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Does the Use of Atrazine in Maize Grown Under Conservation Agriculture Adversely Affect Soybean Productivity in Maize-Soybean Rotation in Zimbabwe?

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Abstract

Weed management challenges in the early years of conservation agriculture (CA) adoption may require the use of herbicides for farmers to realise the immediate benefits of CA practices. The objective of this study was to assess the effects of atrazine on soybean grown after maize in a maize-soybean rotation under conservation agriculture. Atrazine was applied at 1.8 kg ha^{-1} active ingredient (a.i), as a pre-emergence herbicide in the maize phase of the rotation. The study was conducted in Zimbabwe at Domboshawa Training Centre (DTC), Henderson Research Station (HRS) and University of Zimbabwe farm (UZ farm) over two seasons (2011/2012 and 2012/2013). Manual weeding was utilised to keep the study area weed free and eliminate interference from weeds. Weed density, weed biomass, soybean germination, soybean biomass and grain yield were measured. The lowest germination of soybean was recorded at 57% in 2011/2012 at DTC under atrazine + glyphosate + metolachlor in combination with manual weeding treatment. Previous atrazine treatment to maize showed no significant differences on soybean biomass accumulation and broadleaf weed density at all sites in both seasons. The highest soybean yields recorded were 3707 kg ha^{-1} at DTC in 2011/12 season in atrazine + glyphosate + metolachlor plus manual weeding treatment. Based on results obtained in this study it can be concluded that soybean can be grown in plots where atrazine was applied as a pre-emergent herbicide during the maize phase.

Keywords: conservation agriculture, maize-soybean rotation, atrazine, residual effects, smallholder farmers, weeds management

1. Introduction

Conservation agriculture (CA) is promoted in Southern Africa as an input saving cropping system that has been demonstrated to improve the livelihoods of smallholder farmers through increased crop productivity in marginal areas (Kassam et al., 2012). CA is a cropping system based on three important principles; a) maintenance of a permanent soil cover, through crop residue retention and/or the use of green manure cover crops b) diverse crop rotations and/or crop interaction, and c) minimum soil disturbance (FAO, 2002; FAO, 2010). Crop rotations play a key role in CA systems where they facilitate increases in soil fertility while at the same time minimising the development of pest and diseases (Johansen et al., 2012; Wang et al., 2010; Zotarelli et al., 2012). Among the common legumes that are grown in maize rotations in smallholder agriculture are soybean (*Glycine max* L.) and cowpea (*Vigna unguiculata* Walp**.**) (Baldwin, 2006). Both crops are rich in proteins and play a key role in improving the nutrition of people who consume them. CA offers potential benefits such as increased and more stable yields (Hobbs, 2007), reduced operation costs (Derpsch, 2008), improved infiltration, reduced soil erosion (Thierfelder and Wall, 2009) and improved soil biological activities (Mutema et al., 2013).

Although CA offers many potential benefits, it is associated with increased weed pressure especially in the early years of adoption due to the absence of ploughing and tillage practices which had been adopted for many years as a reliable measure for weed control (Vogel, 1994b). There is accumulation of weed seeds in the topsoil where conditions for germination are favourable (Nakamoto et al., 2006). Small weed seeds can germinate with little or no cover thus they are relatively common in CA systems where they easily establish under minimum soil disturbance (Curran et al., 1996).

Most of the smallholder farmers in Southern Africa rely on the use of hand hoes for weed control (Siziba, 2008). Apart from being expensive, hand hoe weeding is also labour intensive (Mandumbu et al., 2011). Weed control under CA can also be achieved through the use of allelopathic green manure cover crops such as *Canavalia ensiformis* (Runzika et al., 2013). Chemical weed control has been demonstrated to be an effective and economically feasible option of weed control under CA (Mashingaidze et al., 2012; Muoni et al., 2013). One of the commonly used herbicides is atrazine.

Atrazine is a pre-emergent herbicide used to control broadleaved weeds and some annual grass weed species in cereals (Williams et al., 2010). Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1, 3, 5-triazine) is an apoplastically translocated photosynthetic inhibitor that binds to the plastoquinone protein binding site in photosystem II (Shimabukuro and Swanson, 1969). It has an average soil half-life of 60 days, hence it can provide effective weed control for much of the growing season depending on soil clay and organic matter content (Lesan & Bhandari, 2000). As a result, the use of atrazine in maize-soybean rotations under conventional tillage is not recommended especially in soils with low cation exchange capacity (sandy soils with low organic matter). Under conventional tillage, the use of atrazine (application rate greater than 50 g ha^{-1} active ingredient (a.i)) in soils with less that 30% clay is not recommended (Croplife, 2006).

Farmers have been discouraged to plant susceptible crops such as soybean in less than 18 months after atrazine application (Reinhardt, 1995). Atrazine has moderate to high affinity to soil colloids which reduces the amount of atrazine molecules in solution (Spark & Swift, 2002). Apart from adsorption, clay soils with high organic matter content have more microorganisms than sandy soils. As a result the microbial degradation of atrazine is high in soils with high organic matter due to the presence of chlorohydrolase enzymes which play a pivotal role in reducing the persistence of this herbicide in the soil (Eapen et al., 2009).

Doran (1980) reported that increased moisture retention and low soil temperatures promote the build up of micro-organisms some of which are important in the degradation of atrazine. The anticipated increase in microbial degradation of atrazine is therefore, likely to reduce the persistence of this herbicide under CA. Thus, the inclusion of soybean in rotations under CA may be done with little damage to the crop. The objective of this study was to assess the productivity of soybean planted in a maize-soybean rotation when atrazine was applied as a pre-emergent herbicide in the maize phase.

2. Materials and Methods

2.1 Site Description

The study was conducted at three on-station sites namely Domboshawa Training Centre (DTC) located 17°37'S, 31°10'E and 1560 meters above sea level (m.a.s.l), Henderson Research Station (HRS) (17° 34' S, 30° 54' E and 1136 m.a.s.l) and University of Zimbabwe (UZ) farm 17°80'S, 31°50'E and 1503 m.a.s.l. All the three sites are in agro-ecological region 2a and receive annual rainfall of between 700 and 1000 mm in a unimodal pattern starting in November and ending in April (Figure 1). Mean maximum temperature in summer exceeds 32 °C. DTC soils are sandy soils classified as moderately deep *Luvisols and Arenosols* (Vogel, 1994a). HRS has sandy soils with more than 83% sandy content (Thierfelder and Wall, 2009) and are classified as *Arenosols* (Nyamapfene, 1991). UZ farm soils have high clay and organic matter content and are classified as *Chromic Luvisols* (clay soils) (Nyamapfene, 1991) (Table 1). The experimental locations therefore, have very distinct and contrasting soil types from very sandy (HRS and DTC) to heavy clay (UZ farm).

Table 1. Soil characteristics at the three research sites used in this study

Soil property	UZ farm	DTC	HRS
Soil depth (cm)	0-10	0-20	0-28
Soil organic carbon (g kg^{-1})	1.68	0.73	0.44
Soil pH	5.1	4.5	4.5
Clay content (g kg^{-1})	400	220	70
Sand content (g kg^{-1})	-	730	770

(Source: Mapfumo et al., 2007; Nyamapfene, 1991; Thierfelder and Wall, 2009).

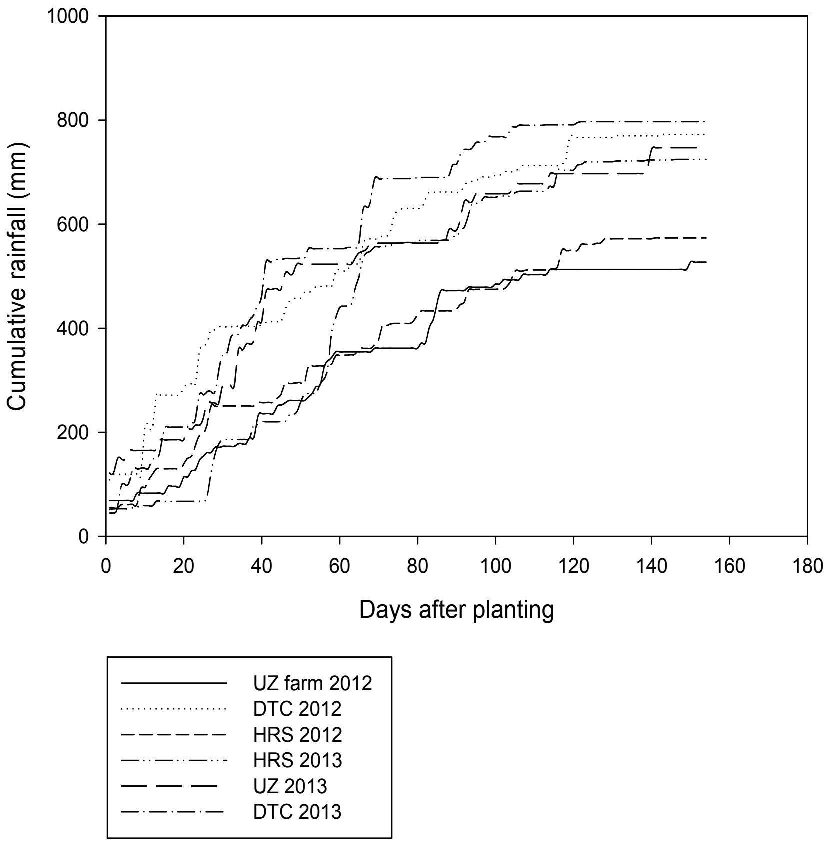

Figure 1. Cumulative monthly rainfall (mm) at Domboshava Training Centre, Henderson Research Station and UZ farm for 2011-12 and 2012-13 season

2.2 Description of Experiments

The experiment involved use of two separate fields that were established in 2010/2011 and 2011/2012 seasons respectively, at each site. In the set-up season of both fields, maize was planted in 6m × 6.3m plots that received different treatments. Soybean (Safari variety) was planted as a rotational crop soon after maize in both fields (2011/2012 and 2012/2013 seasons). During the maize phase, a medium maturing variety Pristine 601 was planted at 0.90m × 0.25m spacing (in rip lines at HRS and DTC, and in basins at UZ farm) targeting a plant population of 44444 plants ha^{-1}. All maize plots received a basal dressing Compound D 150 kg ha^{-1} (11N 21P_2O_5 11K_2O) and a two equal split application of top dressing ammonium nitrate 52N kg ha^{-1} (26N at each application). All the plots were seeded after receiving first effective rains in November and the plots were harvested in May after all the crops had fully matured. Maize stalk borer control was done using dipterex at 3 kg ha^{-1} after scouting for the pest. Maize was harvested from four central rows that were 5m long. All plots were weeded when the weeds were 10 cm tall throughout the growing season. The following treatments were applied in the first season; a soybean crop was planted across all treatments in the second season.

a. Hand hoe weeding only, non-treated check.

b. Atrazine at 1.80 kg ha^{-1} active ingredient (a.i) at seeding plus hand hoe weeding.

c. 1.025 litres ha^{-1} a.i glyphosate + 1.80 kg ha^{-1}a.i atrazine at seeding plus hand hoe weeding.

d. 1.025 litres ha^{-1} a.i glyphosate + 1.80 kg ha^{-1} a.i atrazine + 0.96 litres ha^{-1} metolachlor at seeding plus hand hoe weeding.

Herbicide application in this study was done using the knapsack sprayer and the spray volume used was approximately 187 litres ha^{-1} using a flood nozzle. During the soybean phase first and second weeding was done 46 and 73 days after emergence (DAE) respectively in 2011/2012 season, and in 2012-2013 season at 33 and 49 DAE respectively at DTC. At HRS, first and second weeding was done 42 and 76 DAE respectively in 2011/2012 and at 29 and 75 DAE in 2012/2013 season. At UZ farm, first and second weeding was done 42 and 76 DAE in

2011/2012 season, 31 and 74 days DAE in 2012/2013 season. Soybean was planted at 0.45 m × 0.05 m plant spacing in rip lines to achieve a plant population of 444,444 plants ha^{-1} and all pest control was done using carbaryl at 280 ml ha^{-1} active ingredient. A basal dressing of 150 kg ha^{-1} compound D (11 kg N: 21 kg P_2O_5: 11 kg K_2O) was applied at seeding. All maize residues from the previous crop were retained and uniformly spread in all the plots to achieve a constant ground cover of 30 % which corresponded to an application rate of approximately 2.5 t ha^{-1} of maize harvest residues.

2.3 Field Measurements

Soybean germination percentage was calculated using the number of emerged plants in two central rows in each plot. All weed measurements were done inside a 0.5 m × 0.5 m quadrant that was randomly placed four times in each plot before each weeding. Weeds inside the quadrant were cut at ground level and oven dried at 80 °C for 24 h. The dominant weed species at DTC were *Richardia scabra, Bidens pilosa, Galinsoga parviflora, Eleusine indica* and *Amaranthus hybridus.* At HRS, the dominant weed species were *R. Scabra, Cyperus spp, Digeteria sanguinalis, Bulbostylis hispidula, Eragrostis curvula* and *Dactyloctinum aegyptium*. At UZ farm the dominant weed species were *R. Scabra, Foeniculum vulgare, Leucas martinicensis, G. parviflora, Bidens pilosa* and *A. hybridus.* In addition, soybean plants were cut at ground level and oven dried at 70 °C for 72 hours during the season at 30, 60, 90 and 130 days after emergence (DAE). Grain yields were estimated from eight central rows of 5 m length (total harvest area 18 m²). The grain weight was converted to kg ha^{-1} at 9.0 % moisture content.

2.4 Statistical Analysis

Weed density, weed biomass, soybean germination, soybean biomass, and soybean grain yield data were subjected to a test of normality. A linear mixed model was employed to assess the overall effect of treatments, site, season and their interaction on weed density and weed biomass, growth of soybeans and grain yields. To determine the effects of treatments on soybean germination, soybean biomass, density of broadleaved weeds and soybean grain yields at each site, the data was subjected to the analysis of variance (ANOVA). Treatment × site, treatment × season, site × season and treatment × site × season interactions were considered for analysis in this experiment. All analyses were conducted by using Genstat 6th edition (VSN International Ltd.).

3. Results

3.1 Effect of Atrazine Residues on Emergence of Soybean, Weed Density and Biomass

Atrazine treatments had no effect on the emergence of soybean at all sites in both seasons compared to hand hoe weeding only. However, there was a significant season × site interaction ($P<0.05$) effect on weed biomass at first and second weeding. Previous atrazine applications had no significant effect on the density of weed species at all weeding times, in both seasons and at all sites (Table 2).

Table 2. Effects of weed control strategies on broadleaves and grasses (weeds m^{-2}) at DTC, HRS and UZ farm in 2011/12 and 2012/13 seasons

Treatment	DTC		HRS		UZ farm	
Broadleaf	2011/12	2012/13	2011/12	2012/13	2011/12	2012/13
Hand hoe weeding	61	135	33	93	87	178
Atrazine + hand hoe weeding	42	122	14	82	72	271
Atrazine + glyphosate + hand hoe weeding	37	121	35	78	75	145
Atrazine + glyphosate + metolachlor + hand hoe weeding	43	135	12	110	67	211
Significance	NS	NS	NS	NS	NS	NS
SED	20.15	60.97	15.68	23.88	29.04	73.71
Grasses						
Hand hoe weeding	21	25	5	16	0	8
Atrazine + hand hoe weeding	22	25	17	16	0	4
Atrazine + glyphosate + hand hoe weeding	37	16	28	14	0	11
Atrazine + glyphosate + metolachlor + hand hoe weeding	43	4	7	17	1	8
Significance	NS	NS	NS	NS	NS	NS
SED	12.27	15.96	10.26	5.31	0.47	1.11

Letters NS the table indicate that the data is not significant.

3.2 Effect of Weed Control Strategies on Biomass Accumulation and Grain Yields of Soybean

The results showed that the treatment × site × season interaction was significant (P<0.05) at 30 DAP but not at 60 and 90 DAP. Furthermore, there were no significant treatment effects on soybean accumulation at 60 and 90 DAE. However, soybean biomass at harvesting was significantly lower in the atrazine + glyphosate plus hand hoe weeding treatment than the control in the 2011/2012 season at DTC and HRS (Figure 2). Atrazine + glyphosate + metolachlor plus hand hoe weeding had significantly higher soybean biomass at harvesting in 2011/2012 season. Also atrazine plus hand hoe weeding had significantly larger soybean biomass than hand hoe weeding at harvesting in 2012/2013 season (Figure 3).

The treatment × site × season interaction effect was not significant on soybean grain yields. However, treatment × site interaction had a significant effect on soybean grain yields. Previous atrazine applications did not significantly reduce soybean grain yields at all sites in both seasons (Table 3).

Table 3. Effects of weed control strategies on soyabean grain yields (kg ha^{-1}) at DTC, HRS and UZ farm in 2011/12 and 2012/13 seasons

Treatment	DTC		HRS		UZ farm	
	2011/12	2012/13	2011/12	2012/13	2011/12	2012/13
Manual weeding (control)	3633	1539	132	56	2621	1018
Atrazine + manual weeding (previous season)	3961	1433	127	114	2530	889
Atrazine + glyphosate + manual weeding (previous season)	2884	1322	139	48	2748	1087
Atrazine + glyphosate + metolachlor + manual weeding (previous season)	3707	1340	245	103	2191	969
Significance	NS	NS	NS	NS	NS	NS
SED	453	255	95	28	216	193

Letters NS the table indicate that the data is not significant.

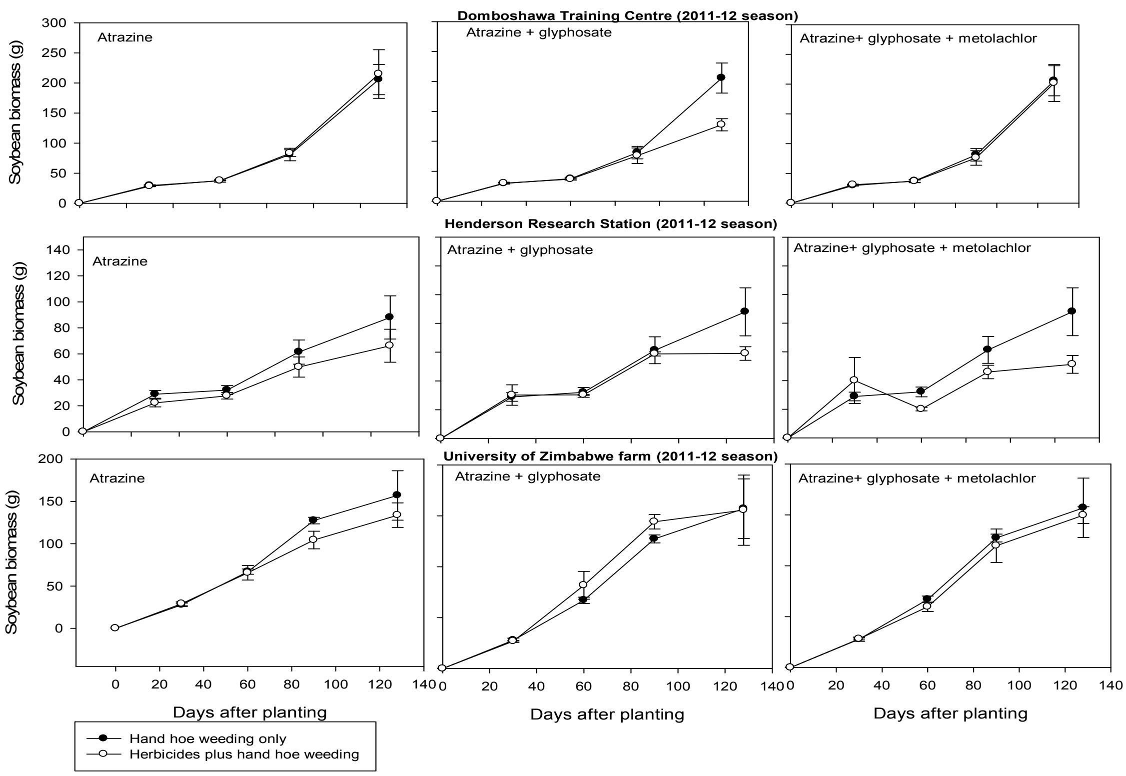

Figure 2. Effect of previous atrazine application on soybean biomass accumulation at Domboshava Training Centre, Henderson Research Station and University of Zimbabwe farm in 2011-12 season

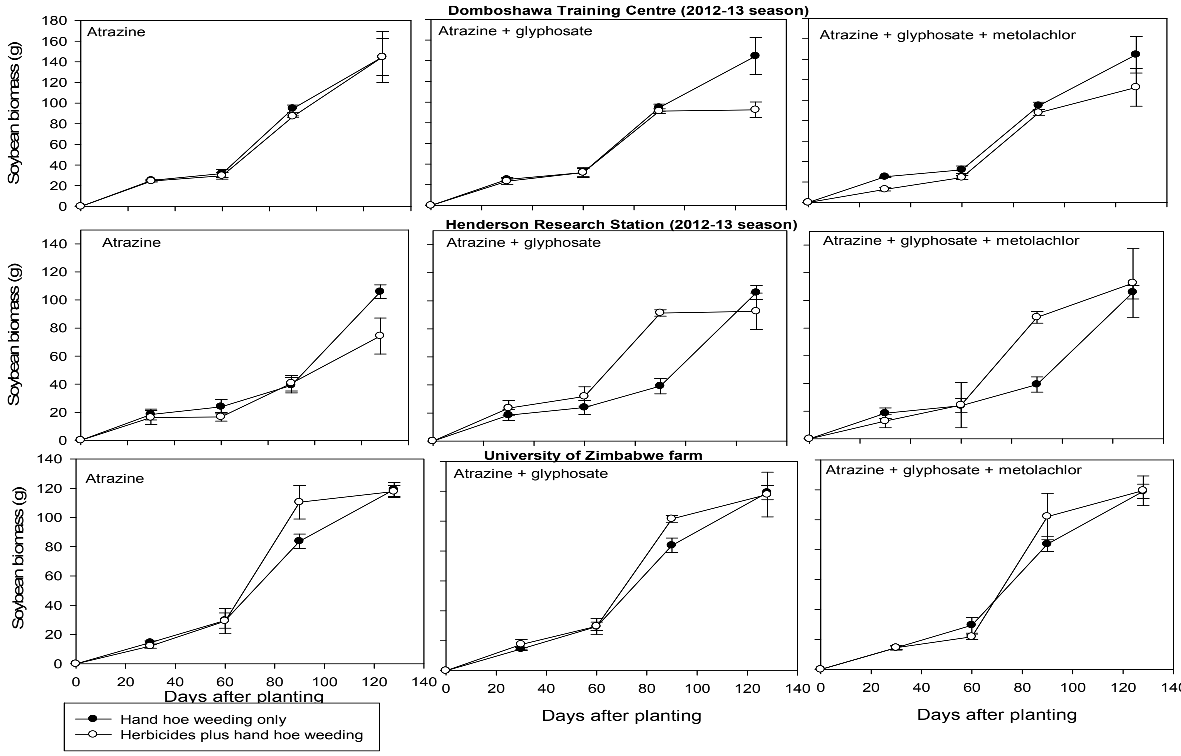

Figure 3. Effect of previous atrazine treatment on soybean biomass accumulation at Domboshava Training Centre, Henderson Research Station and University of Zimbabwe farm in 2012-13 season

4. Discussion

In this study, maize was rotated with soybean under CA in high rainfall areas at sites with contrasting soil types. The soybean crop followed the maize crop at approximately 12 months after the application of atrazine at 1.8 kg ha^{-1} in maize. The residual effects of atrazine did not cause any visible phytotoxicity symptoms in the soybean cv "Safari" phase. In addition, the soybean emergence, growth and grain yields were not affected by the previous atrazine application of the herbicide in the two seasons. Better emergence recorded at DTC in 2012-2013 season was due to rainfall that was received soon after planting. Furthermore, weeds which are normally controlled by atrazine emerged in the second season, probably indicating that atrazine had been biodegraded in the field. If atrazine was still present, it was not sufficient to cause phytotoxicity in the soybean crop. For a plant to express the phytotoxic symptoms, the herbicide has to reach the site of action in sufficient quantities. These results agree with Brecke et al. (1981), who reported that the application of 1.12 to 4.48 kg ha^{-1} atrazine in maize, needed a period of at least 14 to 20 weeks in order for soybean crop to tolerate the toxic effects of atrazine residues. In contrast, Mushambi (1992) reported that atrazine residues caused phytotoxicity effects to soybean cv "Duiker", resulting in reduced yields on clay and sand soils, after applying atrazine at 1.7 to 2.2 kg ha^{-1} in a maize crop.

However, Chivinge and Mpofu (1990) found that when atrazine was applied in maize at 1.75 and 3.00 kg ha^{-1} it was slightly phytotoxic to groundnut in 1 out of 3 seasons and 2 out of 3 seasons, respectively. These authors pointed out that the herbicide injury on groundnuts was not reflected in crop yield. Although, different crop genotypes were used, some of the results obtained on groundnut in 2 out of the 3 seasons, when atrazine was applied at 1.75 kg ha^{-1} by Chivinge and Mpofu (1990) are closely similar to those obtained in soybean in this study, where atrazine residues did not cause any crop phytotoxicity. This study was under CA conditions, whereas those of Chivinge and Mpofu (1990) and Mushambi (1992) were under conventional tillage systems.

The contrasting results obtained in this study compared to that of Mushambi (1992) could probably be explained by the different genotypes of soybean used in this study. There is a possibility that the two different tillage systems by the different researchers could explain the different results which were obtained. On the other hand, the variable atrazine residual effects on groundnut (Chivinge & Mpofu, 1990) could mean that these effects are complex to explain. Consequently, the results of this study do not guarantee that atrazine phytotoxicity is not likely to happen under CA.

The challenge of this study was that the atrazine concentration in the soil remained unknown, especially at the time of planting the soybean crop. The atrazine residues data in the soil is vital for the prediction for the safety of growing crops which are usually sensitive to atrazine such as soybean. This is more feasible, if the atrazine soil residues data is used together with the crop response for this purpose. However, Chivinge and Mpofu (1990) reported that atrazine residues range from 0.056 and 0.086 mg kg^{-1} in the course, acidic loamy soils at Henderson, 12 months after application. Working at a different site in Zimbabwe, Mushambi (1992) reported atrazine residues which ranged from 0.105 to 0.205 mg per kg of soil after seven and nine months, respectively after atrazine application in a maize crop. The fact that atrazine was sampled at 12 months (Chivinge & Mpofu, 1990) and 7 to 9 months (Mushambi, 1992), could partly explain the differences in atrazine concentration obtained by the authors. This could also account for the different atrazine residue responses of soybean and groundnut used in the above studies. Frank et al. (1983) detected soybean damage when the concentration of soil atrazine was 0.20 and 0.30 mg kg^{-1} for the sandy loam and loam soils, respectively. Therefore, it can only be speculated that the range of atrazine concentration of 0.056 to 0.086 mg kg^{-1} of soil (Chivinge & Mpofu, 1990), could possibly be safe for soybean. Nevertheless, it is recommended that studies which are focused at monitoring atrazine residues in CA systems under different soil types and also determining the sensitivities of soybean genotypes to residual atrazine are needed.

When herbicides such as atrazine with soil activity, are applied to the soil, they are subjected to various degradation processes and this is likely to affect their soil persistence and efficacy. The following processes could have been responsible for reducing the levels of atrazine in the soil: photodecomposition, chemical decomposition, adsorption by soil colloids and organic matter, leaching processes, uptake by plants, microbial activities and volatilization (Devlin et al., 1992). Because of the limitations of this study, it would be difficult to pin point the dominant process which influenced the degradation of atrazine at the three sites. For example, there were no determination of atrazine residues in plants and soils, and there was no monitoring of the impact of soil microbial activity on atrazine. It can be suggested here that such studies would be necessary in-order to understand the fate of atrazine after application in the CA systems.

When atrazine has been applied to the soil surface, it is likely to undergo photodecomposition. The latter is responsible for changing the molecular structure of a herbicide when applied to the soil surface. These changes in the molecular structure, causes the herbicides to lose its activity. Probably a fraction of the atrazine herbicide could have been lost through this process. There is also a possibility that the atrazine molecule could react with soil chemicals leading to the loss of its activity. For example, the atrazine molecules could undergo hydrolysis leading to loss of the chlorine atom and its replacement by the hydroxyl group leading to the loss of atrazine activity.

It is also possible that atrazine was adsorbed by clay minerals to an extend that very little was available for plant uptake. This is likely to have been operative at the UZ farm soils characterised by high clay mineral. The organic matter in the CA systems could also have adsorbed atrazine. The low soil pH at Henderson site could have caused the protonation of the atrazine molecule at two positions causing it to be positively charged, leading to the strong adsorption to the soil surfaces. This could facilitate the rapid breakdown of atrazine, especially on sandy soils.

The high rainfall experienced at the three sites could have facilitated considerable leaching of atrazine to levels which could not be accessed by the soybean plants and weeds. During the first season of herbicide application, atrazine was also taken up by the maize plants. Maize plants contain with enzymes which decompose atrazine to less toxic substances. This process could have been important at DTC and the UZ farm where high yields of maize were achieved.

Microbial activity also plays an important role in degrading herbicides in the environment, since they are equipped with enzymes to facilitate this process. Atrazine is likely modified into molecules which are less toxic. Also atrazine could be lost from soil surfaces through volatilisation into the atmosphere. However, if vapour pressure is low and it is likely that very small amounts of atrazine are lost through this process.

5. Conclusions

The study showed that soybean emergence, growth and grain yields were not affected by previous atrazine application of the herbicide in the two seasons. Furthermore, weeds which are normally controlled by atrazine emerged in the second season, probably indicating that atrazine had been biodegraded in the field. These results suggest that CA results in accelerated degradation of atrazine in the soil hence; soybean can be grown in plots where atrazine was applied as a pre-emergent herbicide during the maize phase. However, this study has only examined the effects of previous atrazine treatments on soybean crops further research is needed to trace the residues of atrazine in the soil during the growing season and also over a long time. The atrazine residues data should be used together with the response of the crop to make more reliable recommendations to the farmers.

Hence, the results of this study do not guarantee that atrazine phytotoxicity is not likely to happen under CA. More work is needed to evaluate the effect of different residue types and the amount of atrazine degradation and also assess the relationship between changes in microbial population changes and atrazine degradation. In addition, the effect of atrazine on other important legumes in southern African farming systems (e.g. cowpea) should be explored.

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