effects on succeeding crops.

Atrazine (6-chloro-N2-ethyl-N4-isopropyl-1, 3, 5-triazine-2, 4-diamine) is also a widely used herbicide in maize crop that has high mobility in soil, pka = 1.7, characterizing a very weak base and $t_{1/2}$ soil = 75 days under laboratory conditions (PPDB, 2017b). Atrazine carryover potential associated with other herbicides was investigated in cabbage and beet (Soltani, Sikkema, & Robinson, 2005), carrot (Bontempo et al., 2016), potato, broccoli, onion and cucumber (Robinson, 2008). According to Robinson (2008) the atrazine accentuates the toxic effects caused by the mesotrione carryover in the soil on several vegetable crops. In a study completed in Brazilian soils, under tropical conditions, a reduction of the total yield of carrot was observed, grown in succession to corn, caused by the carryover of atrazine + tembotrione (Bontempo et al., 2016). This fact reinforces the need to also investigate the effects of atrazine associated with tembotrione in potato cultivation.

There may be considerable time from the start to the manifestation of physiological disorders, making it difficult to identify the causative factor and the time of initiation. Some disorders become an issue close to or during the harvest (Hiller, Koller, & Thorton, 1985). The identification of the causative factor becomes more complicated when the suspect factor may be present in the soil even before cultivation of potatoes, such as, for example, with herbicide carryover.

Thus, the objective of this study was to evaluate the carryover effects of tembotrione and atrazine on the quality and yield of potato tubers under field conditions.

Material and methods

Experimental details

Two experiments were evaluated, one in the summer of 2013/14 in Rio Paranaíba (19°12'29" S, 46°07'57" W and 1.136 m above sea level) and the other in the summer of 2014/15 in Serra do Salitre (19°6'41" S, 46°41'23" W and 1.203 m above sea level), both municipalities of Minas Gerais State, Brazil. In the area of Rio Parnaíba, the soil is classified as an Oxisol containing 42% clay, 51% silt and 7% sand, with a cation exchange capacity (CEC) of 5.79 $cmol_c$ dm^{-3}, 2.9% organic matter and pH of 5.5. In Serra do Salitre, the potatoes were grown in an Oxisol of medium texture with 19.4% clay, 2.7% silt and 77.9% sand, CEC of 5.79 $cmol_c$ dm^{-3}, 2.25% organic matter and pH of 6.2. The medium texture soil in Serra do Salitre was chosen because of its reduced sorption of herbicides that would enhance the phenomenon under study.

In the two experimental areas, herbicide treatments were applied in late spring, the season for corn planting in Brazil. The climatic data (rainfall, maximum and minimum temperatures) were collected daily in both areas (Figure 1A and B).

In both areas, the potato cultivar "Atlantic" was planted in a spacing of 0.87 m between rows and 0.22 m between plants. This cultivar was selected for being the most cultivated cultivar in the major potato-producing regions of Brazil. Cultural practices of fertilization, irrigation and pest management followed the standard management of potato-producing areas.

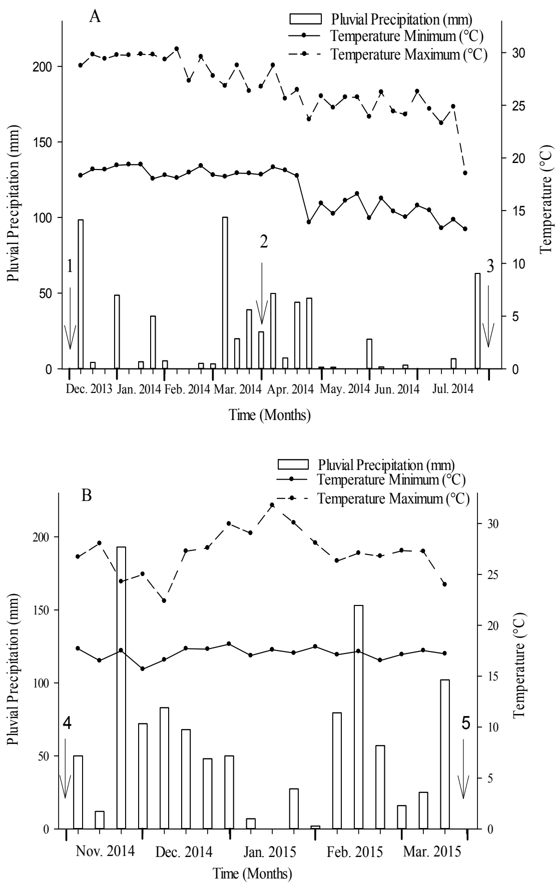

Figure 1. Pluvial precipitation (mm), maximal and minimal air temperature (°C) over experimental period in the experimental area of Rio Paranaíba (A) and Serra do Salitre (B). 1 - Herbicide application; 2 - potatoes planting; 3 - harvest; 4 - herbicide application and incorporation; and 5 - harvest.

Experimental design

In Rio Paranaíba, the treatments were tembotrione (50.4 and 100.8 g ha^{-1}), atrazine (2,000 g ha^{-1}), atrazine + tembotrione (2,000 + 100.8 g ha^{-1}) and a control with no application of herbicides that was manually weeded. The doses of herbicides are those recommended for corn on the labels of the products sold in Brazil. Treatments were applied at post-emergence in corn at the V3 (three fully expanded leaves) stage on December 12th, 2013. After corn harvest and soil preparation in the 0 - 40 cm layer, the potatoes were planted on March 28th, 2014.

In Serra do Salitre, the treatments were tembotrione (33.6 and 50.4 g ha^{-1}), atrazine (2,000 g ha^{-1}), atrazine + tembotrione (2,000 + 50.4 g ha^{-1}) and a control with no application of herbicide that was manually weeded. The herbicides were applied and incorporated into the soil layer of 0-40 cm on November 9th, 2014, and the potatoes were planted the day after to ensure greater herbicide-tuber contact. Half of the dose of tembotrione in the Rio Paranaíba area was used due to the higher bioavailability of the product in the medium texture soil, which could cause severe injury resulting in the death of plants. A sprayer pressurized with CO_2 operating at 200 kPa and spray volume of 200 L ha^{-1} were used in all treatments.

A randomized block experimental design with four replications was used in both areas. Each plot consisted of four potato rows with 8 m in length (27.8 m^2), and the useful area for evaluation consisted of two central rows of 6 m in length (10.5 m^2).

Evaluations

The injuries in the shoots of the potato plants were evaluated on days 15 and 30 after sprouting, when scores from 0 (no symptoms in the shoot) to 100% (total plant death) were assigned. The presence of cracks in tubers was evaluated in 20-day intervals on two potato plants by plot.

Harvest was carried out on July 18th, 2014 in Rio Paranaíba and on March 14th, 2015 in Serra do Salitre, fifteen days after the chemical desiccation of the shoots with paraquat (1,1-dimethyl-4,4'-bipyridinium dichloride) (400 g ha^{-1}). Tuber yield and percentage of tubers with cracks were evaluated.

Statistical analysis

Data were submitted to ANOVA ($p < 0.05$) using the SISVAR software for each experiment. The data were submitted to Tukey's test ($p < 0.05$).

Results

No symptoms caused by the herbicides could be seen on the shoots in the two experimental areas (data not shown).

In the Rio Paranaíba area, the potato tuber yield was not affected by tembotrione or by atrazine in the soil (Table 1).

Tembotrione promoted cracks in the tubers in both areas. The percentage of cracked tubers varied according to dose applied. Atrazine alone did not cause cracks in the tubers in the two areas (Table 1). In the area of Serra do Salitre, total tuber yield was reduced when tembotrione was applied in combination with atrazine or alone at both evaluated doses (Table 1).

Table 1. Total yield and yield of cracked potato tubers grown in Rio Paranaíba (Minas Gerais State) in clay soil and in the medium texture soil in Serra do Salitre (Minas Gerais State) with tembotrione and atrazine applications.

Treatments	Yield potato tubers (t ha^{-1})		% C/T[1]
	Total	Cracked	
		Rio Paranaíba	
Control	35.4 a [2]	0 c	0.0
Atrazine (2,000 g ha^{-1})	35.3 a	0 c	0.0
Tembotrione (50.4 g ha^{-1})	34.9 a	2.0 b	5.7
Tembotrione (100.8 g ha^{-1})	34.4 a	4.2 a	12.2
Atraz. + Temb. (2,000 + 100.8 g ha^{-1})	36.0 a	2.4 ab	6.6
Variation Coefficient (%)	6.3	48.3	
		Serra do Salitre	
Control	33.8 a	0.0 c	0.0
Atrazine (2,000 g ha^{-1})	34.0 a	0.0 c	0.0
Tembotrione (33.6 g ha^{-1})	27.5 b	0.1 a	0.3
Tembotrione (50.4 g ha^{-1})	26.4 bc	0.1 a	0.3
Atraz. + Temb. (2,000 + 50.4 g ha^{-1})	22.8 c	0.03 b	0.1
Variation Coefficient (%)	5.4	22.1	

[1] % C/T: Mass percentage of cracked tubers in relation to the total tuber mass. [2] Means followed by the same letter do not differ by Tukey's test ($p > 0.05$).

The percentage of tubers with cracks was higher when tembotrione was applied in the medium texture soil (Serra do Salitre), and a lower percentage was found in the tembotrione and atrazine mixture (Table 1). In accordance with the results from Rio Paranaíba, atrazine did not cause cracks in the potatoes when applied alone.

Discussion

No symptoms were found in the shoots of potato plants planted in Rio Paranaíba and Serra do Salitre. Potato plants grown one year after application of atrazine (1,120 g ha^{-1}) and mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione) (280 g ha^{-1}) did not show injuries in the shoot (Robinson, 2008). Mesotrione is also an HPPD inhibitor and recommended for weed control in corn.

The reduction in potato yield in the presence of tembotrione only in the Serra do Salitre area can be attributed to the medium textured soil (19.4% clay), to the one-day interval from application to planting of potatoes, with a larger absorption of the herbicide by the plant and to the stress caused by the herbicide in the plant associated with higher maximum and minimum temperatures (Figure 1B) regarding the area of Rio Paranaíba (Figure 1A).

Atrazine alone did not reduce yield nor promote cracks in tubers in the two evaluated areas (Table 1). Robinson (2008) did not observe reduction in the yield or physiological disorders in potato tubers caused by the application of atrazine (1,120 g ha^{-1}). This result reinforces the observation that the reductions in the yields in Rio Paranaíba and Serra do Salitre and the increase in the percentage of cracked potatoes in Rio Paranaíba and Serra do Salitre resulting from the application of the atrazine + tembotrione mixture had been caused by tembotrione.

Cracks in tubers of potatoes are associated with the presence of tembotrione in the soil, being more intensified in the area of Rio Paranaíba (Table 1), where tembotrione (100.8 g ha^{-1}) caused cracks in 11.4% of the total tubers. Cracked tubers are devalued by the industry due to low or no income from processing and by the consumer due to the poor appearance (Hiller et al., 1985).

The crack pattern observed was three branches from a single point regardless of the size of the tuber, with variable width, length and depth of cracks (Figure 2). This phenomenon has been associated with physiological disorders caused by herbicide drifting or in the soil (Eberlein et al., 1997), however, with no physiological explanations for the disorder. The identification of the causative factor of the physiological disorder may be induced or initiated at the beginning of the cycle and manifests only near or during harvest (Hiller et al., 1985). In experiments conducted in this work, no symptoms of crack initiation or induction in tubers of some plants monitored over the potato cycle were seen (data not shown).

There are reports associating the cracking of tubers to the presence of ALS-inhibiting herbicides (acetolactate synthase) such as nicosulfuron, metsulfuron and tribenuron, EPSPs-inhibiting herbicide (5-enolpyruvylshikimate-3-phosphate synthase) such as glyphosate and auxin mimics such as dicamba and clorpyralid (Eberlein et al., 1994; Wall, 1994; Novo & Miranda Filho, 2006; Hutchinson et al., 2014). No reports were found linking HPPD inhibitor herbicides to any physiological disorder in potato tubers.

The mass of cracked tubers accounted for 12.2% of the mass of total tubers with 100.8 g ha^{-1} tembotrione in the area of Rio Paranaíba; however, this value did not exceed 0.3% in the area of Serra do Salitre (Table 1). The lower incidence of this injury in Serra do Salitre can be attributed to a greater leaching of tembotrione in the soil, explained by the weak acid characteristic and pKa of this herbicide, associated with rainfalls of 50 and 194 mm that occurred on the third day and on the third week after application of product, respectively (Figure 2). Weak acid characteristic herbicides in soils with pH (6.2) higher than the pKa (3.17) predominate in the ionic form, being less retained on soil colloids (Muller et al., 2014). Consequently, they remain in solution making them more prone to leaching in cases of high rainfall.

Figure 2. Cracks in potato tubers caused by tembotrione residues in the soil evidenced in Rio Paranaíba (Minas Gerais State).

In Serra do Salitre, it is likely that tembotrione was first absorbed by the plants, which promoted the stress and reduction in the yield. However, during the tuberization phase, the reduced amount of the product in the soil due to leaching was not sufficient to induce cracks in the tubers.

Conclusion

Tembotrione reduced the quality of "Atlantic" potato tubers since it promoted the occurrence of cracks. Atrazine did not promote cracks in tubers of "Atlantic" potatoes.

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