J Sust Dryland Agric Syst, 1(1), 47-57 (Jun, 2021)
Journal website: https://jurnalpasca.unram.ac.id/index.php/josdas
Article DOI: https://dx.doi.org/10.29303/josdas.v01i1.05

Interactive Relationship between Sorption and Decomposition: The Importance of Temperature in Influencing the Availability of Glyphosate for Decomposition in Australian Soils

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Article Info:
First submitted:
May 15th, 2021
Revised:
June 15th, 2021
Accepted:
June 19th, 2021
Published online:
June 30th, 2021
Corresponding author:
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Keywords:
14C glyphosate;
adsorption;
desorption;
decomposition;
temperature

Abstract. A laboratory experiment was conducted to investigate the sorption-decomposition behavior of glyphosate in four Australian soils. At low temperature (5°C and 12°C), only small amounts of glyphosate were partitioned into the soluble phase ranging from 1.4-2.1% in these soils. As the incubation temperature increased from 12° to 17° and 22°C, the amount of glyphosate partitioned into the soluble phase substantially increased and ranged from 23.2-36.2%. Further increase of the temperature from 22° to 28°C markedly increased the partitioning of glyphosate into the soluble phase in two soils (Walpheup Rendzina and Walpheup Sandy Soil), but the partitioning of glyphosate into the soluble phase slightly decreased in the other two soils (Hay Alluvium and Ladysmith Red Podzolic). Half lives of the soluble phase were relatively in a similar order of 1-2 weeks among the four soils tested. However, half lives of the sorbed phase varied widely (67- 4950 days). Differences in the strengths of binding existed within the sorbed phase in the four soils investigated in this study. Glyphosate was shown to be more strongly held in acidic soil than in alkaline soil and its desorption rate from the sorbed form was correlated with the soil pH, the amount of exchangeable Fe and Al, and the incubation temperature. This study showed that temperature not only influences partitioning of glyphosate into the soluble and sorbed phases which affect the amount glyphosate availability for microbial degradation but also influences the amount of residual glyphosate that may be biologically active for non-target organisms.

Cite as: Suwardji, S., Eberbach, P., & Sudantha, I.M. (2021). Interactive relationship between sorption and decomposition: The importance of temperature in influencing the availability of glyphosate for decomposition in Australian soils. *Journal of Sustainable Dryland Agricultural Systems*, 1(1), 47-57. DOI: https://dx.doi.org/10.29303/josdas.v01i1.05

1. INTRODUCTION

Glyphosate, the active ingredient of the herbicide Roundup, is widely used in agriculture to control a wide range of weeds. Glyphosate is rapidly inactivated when in contact with soils (Sprankle et al., 1975a). Sprankle et al. (1975b) showed that rapid activation of this compound in soil was due to rapid adsorption, and not necessarily to rapid decomposition. However, its residual activity in some soils has been found to be able to injure some plant species (Cornish, 1994; Eberbach, 1989; Salazar and Appleby, 1982). Working on loamy sand soil, Cornish (1994) reported that soil residues of glyphosate was capable of injuring tomato seedling transplanted 16 days after application of glyphosate applied at 1728 g active ingradient (a.i) L-1 ha^{-1}. Similarly, Eberbach (1983) in a laboratory study showed residues of glyphosate applied at 360 g a.i. L^{-1} ha^{-1} were able to affect plant growth in a Walpeup Sandy Soil. These findings suggest that not all of the applied glyphosate was adsorbed in all soils.

The time taken for glyphosate to disappear from soil varies greatly between soil types and its half life may range from a few weeks to several years (Nomura & Hilton, 1977; Tortensson & Stark, 1981; Eberbach, 1998). Decomposition of glyphosate has been reported to be very rapid in the first few days and slowing down with time to steady state rate (Nomura & Hilton, 1977; Eberbach, 1998; Kanissery et al., 2019). The rapid decomposition of glyphosate in the first few days is ascribed to the decomposition of soluble glyphosate, while the slow rate of decomposition at the steady state curve is suggested to be decomposition of glyphosate from the most slowly available pool (Eberbach, 1998; Nomura & Hilton, 1977).

Glyphosate and phosphate may be bound to soil solids in a similar manner with phosphate. Hance (1976) reported that adsorption of glyphosate showed some correlation with un-occupied phosphate adsorption sites. While Orcelli et al. (2018) found glyphosate interact with goethite through the phosphate group and the high pH, the amine group could be involved. Pereira et al. (2020) also found that Ca^{+2} interacts with glyphosate of the phophonate group. Since adsorption of phosphate has been shown to vary with temperature (Barrow, 1979; Chien et al., 1982; Sah & Mikkelsen, 1986), the adsorption of glyphosate may also be influenced by temperature.

The objective of this work reported here was to investigate the influence of temperature on the partitioning of glyphosate into soluble and sorbed phases; and on the rate of desorption of sorbed glyphosate back into the soluble-bioavailable phase in four Australian soils using non-steady state compartment analysis (NSSCA).

2. MATERIALS AND METHODS

2.1. Soils

Four soils from different regions of South-East Australia were selected for use in this study. These soils were chosen for their wide range of physical and chemical properties and their importance in crop production. Only surface soils (0-5 cm) were used in this study. After collection, soils were mixed thoroughly, placed in plastic bags and stored in a cool room (4^oC). When required, soils were spread out in thin layer on a plastic sheet and dried at room temperature overnight. After drying soils were carefully sieved to pass through 2 mm diameter. Sub-samples of soil were taken to determine the air-dry soil moisture content. Soils to be used for physical and chemical analysis were then ground and sieved to pass through a 0.15 mm in diameter.

Some physico-chemical properties of soils used in this study are presented in the TABLE 1. Water content at -33 k Pa was determined using the pressure plate apparatus. Particle size distribution was determined using the hydrometer method (Gee & Bouder, 1986). Soil pH in water was determined using a glass electrode. Organic carbon was determined by spectrometric method (Haines, 1984) after chromic digestion. Sesquioxides of Fe and Al was estimated using two extractants mainly acid oxalate extractant (Rayment & Higginson, 1991) and citrate-dithionite extractant (Holmgren, 1967). The amount of Fe and Al was quantified using atomic absorption spectrophotometer (Rayment & Hingginson, 1992).

Table 1. Physical and chemical properties of soils used in this study

SOIL	Water content 75% field capacity	pH H_2O (1:5)	Clay content (%)	Organic carbon (%)	Exch-Fe (mg/kg)	Oxalate-Fe (%)	Citrate-dith-Fe (%)	Oxalate - Al (%)	Citrate-dith-Al (%)
Hay Plains Alluvium	20.70	8.30	27	0.74	4.5	0.08	0.37	0.15	0.10
Waurn Ponds Rendzina	17.08	8.14	31	3.46	3.1	0.17	1.87	0.30	0.18
Walpeup Sand	3.76	6.41	7	0.66	7.7	0.02	0.13	0.0044	0.003
Ladysmith Red Podzolic	13.41	5.30	17	1.96	7.0	0.08	1.48	0.05	0.11

2.2. Decomposition study

A decomposition study was carried out using flow through apparatus similar to Goswami and Koch (1976) with modifications previously described by Eberbach (1998).

Air dried soil samples (10 g) were placed into a 125-mL side inlet incubation vessel and replicated four times. Soil moisture was raised by adding deionised water such that when 1 mL of ^{14}C-glyphosate solution was added to the soil, soil moisture content would be 75% of field capacity (-33 k Pa). The incubation vessels were then sealed with aluminium foil. To allow moisture to evenly distribute throughout the soil, these incubation vessels were incubated in the prescribed temperature treatments (5^o, 12^o, 17^o, 22^o and 28^{o}C) for 48 hours. After the 48 hours incubation period, 1mL solution of glyphosate containing (14C-glyphosate with specific activity 37 kBq and non-labelled glyphosate, 99.5% purity) in deionized water was added into the soil such that the final concentration of glyphosate was 2800 ng g-1 air dry soil. The incubation vessels were then immediately connected to the flow through system and placed in the prescribed incubation temperature in the incubator.

The $^{14}CO_2$ evolved from the decomposing ^{14}C-glyphosate was flushed with a moist carbon dioxide-free air (100 mL vessel-1 min-1) for 15 minutes every 3 hours. ^{14}-C-Carbon dioxide was trapped in a 4-mL of trapping solution [(ethylene glycol monomethyl ether: ethanolamine (3:1 v/v)]. The traps were removed and 1 mL of $^{14}CO_2$ containing trapping solution was transferred into a 6 mL scintillation vial. Four mL of scintillation cocktail (toluene :ethylene glycol monoether, 2:1 v/v) (Jeffay & Alvarez, 1961) were added to the vials and samples were counted in Packard Liquid Scintillation Analyser Model T 1600 for 20 minutes or until the equivalent of 10,000 counts were reached. During the initial stage of the incubation period, the trapping solution was removed every 24 hours for 4 days and after which the traps were removed at 3 days intervals for a total of about 60 days. Incubation temperatures used in this study were 5^o, 12^o, 17^o, 22^o and 28^{o}C.

At the end of the experiment, soil moisture content was determined. Statistical analysis showed that soil moisture content at the beginning and completion of the experiment was not significantly

different at $P < 0.01$ (data not shown). Therefore any differences occurring in the rate of degradation in each soil investigated were presumed to be due to incubation temperatures and not due to variability in soil moisture content during the incubation period.

The glyphosate remaining in each soil was calculated by measuring the evolution of $^{14}CO_2$, subtracting the cumulative $^{14}CO_2$ evolved from the soil over time from the amount of 14C-glyphosate initially added. Non-steady state compartmental analysis was used to discriminate between soluble and sorbed fraction in each soil and temperature combination using the technique described by Eberbach (1998). In this study, the rate constants degradation of the sorbed phase are used to represent the rate of desorption of glyphosate from the sorbed phase into labile phase.

2.3. Statistical Analysis

Homogeneity of variance of the original data set was tested using Bartlett's test (Sokal & Rohlf, 1981) and found to be heterogeneous. Data were then transformed logarithmically and found to be homogenous. Statistical analysis was done using the transformed data. The data of regression lines were analysed using analysis of co-variance, and the significant differences among the coefficients of slope were tested using multiple slope analysis at $P < 0.05$ (Sokal & Rohfl, 1981). The rate constants degradation of the soluble and sorbed glyphosate were regressed against several key soil properties (Table 1) using multiple regression analysis using Genstat Release 5.3.

3. RESULTS AND DISCUSSION

An assumption has been made in this paper, that the measured evolution of $^{14}CO_2$ reflects the decomposition rate of ^{14}C-glyphosate. This assumption is made based on previous work by Eberbach (1989; 1998), which showed that the loss of extractable glyphosate (using triethylamine as an extractant) at 25^{o} C occurred at the same rate as did the evolution of $^{14}CO_2$. In support of this assumption, other work showed that aminomethylphosphonic acid (AMPA) is the only a transitory intermediate of glyphosate metabolism (Eberbach & Bowmer, 1995). These results suggest that once catabolism of glyphosate occurs, decomposition is rapid and complete (Eberbach, 1998).

Decomposition of ^{14}C-glyphosate in the 4 soils at each of the five incubation temperatures varied widely as shown in Fig. 1, 2, 3, and 4. In each soil, regardless of temperature, glyphosate decomposition was much more rapid in the first few days, slowing with time to a steady rate of decomposition. This pattern of decomposition has been commonly reported in the field and laboratory experiment for glyphosate (Nomura & Hilton, 1977; Moshier & Penner, 1978; Torstensson & Stark, 1982; Eberbach, 1998) and for various denitroanilines (Zimdahl & Gwynn, 1977), trifluralin (La Fleur et al., 1978), and chlorsulfuron (Thirunarayanan et al., 1985). Nomura and Hilton (1977) suggested that the initial steep part of the curve represents the degradation of soluble glyphosate, while the final steady state section of the curve reflects decomposition of bound herbicide. Eberbach (1998) using non steady state compartmental analysis (NSSCA), resolved this curve into its two compartments, and showed that the initial rapid decomposition was due to decomposition of weakly held glyphosate while the slower steady state section of the curve was due to decomposition of bound glyphosate. Further this technique allowed for the kinetics of each phase to be resolved, and hence this technique was adopted for use in this present study to determine how temperature influences the kinetics of sorption and decomposition of glyphosate in soil.

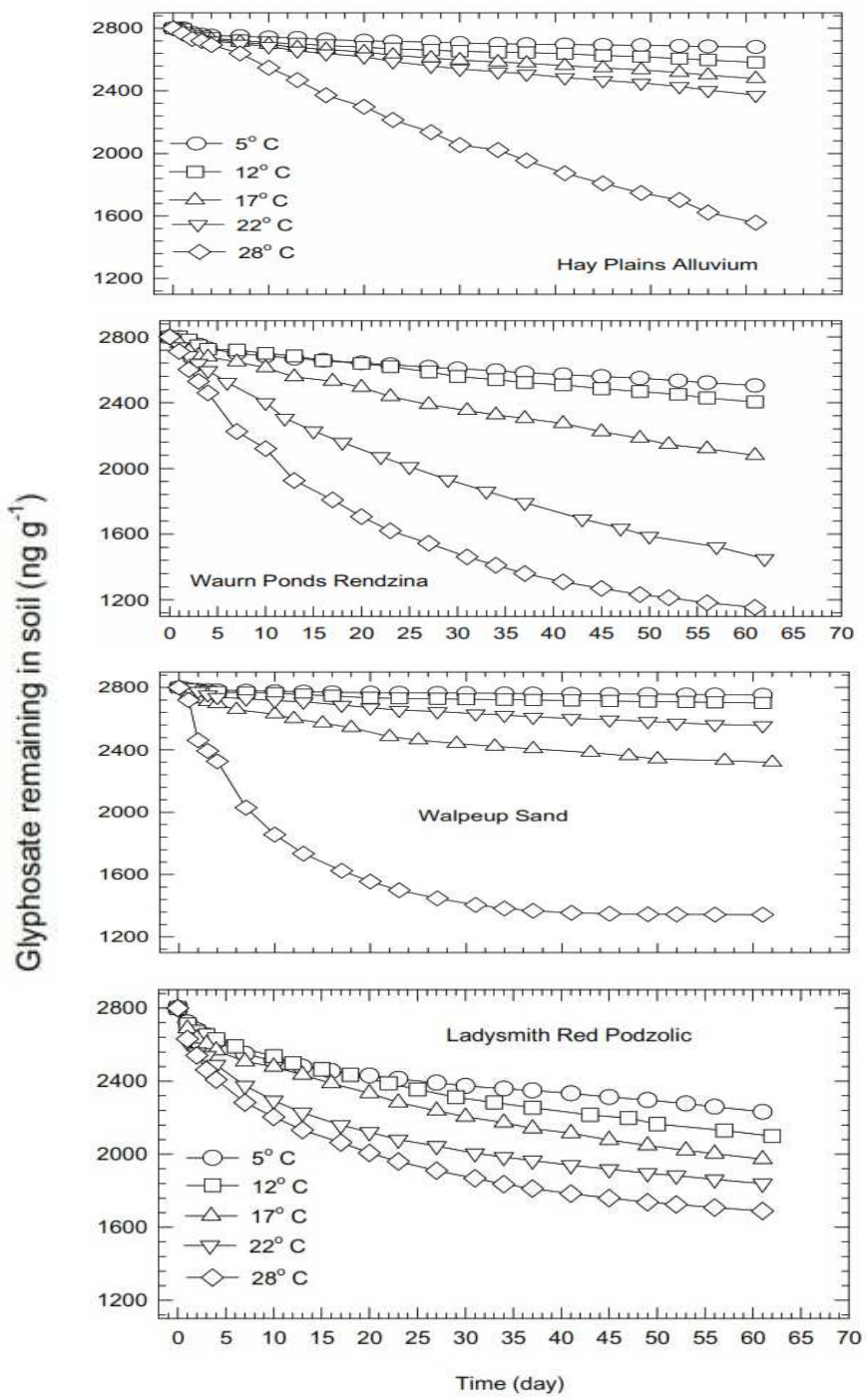

Fig. 1, 2, 3, and 4. Decomposition of ^{14}C-glyphosate under five temperature regime in Hay Plain Alluvium, Walpeup Pond Renzina, Walpeup Sand and Lady Smith Yellow Podzolic.

3.1. The effect of temperature on partitioning glyphosate into the soluble and sorbed phases

Temperature strongly influenced the partitioning of glyphosate into the soluble and sorbed phases in the all soils examined (Hay Alluvium, Walpeub Rendzina, Walpeup Sandy Soil, and Lady Smith Red Podzolic) analysed using NSSA (Eberbach 1998) (Table 2, 3, 4, 5 and 6). Regression analyses of the

soil and temperature combination data curves were highly significant (P <0.01) (Table 2, 3, 4, 5 and 6). At low incubation temperature (5^o and 12^o C), only a small amount of glyphosate was partitioned into the soluble phase in these soils ranging from 1.4 - 2.1 %. As the temperature increase from 5^o and 12^o, to 17^o C and 22^o C, the amount of glyphosate partitioned into the soluble phase markedly increased, ranging 23.20 to 36 % for the incubation temperature 17 ^{o} and 22^o C respectively. Further increase of the incubation temperature from 22^o to 28^o C substantially increased the partitioning of glyphosate into the soluble phase for the all soils examined ranging from 39.6 to 52.8 %. Previous studies have shown that Al and Fe oxides have a strong influence for sorption of soil phosphate (Parfitt 1978). As all of soils examined contains high amount of Fe oxides and glyphosate is reported to compete with soil phosphate for sorption site (Hance, 1976; Sprankle et al., 1975b; Torstensson, 1985), then it is likely that this fraction contributed for the strong ability to sorb glyphosate in this soil. While strong sorption of glyphosate in two acid soils (Walpheup Sandy and Yellow Podzolic) may be due to the high amount of exchangeable Al and Fe as well as low soil pH. In these two acid soils, a chelation mechanism between glyphosate and Fe or/and Al in the exchangeable sites and/or in the soil solution appeared to be the dominant binding mechanism. This mechanism is likely to be responsible for strong sorption of this compound. As reported by McBridge (1994) that a chelation between Fe and glyphosate produced very strong sorption. In addition low pH may generate the positive charge of soil solids and may partly contribute for strong binding of glyphosate in these two soils.

Table 2. Regression equation, adjusted R^2, rate constant, pool size and half live of the soluble and sorbed phase at incubation temperature 5°C (Analyzed using non steady state compartmental analysis)

Soil Type	**Phase**	**Regression equation**[1]	**R^2**	**Rate constant (ng/day)**	**Pool**[3] **size (%)**	**Half life (days)**
Hay Plains	Soluble	LnY= 4.48257-0.48335X	0.961***[2]	-0.48335	3.15	1
Alluvium (HPA)	Sorbed	LnY= 7.91074-0.00086X	0.991***	-0.00086	97.37	806
Waurn Ponds Terra	Soluble	LnY= 4.24942-0.14384X	0.970***	-0.14384	2.50	5
Rosa (WPTR)	Sorbed	LnY= 7.90982-0.00047X	0.995***	-0.00047	97.28	1474
Walpeup Sand (WS)	Soluble	LnY= 3.84325-0.04157X	0.900**	-0.04157	1.66	16
	Sorbed	LnY= 7.92845-0.00014X	0.981***	-0.00014	99.11	4950
Ladysmith Red	Soluble	LnY= 5.54418-0.21689X	0.998***	-0.21689	9.13	3
Podzolic (LRP)	Sorbed	LnY= 7.83601-0.00202X	0.997***	-0.00202	90.36	343

Table 3. Regression equation, adjusted R^2, rate constant, pool size and half live of the soluble and sorbed phase at incubation temperature 12°C (Analyzed using non steady state compartmental analysis)

Soil Type	**Phase**	**Regression equation**[1]	**R^2**	**Rate constant (ng/day)**	**Pool**[3] **size (%)**	**Half life (days)**
Hay Plains	Soluble	LnY= 4.23780 -0.51774X	0.978***[2]	-0.51774	2.47	1
Alluvium (HPA)	Sorbed	LnY= 7.91468 -0.00232X	0.996***	-0.00232	97.75	298
Waurn Ponds	Soluble	LnY= 4.62550 -0.77550X	0.967***	-0.77550	3.64	1
Rendzina (WPR)	Sorbed	LnY= 7.90632-0.00442X	0.996***	-0.00442	96.94	156
Walpeup Sand	Soluble	LnY= 3.69365-0.07868X	0.933***	-0.07868	1.44	8
(WS)	Sorbed	LnY= 7.91859-0.00028X	0.997***	-0.00028	98.14	2475
Ladysmith Red	Soluble	LnY= 5.64699-0.09266X	0.951***	-0.08208	12.12	7
Podzolic (LRP)	Sorbed	LnY= 7.78594-0.00325X	0.990***	-0.00325	85.94	213

Table 4. Regression equation, adjusted R^2, rate constant, pool size and half live of the soluble and sorbed phase at incubation temperature 17°C (Analyzed using non steady state compartmental analysis)

Soil Type	Phase	Regression equation[1]	R^2	Rate constant (ng/day)	Pool[3] size (%)	Half life (days)
Hay Plains	soluble	Ln Y = 6.05689 - 0.06896X	0.950***[2]	-0.06896	15.25	10
Alluvium (HPA)	sorbed	Ln Y = 7.76209 - 0.00589X	0.993***	-0.00589	83.92	117
Waurn Ponds	soluble	Ln Y = 6.44255 - 0.14162X	0.963***	-0.14162	22.43	5
Rendzina (WPR)	sorbed	Ln Y = 7.70216 - 0.00518X	0.974***	-0.00518	79.40	133
Walpeup Sand	soluble	Ln Y = 5.23917 - 0.07535X	0.973***	-0.07535	6.74	6
(WS)	sorbed	Ln Y = 7.85548-0.001186X	0.987***	-0.001186	92.13	584
Ladysmith Red	soluble	Ln Y = 5.29110-0.16960X	0.914***	-0.16960	7.09	4
Podzolic (LRP)	sorbed	Ln Y = 7.86276-0.00367X	0.985***	-0.00367	92.81	188

Table 5. Regression equation, adjusted R^2, rate constant, pool size and half live of the soluble and sorbed hase at incubation temperature 22°C (Analyzed using non steady state compartmental analysis)

Soil Type	Phase	Regression equation[1]	R^2	Rate constant (ng/day)	Pool[3] size (%)	Half life (days)
Hay Plains	Soluble	Ln y = 6.41747-0.08792X	0.965**[2]	-0.08792	21.86	8
Alluvium (HPA)	Sorbed	Ln y = 7.6977 - 0.01036X	0.984***	-0.01036	79.19	67
Waurn Ponds	Soluble	Ln y = 6.97681-0.08426X	0.996***	-0.08426	38.16	7
Rendzina (WPR)	Sorbed	Ln y = 7.45766-0.00681X	0.996***	-0.00681	61.89	102
Walpeup Sand	Soluble	Ln y = 7.30051-0.10946X	0.991***	-0.10946	52.89	6
(WS)	Sorbed	Ln y= 7.2818 - 0.00027X	0.963***	-0.00027	51.00	2566
Ladysmith Red	Soluble	Ln y = 6.33093. - 0.12102X	0.990***	-0.1210	20.05	6
Podzolic (LRP)	Sorbed	Ln y = 7.66229-0.00411X	0.973***	-0.00411	75.95	169

Table 6. Regression equation, adjusted R^2, rate constant, pool size and half live of the soluble and sorbed phase at incubation temperature 28°C (Analyzed using non steady state compartmental analysis)

Soil Type	Phase	Regression equation[1]	R^2	Rate constant (ng/day)	Pool[3] size (%)	Half life (days)
Hay Plains	Soluble	Ln y = 6.41747-0.08792X	0.965**[2]	-0.08792	21.86	8
Alluvium (HPA)	Sorbed	Ln y = 7.6977 - 0.01036X	0.984***	-0.01036	79.19	67
Waurn Ponds	Soluble	Ln y = 6.97681-0.08426X	0.996***	-0.08426	38.16	7
Rendzina (WPR)	Sorbed	Ln y = 7.45766-0.00681X	0.996***	-0.00681	61.89	102
Walpeup Sand	Soluble	Ln y = 7.30051-0.10946X	0.991***	-0.10946	52.89	6
(WS)	Sorbed	Ln y= 7.2818 - 0.00027X	0.963***	-0.00027	51.00	2566
Ladysmith Red	Soluble	Ln y = 6.33093. - 0.12102X	0.990***	-0.1210	20.05	6
Podzolic (LRP)	Sorbed	Ln y = 7.66229-0.00411X	0.973***	-0.00411	75.95	169

[1]Regression equation in the form of ln y = a + bx, where y is the loss of glyphosate from particular compartment; a is intercept or pool size; b is the slope of regression or rate constant; and x is time in day.

[2]*** significant at a P <0.001

[3]Pool size is the amount partitioned into each compartment (soluble and sorbed compartment) and expressed as a percentage of the glyphosate initially added.

3.2. The effect of temperature on half lives of the sorbed and soluble phases of glyphosate

The residence time period for glyphosate in the soluble and sorbed phases varied widely between the 4 soils investigated (Table 2, 3, 4, 5 and 6). While the half lives of the soluble phase were relatively similar between 4 soils, ranging from 1- 14 days, the half lives of glyphosate in the sorbed phase varied widely (67-4950 days). This result suggested that soluble glyphosate decomposed readily and that temperature had little effect on the residence time. However differences in binding strength in the sorbed phase between 4 soils investigated affect the availability of glyphosate to be decompose by microbes and was affected by temperature.

Temperature significantly ($P < 0.05$) influenced the half life of glyphosate in the sorbed phase of the soils studied. Increasing temperature from 5 ^{o} to 28 ^{o} C progressively reduced the residence time of glyphosate in the sorbed phase in all soils examined except the Walpeup sandy soil at 17 ^{o} C. The reason for that is not fully understood.

The rate of glyphosate desorption was calculated from the rate of constant of the sorbed phase (Table 2, 3, 4, 5 and 6) and varied with soil type and temperature. Results in this study show that glyphosate appeared to be less strongly bound in alkaline soils (Alluvium and Rendzina) than the neutral and acid soils (Walpeup Sandy Soil and Ladysmith Yellow Podzolic) with exception of Walpeup terra rossa and Ladysmith red podzolic. As previously suggested, the strong binding of glyphosate in the sorbed phase for the Terra rossa may be due to the high amount of Fe and Al oxides and high amount of clay content present in this soil. While the high rate of desorption of glyphosate in Ladysmith Red Podzolic soil might be due to the low amount of the exchangeable Fe (Table 1) and pH of this soil. At pH above 5, Fe cation in the exchangeable sites is able to form hydroxy complexes and precipitates. The hydroxy polymer of Fe and precipitates are considered to be less reactive to glyphosate (McBridge & Kung 1989). The apparent of weak sorption of glyphosate in Ladysmith red podzolic compared with Walpeup Sandy Soil is likely due to soil pH which influence the stability of Fe cation in the exchangeable sites. Moreover, our data showed that the increase of temperature increased the rate of desorption, therefore making a substantial amount of this compound available in the soil solution for microbial catabolism. If was the case then the sorbed glyphosate may not permanently in-activated in the sorbed form. Hence temperature may not only influence the partitioning of glyphosate into the soluble and sorbed phase, but also influence the rate of glyphosate desorption into the soluble form.

Multiple regression analysis between the selected soil chemical-physical properties (Table 1), temperature and the rate of glyphosate desorption showed that glyphosate desorption was correlated with the soil pH, the amount of exchangeable Fe and Al in soils and incubation temperature. The regression equation describing desorption (D_{sorp}) is :

$$D\text{-}_{sorp} = -0.0773 + 0.02314\ pH - 0.001707\ pH^2 + 0.0000717\ Exch.\ (Fe+Al) - 0.0773\ Temperature;\ R^2 = 0.70$$

Previous studies have reported that sorption of glyphosate is influenced by soil pH and the amount of exchangeable Fe in soil (McConnell & Hossner, 1985; Glass, 1987) as well as the amount of clay and montmorillonite (McConnell & Hossner, 1985; Shoval & Yariv, 1979). Our findings concur with those of McConnell & Hossner (1985); Shoval & Yariv (1979) that there were significant correlation between soil pH and exchangeable Fe, but showed little correlation with the amount of clay mineral and type clay mineral dominant in the 4 soils investigated. Little correlation between the sorption of glyphosate and the amount of clay and the dominant type of clay mineral observed in this study may be due to less variance of the amount of unoccupied phosphate adsorption

sites of clay mineral of the 4 soils used in this study. As glyphosate is a zwitterion, the sorption of this compound may be dependent on soil pH. Sprankle *et al*. (1975b) showed that as the soil pH decreases, glyphosate becomes progressively less negatively charged. In acid soils below the dissociation constant of glyphosate (pKa 5.6), a substantial proportion of glyphosate is in the monovalent anionic form compared with the divalent anionic form in alkaline soils. Data presented here suggests that the differences in the charge of molecule as a result of soil pH may influence the strength of adsorption in acid soil relative to neutral-alkaline soils. Recent work with glyphosate and other herbicides agree with this assertion (Eberbach, 1998; Stougaard et al., 1990). However, an exception may apply in the cases of the Walpeup Terra Rossa and Ladysmith Red Podzolic soils as used here. A similar reason to the one previously mentioned may apply for Walpeup Terra Rossa. However red podzolic with pH beneath the dissociation constant of glyphosate, showed a rapid desorption from the sorbed phase. The reason for this is not fully understood but this may be due to lower exchangeable Al and Fe in comparison with two other acid soils. Further study is required to investigate the sorption dynamic of glyphosate in this soil.

In the present study, desorption of the sorbed glyphosate for each soil was slow at 5^{o} C and as the temperature increased the rate of desorption increased achieving a high rate at 28^{o} C with one exception for Walpeup Sandy Soil. Our data suggest that sorption of glyphosate is an exothermic reaction. Conversely, Eberbach (1998) showed that at low temperature glyphosate was weakly bound in alkaline soil. Our result reported here is thermodynamically consistent with sorption behaviour of many other herbicides, i.e. picloram (Farmer & Aochi, 1974), dinitroanilines (Harvey, 1974) and chlorsulfuron (Thirunarayanan et al., 1985). Thirunarayanan et al. (1985) suggested that this phenomenon may be explained on the basis of free energy of the solute and adsorbed molecule. They hypothesised that an increase in temperature may increase the internal energy of the molecule which results in less electrostatic attraction between the herbicide and the soil sorbent, hence decreasing the adsorption of the compound in soil

4. CONCLUSION

Temperature has strong influence on partitioning glyphosate into the soluble and sorbed phase in Alluvium and Walpeup sandy soils, whereas in Walpheup Renzina, temperature had little influence on partitioning glyphosate. Strong binding of glyphosate in Terra rossa was though to be due to the high amount of Al and Fe oxides, while low pH is responsible for strong binding of glyphosate in Book Book acid soils. Furthermore, sorption has some correlation with pH, exchangeable Fe and Al, and temperature. This study showed that sorption kinetic of glyphosate is an exothermic reaction.

ACKNOWLEDGEMENT

Authors thank for financial support provided by Aus-Aid for Suwardji during his study leave at Charles Sturt University Australia is gratefully acknowledged.

AUTHORS' CONTRIBUTION

All authors contributed almost equally in preparing and finishing the manuscript until it was ready to be submitted by the corresponding author.

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