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REGULAR ARTICLE

Glyphosate translocation from plants to soil – does this constitute a significant proportion of residues in soil?

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Abstract Translocation of glyphosate (*N*-(phosphonomethyl)glycine) to plant roots and its impact on detected herbicide residues in sandy loam soil were studied in a glasshouse pot experiment in Finland. Quinoa (*Chenopodium quinoa*, Willd) plants in two different growing phases (6–8 and 12–14 leaf stages, groups A and B, respectively) were sprayed with non-labelled glyphosate. Bare soil pots were included as controls (group C). Soil surface contamination with glyphosate was prevented in groups A and B but not in group C. Soil samples were collected 1 h, 8 days and 44 or 53 days after the glyphosate applications. Root samples were taken 8 days after the application from group B. After 8 days from the treatment, 4% of the applied glyphosate was detected in soil and about 12% in roots (group B). One and a half months later 12% and 8% of the applied glyphosate (groups A and B, respectively) was detected in soil samples incubated with roots. The main metabolite of glyphosate, aminomethyl phosphonic acid (AMPA), was not found in root samples. Glyphosate fate was simulated with the PEARL 3.0 model. Simulated concentrations in bare soil pots were very close to the observed ones. However, the model lacks a process description for herbicide transport within a plant and, therefore, the observed and simulated glyphosate residues in soil after canopy applications did not correlate. Simulations highlight the importance of the translocation process in glyphosate fate. We conclude that also in field studies part of the detected glyphosate soil residues must originate from plant roots, and translocation process should be included both in leaching assessments and pesticide fate models.

Keywords PEARL model · Pot experiment · Simulation · Transport

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Introduction

Glyphosate (*N*-(phosphonomethyl)glycine) has been one of the world's most widely used herbicides since it came to the market in 1974. It is a systemic herbicide that is first absorbed by foliage and then translocated throughout the plant via the phloem and further transported to metabolic sinks such as meristems of shoots and roots. Translocation has been shown to take place both in genetically modified and non-modified plants (Feng et al. 1999; Hetherington et al. 1999).

One of the earliest findings on translocation of glyphosate in plants was reported by Sprankle et al. (1975). They showed rapid translocation of ^{14}C-

glyphosate in quackgrass [*Elymus repens* (L.) Gould]. A few years later Coupland and Caseley (1979) reported that significant amounts of ^{14}C-glyphosate were exuded from intact roots of quackgrass into surrounding solution. Rodriques et al. (1982), Pline et al. (2002), Guldner et al. (2005), and Neumann et al. (2006) have shown that glyphosate can be exuded from roots to soil, and cause growth inhibition to adjacent plants and seedlings. However, no studies have been reported so far where translocation would have been addressed together with glyphosate residues in soil.

In general, glyphosate adsorbs strongly to soil and is therefore practically immobile. Moreover, the desorption of adsorbed glyphosate is low (e.g. Mamy and Barriuso 2007). Its leaching via soil matrix is therefore improbable. Also our earlier studies using Finnish soils (Autio et al. 2004) indicated high adsorption. Nevertheless, transport may occur via preferential pathways like macropores and cracks (de Jonge et al. 2000; Kjær et al. 2005; Stone and Wilson 2006), probably together with colloidal particles.

Glyphosate residues were detected below topsoil in our field studies (Laitinen et al. 2006). This can not be explained by preferential flow because the field sites were very dry and no rainfall occurred between glyphosate applications and soil sampling. Because glyphosate is exuded from roots, we postulated that glyphosate may be transported below topsoil via translocation in plants, and further released into soil. In addition, because it is impossible to take soil samples with no root fragments in field scale experiments, residues of glyphosate originating from root material may affect the results of soil residues.

The objective of this study was to clarify the significance of glyphosate translocation via plants to glyphosate residues in soil. The transport behaviour of glyphosate was studied in a glasshouse pot experiment and in a simulation study. The supplementary simulation study was designed in order to overcome the limitations of empirical data from the pot experiment. Models that are used to estimate pesticide leaching do not have a process description for translocation from shoots to roots and further to soil. Therefore, simulations provided us a reference dataset, without translocation process, for observed values obtained in cropped soil. This allowed us to focus our estimations on the translocation process and evaluate its relevance to the environmental fate of glyphosate.

Materials and methods

Experimental design

Transport of glyphosate from quinoa (*Chenopodium quinoa*, Willd) plants to soil was monitored in a glasshouse study at MTT Agrifood Research Finland in Jokioinen, Finland. Seed source: stock I, year 1999, original stock from Denmark, year 1997. Concentrations of glyphosate were determined from soil and root samples. In addition, aminomethyl phosphonic acid (AMPA), the metabolite of glyphosate, was also analysed from root samples.

The sandy silt loam soil originated from MTT experimental farm in Toholampi, Finland (63°49′N, 24°09′E), and was collected from tillage layer (0–30 cm). This area has intensively cultivated for many years but glyphosate had not been applicated for last ten years in this field. The soil was sieved (4 mm in diameter), and further, the chemical and physical properties of the soil (Table 1), and the background residues of glyphosate were analysed.

Quinoa seedlings (groups A and B) were grown in 0.62 l pots (14 cm in height). Also bare soil pots without seedlings were included in the study (group C). Pots were filled with soil and covered with a 0.2 cm layer of quartz sand. See Table 2 for cultivation history. Seedling pots were covered with a lid pierced with fourteen holes. Seeds were sown to

Table 1 Selected soil properties

Soil property	Value
Particle size fractions	
<0.002 mm (clay) (%)	4.0
0.002–0.02 mm (%)	10.0
0.02–0.06 mm (%)	42.0
0.06–0.2 mm (%)	42.0
0.2–2.0 mm (%)	2.0
Organic carbon content (%)	5.1
pH[a]	5.9
Plant available phosphorus[b] (mg l^{-1})	15.8
Bulk density (kg l^{-1})	1.4
Wilting point (vol.%)	13
Field capacity (vol.%)	46
Porosity (vol.%)	52

[a] pH was determined using 1:2.5 soil/water suspension.

[b] Phosphorus dissolved in solution of 0.5 M ammonium acetate and 0.5 M acetic at pH 4.65, method used in Finnish soil fertility test (Vuorinen and Mäkitie 1955)

Table 2 Cultivation history

Operation	date
Germination of inborn weeds	6/3–4/4/2002
Fertilization	04/04/2002
Background samples	17/04/2002
Sowing	23/05/2002
First leaf stage	03/06/2002
Glyphosate application A and C pots	11/06/2002
Glyphosate application B pots	25/06/2002

the depth of 1 cm through each hole. The seedlings were grown in a glasshouse with air temperature and humidity control (22/16±2°C day/night and 65% relative humidity). After the glyphosate application the A and B pots were sub-irrigated. Sub-irrigation was selected in order to prevent possible glyphosate transport together with irrigation water from pot surface or sprayed plants. Contrary to this, the C pots were irrigated from surface in order to estimate the potential leaching with added water.

Group A was sprayed with glyphosate when quinoa plants were at 6–8 leaf stage and group B when plants had reached 12–14 leaf stage. For herbicide applications the pots were covered with a 5 cm layer of dry peat. Both the lid and peat layer were used to prevent soil surface contamination by glyphosate sprayings. Applications were done outdoors in a windless spot. The pots were sprayed with glyphosate (360 g of active ingredient l^{-1}, Roundup Bio; Monsanto, Copenhagen, Denmark) with an application rate of 720 g ha^{-1}. Glyphosate was mixed with water and sprayed at 200 l ha^{-1}. A portable trial boom with HARDI 4110–12 nozzles 50 cm apart was used at 2.1 bar pressure. The sprayer boom was set at 40 cm distance from vegetation. Application dates are given in Table 2. After the plants had dried up, the peat was shaken off and the pots were placed in clean plastic boxes and moved back to the glasshouse.

Soil samples for glyphosate analyses were taken 1 h (sample sets A0 and B0) and 8 days (sample sets A8 and B8) after the herbicide sprayings. Plants were harvested before soil sampling. Sampling times and depths are given in results. The first soil samples after applications were taken only from surface layers (0–1 cm) about 40–60 min after applications. These samples were pooled before analyses. For all other samples four replicates were separately analysed. Samples were stored intact in plastic containers (0.4 l) and frozen at −18°C. A subset of the soil samples taken 8 days after the treatment were incubated at +22°C for 36 or 45 days, groups A and B, respectively (sample sets A44 and B53). These soil samples were collected in plastic containers (as above) but the soil was manually stirred to break the roots into smaller pieces and moistened to 55% of field capacity. In order to speed up decomposition of the roots, samples were stirred again after two weeks.

Root samples (B8r) were taken from group B pots at the same time as soil samples (8 days after treatment). The pots were immersed into water for 2 hours in order to soften the soil before collecting the root samples. Roots were washed for 5 min using the hydropneumatic elutriation system (Smucker et al. 1982). The average root yield was approximately 5.5 g pot^{-1}. About 68 % of roots were in the layers of 0–5.5 cm. Estimated root losses during the washing processes were 3 to 4%. Root samples were stored frozen at −18°C.

Glyphosate and AMPA analyses

Glyphosate and AMPA residues were analysed in the MTT. Defrosted soil samples were homogenised manually before analyses. Any remains of root matter were removed carefully before homogenisation from the soil sample sets A8 and B8. The dry matter contents of the soil and root samples were determined according to the Finnish Standard SFS 3008.

Stock standard solutions (ca. 100 μg ml^{-1}) of glyphosate (Dr Ehrenstorfer GmbH, Augsburg, Germany) and AMPA (Sigma, St Louis, MO, USA) were prepared with HPLC-grade water.

A Hewlett Packard series *II* 1090 high-performance liquid chromatograph (HPLC) and Hewlett Packard 1046A programmable fluorescence detector (Hewlett Packard GmbH, Waldbronn, Germany) were used for compound separation and identification. A Pickering Laboratories PCX 5100 post-column reaction module was used for derivatisation of glyphosate and AMPA.

For glyphosate analyses soil samples (10 g) were extracted with potassium hydroxide solution (0.1 M, 75 ml) as described by Spann and Hargreaves (1994), with minor modifications which were required because of high organic matter content of the soil. The modified method (assigned as method C) is described in Laitinen et al. (2006). Root samples (21 g) were

extracted as described by Alferness and Wiebe (2001), except that we had less root matter to work with due to availability. Glyphosate eluted almost immediately in cation exchange clean-up, because DOWEX 100–200 mesh was used instead of DOWEX 200–400 mesh. All eluate was collected and concentrated to almost dryness and 1 ml of K200-solution (5 mM potassium dihydrogen phosphate, pH 2.0) was added (final volume of 1.00–1.15 ml). Glyphosate and AMPA residues were analysed by HPLC as described in Laitinen et al. 2006.

Quality assurance of the residue analyses

For recovery analyses 2.6 mg of glyphosate standard was added to soil (kg^{-1} of wet weight) and about 0.3 mg (glyphosate and AMPA standards) to root matter (kg^{-1} fresh weight). Parallel residue analyses were carried out from the soil background samples and the pooled A0 and B0 samples. The observed deviation was almost zero. Only a single extraction was carried out from the root samples (due to limited availability of root material) but parallel DOWEX clean-up procedures were performed and both eluates were analysed.

A supplementary simulation study

Simulations were designed to compensate for the gaps in the data series C (limited number of samples; sampling depths not directly comparable to A and B groups; background contamination). In addition, simulations provided us datasets, where glyphosate transport in cropped pots took place only via leaching in cropped pots. These simulated datasets were compared to observed glyphosate concentrations in cropped pots (groups A and B). PEARL 3.0 model (FOCUSPEARL 3.3.3; Leistra et al. 2001; van den Berg et al. 2006) was selected to be used in simulations because it describes water and solute movement in uniform soil matrix most accurately according to the current knowledge. The sieved sandy loam used in the experiment was assumed to be a uniform matrix. Glyphosate fate in bare soil pots (group C) was simulated and observed residues (C0 and C8 sample sets) were used to calibrate chemical properties. The same parameters were then used to simulate glyphosate behaviour in pots with plants (group A and B). The discrepancy between simulated and observed concentrations in cropped pots was assumed to result from the lacking translocation process description.

The 13 cm thick soil profile used in simulations was divided into three horizons: 0–1, 1–5.5 and 5.5–13 cm, and further into 0.5 cm thick calculation layers. Identical soil properties were used for all horizons (see Table 1). Free drainage was selected for lower boundary conditions for bare soil pots and ground water in soil profile for sub-irrigated pots, because the base of each pot was pierced. The ground water depth was set to −13.5 cm, except for the sub-irrigation periods it was set to −10 cm. Water retention parameters were obtained by fitting the Van Genuchten equation to three measured points of the pF-curve of undisturbed soil. Hydrological and solute transport parameters are given in Table 3. Moreover, available meteorological data from the glasshouse was used and the potential evapotranspiration was calculated separately using the Penman–Montheith equation and given as an input to the model. The surface irrigated water amounts were added for bare soil pots (group C). The simulated period was from April 17 to August 15 2002.

Table 3 Soil hydrological parameters used in simulations

Parameter	Value	Remarks
Moisture at saturated soil ($m^3\ m^{-3}$)	0.52	Fitted value[a]
Residual water content ($m^3\ m^{-3}$)	0.065	Fitted value[b]
Van Genuchten alpha (cm^{-1})	0.01	Fitted value[c]
Lambda (−)	0	Assumed
van Genuchten n (−)	1.42	Fitted value
Saturated hydraulic conductivity (m day^{-1})	0.6	The mean of observed values in undisturbed soil
Dispersion length (m)	0.05	Default value of the model
Relative diffusion length option	Millington Quirk	Default value of the model

[a] Accepted range in the fitting of pF-curve was set between observed field capacity and total porosity without macropores.

[b] Accepted range in the fitting of pF-curve was set between zero and observed wilting point.

[c] No hysteresis was simulated and thus: alpha wet = alpha dry

The glyphosate application method was set either to the option of soil surface application (for group C) or to the option of foliage application (for groups A and B). In both cases the dosage was 720 g ha^{-1}. In the foliage application the total dosage was intercepted. In addition, a hypothetical case, where soil surface was assumed to become contaminated at spraying (by 2% of the applied amount), was simulated using a crop interception value of 98%. Crop parameters were obtained from available FOCUS scenario "Jokioinen-grass" (FOCUS 2000), but emergence and harvest days were reset. FOCUS default values were used for herbicide canopy processes.

Herbicide parameters were selected using a stepwise procedure. First, the potential range of parameter values was selected. Second, observed concentrations were corrected using laboratory recovery values. The mean of the observed values was used, except for glyphosate background concentration (the mean minus standard deviation of recovery), and for the bare topsoil just after application (the mean plus standard deviation). Third, simulated and observed concentrations (C0 and C8) were compared and parameter values were manually calibrated. The calibrated pesticide parameter values are given in Table 4.

Table 4 Glyphosate input parameters used in PEARL simulations

Parameter	Value	Remarks
Molar mass (g mol^{-1})	169	
Saturated vapour pressure (Pa)	2.59 E−6	At +25°C
Solubility in water (mg l^{-1})	1,200	At +25°C
Molar enthalpy of vaporisation (kJ mol^{-1})	95	Default value of the model
Molar enthalpy of dissolution (kJ mol^{-1})	27	Default value of the model
Freundlich sorption coefficient K_F (l kg^{-1})	60	Calibrated value given at +20°C; an adequate range: 37–159 [a]
Freundlich exponent (−)	0.93	Typical value, range: 0.76–1.05[a]
Desorption rate coefficient (day^{-1})	0.008	Default value (0.01) slightly decreased
Fraction of sorption sites in the non-equilibrium domain	0.93	The non-desorbed fraction calculated as (1 – desorbed fraction)[b]
Half-life (days)	13	Calibrated value at +20°C; available range: 1–197 with a median of 17 days (Giesy et al. 2000)
Initial conditions for pesticides in equilibrium and in non-equilibrium domains (mg kg^{-1})	0 and 0.036	After test simulations, the whole observed (recovery-corrected) glyphosate background residue was set to non-equilibrium domain (identical values for all soil layers)

[a] Measured glyphosate K_F and Freundlich exponent values in Finnish soils (only soils with less than 10% clay included; Autio et al. 2004)

[b] Glyphosate desorption in Finnish soils is typically 7% (variation between 6–17% depending on soil phoshorus status; Laitinen, personal communication). Similar results are found in literature e.g. 0.1–14% for three French soils (Mamy and Barriuso 2007)

Results

Efficiency of glyphosate recovery and analytical accuracy

The uncertainty of the analysis method for soil samples was 47% for glyphosate and 28% for AMPA. The obtained residue recoveries for glyphosate were 45±14% and 114±3% (soil and roots, respectively), and for AMPA 70±4% in soil and root samples (data not shown). The main reason for high uncertainty is the low recovery efficiency of the used method for glyphosate. Even the long alkali elution combined with boiling does not fully liberate the soil-bound glyphosate. It is well documented that recoveries of glyphosate from soil often remain low (Börjesson and Torstensson 2000; Stalikas and Konidari 2001; Laitinen et al. 2006). The random error calculated from the relative standard deviation of parallel samples was 10.0 and 10.3% for glyphosate and AMPA, respectively.

Glyphosate and AMPA residues in soil and roots

Residue results for glyphosate are presented in Table 5. The mean and the standard deviation consist of all parallel samples including those below the quantification limit. If no residues were detected in a given sample the value 0 was used for calculating the mean. Glyphosate residues below the quantification limit (0.016 mg kg^{-1}) were detected from the background sample taken in May 2002. The AMPA

Table 5 Glyphosate residues (mg kg^{-1} dry matter) in soil and roots

Time from application (days) Background	Depth (cm)	*n*	Glyphosate Mean	SD
−55	0–14	1[a]	*0.016*	
A soil				
A0[b]	0–1	1[a]	0.056	
A8[c]	0–6	4	0.069	0.010
A8[c]	6–14	4	*0.018*	0.006
A44[b]	0–6	4	0.074	0.01
A44[b]	6–14	4	0.024	0.006
B soil				
B0[b]	0–1	1[a]	*0.015*	
B8[c]	0–6	4	*0.024*	0.008
B8[c]	6–14	4	*0.010*	0.001
B53[b]	0–6	4	0.057	0.004
B53[b]	6–14	4	*0.012*	0.005
B roots				
B8r	0–14	1[a]	9.400	
C bare soil				
C0	0–1	1[a]	2.995	
C8	0–1	1[a]	1.420	
C8	1–6	4	0.040	0.001
C8	6–14	4	*0.020*	0.004

The quantification limit was 0.025 mg kg^{-1} dry weight for soil and 1.0 mg kg^{-1} dry weight for roots. Values below the quantification limit are italicized.

[a] Results of four combined sub-samples (four pots)

[b] Roots included

[c] No roots

background residues in soil was 0.13 mg kg^{-1}. Therefore the AMPA residues results are not given.

About an hour after the herbicide sprayings 1.1 and 0.3% of the applied glyphosate was detected in soil samples from A0 and B0 pots, respectively. In bare soil pots (C0) 58% of the applied glyphosate was found. Background contamination was deducted from the observed residue amounts. The used glyphosate dose per pot was estimated based on the herbicide application rate and the surface area of the pot.

Further, after 8 days of sprayings up to 10 and 4% of the applied glyphosate was detected in soil samples (roots had been removed) of A8 and B8 pots, respectively. Moreover, a much higher glyphosate concentration was detected in root samples from B8 pots (see Table 5) corresponding up to 12% of the total applied amount. The combined glyphosate recovery (soil and roots) from B8 pots was therefore 16% of the total amount. Over two thirds of the detected glyphosate was found in the upper layers of the pot (0–5.5 cm) where also most of the roots were found. In bare soil pots (C8 sample set) 35% of the applied glyphosate was detected of which over 90% was found in the upper layers of the pot (0–5.5 cm). After one and a half months 12 and 8% of the applied glyphosate was found in soil samples from A44 and B53 pots, respectively. These pots had been incubated from day 8 up to day 44 and 53, respectively, together with roots. No AMPA residues were detected in the root samples (data not shown).

Simulation results

The model calibration to simulate glyphosate concentrations in bare soil pots (C group) was very successful (see Fig. 1). Observed and simulated glyphosate concentrations after canopy application are shown in Fig. 2. The figure indicates clearly that simulations without the translocation process do not give correct estimations on glyphosate residues in soil. Glyphosate concentration profiles in rhizosphere soil after herbicide application to bare soil and to foliage are illustrated in Fig. 3.

Discussion

Glyphosate translocation in plants

Our results show that in very young plants (herbicide spraying at 6–8 leaf stage) about 1% of the applied glyphosate was found in 0–1 cm soil layer within 1 hour after the application (A0 samples; samples included roots). This is about four times higher than the observed background contamination and can not be due to direct spraying contamination because the soil was very carefully covered. We conclude that the found residues derive from translocation via shoots to roots and further exudation from roots to soil. Translocation process is further supported by our results both from soil samples taken 8 days after sprayings (A8 and B8) and root samples (B8).

Rapid penetration and translocation of glyphosate were also shown by Sprankle et al. (1975). In their studies ^{14}C-glyphosate translocation occurred rapidly in 3–4 leaf stage of quackgrass. In the untreated rhizome and shoots the quantity of glyphosate increased significantly over the studied time period

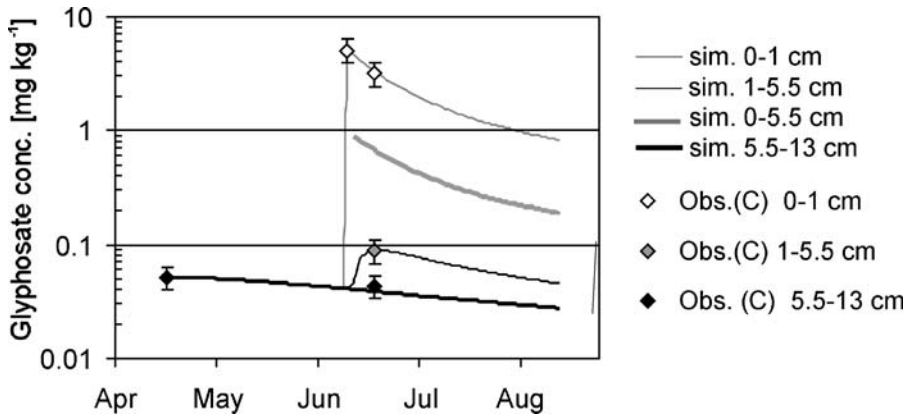

Fig. 1 Observed and simulated glyphosate concentrations in soil after application on bare surface (group C). The simulated concentration in depth 0–5.5 cm is shown in order to facilitate comparison with cropped pots (groups A and B)

(4, 8, 24, and 48 h) with 9.1, 26.0, 48.9, and 66.7%, respectively, of the total ^{14}C-glyphosate absorbed fraction. Moreover, also Geiger et al. (1999) found a rapid initial uptake and translocation of glyphosate by sugar beet plants. About 5.5% of the total absorbed glyphosate was exported per hour in glyphosate susceptible plants.

In the older plants (application at 12–14 leaf stage, group B) the concentration of glyphosate in 0–1 cm soil depth did not significantly differ from the obtained background value. However, 8 days after the application glyphosate was detected both in soil and roots, but soil concentration was lower than that observed in younger plants (group A). No AMPA was detected in the roots (data not shown). This is consistent with earlier studies (e.g. Eberbach and Bowmer 1995). On the other hand, little is known about the degradation of glyphosate in plant. Reddy et al. (2004) found very low amounts of AMPA in genetically modified, glyphosate resistant soybean leaves, and suggested that plant injury was caused by AMPA formed from glyphosate degradation in plant.

Further evidence for translocation to soil was obtained from our soil samples that had been incubated together with root matter. Glyphosate concentration had either risen (B53 samples) or remained the same (A44) compared with soil samples taken without roots and not incubated (A8, B8). It is to be noted that the incubation circumstances were very favourable to glyphosate degradation. This is indeed a strong evidence for the glyphosate translocation process.

Uncertainty due to background contamination

We tested four separate soil samples and selected the soil with lowest background concentrations. The

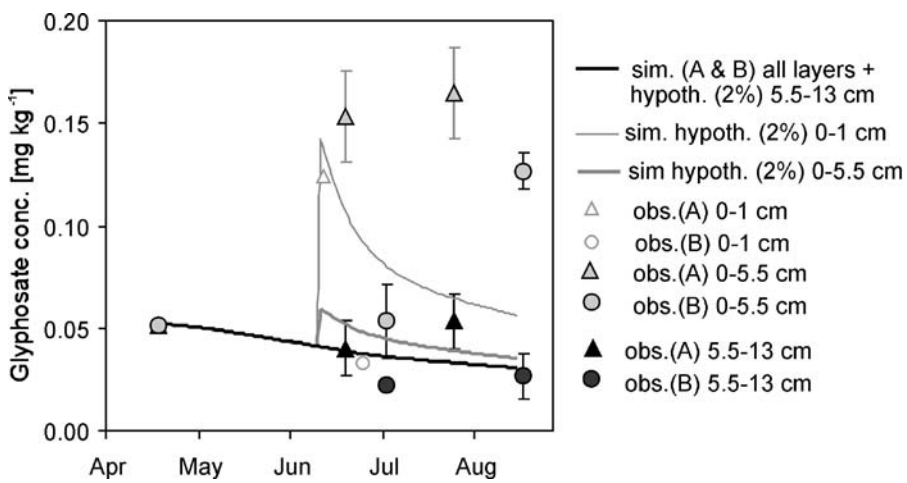

Fig. 2 Observed and simulated glyphosate concentrations in soil after canopy application (groups A and B), and in hypothetical case, where 2% of applied amount contaminated soil surface

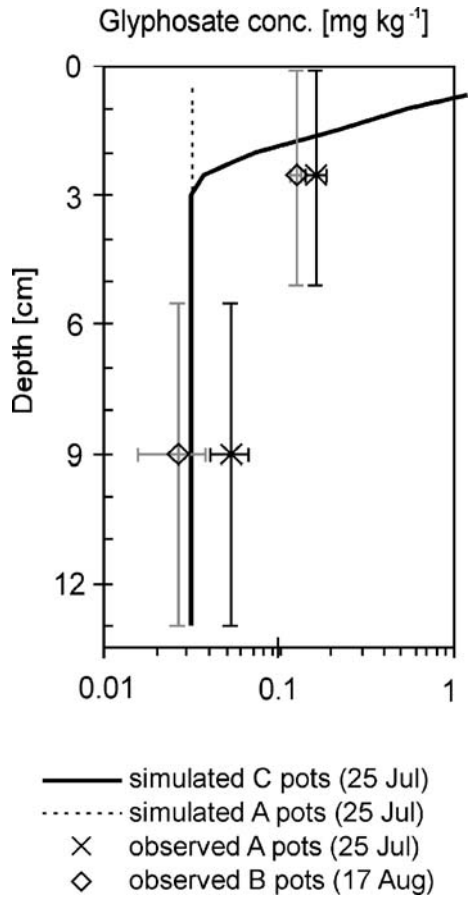

Fig. 3 Glyphosate concentration profiles about 1.5 months after herbicide application

background residues were unexpected because glyphosate had not been used in the sampling site since 1989. The background concentrations clearly impeded our analyses because they could not be separated from applied glyphosate. On the other hand, our results showed that in intensively cultivated regions spray drift may lead to detectable amounts of residues in untreated fields.

Our background samples were collected about two months before sprayings and do not tell us how much background contamination was still present just before the actual sprayings. Our analyses from deeper layers in bare soil pots just after sprayings (group C; see Table 3) show that not all background residues had degraded. However, in pots with vegetation (groups A and B) degradation is presumably more rapid due to higher microbial activities. Torstensson (1985) concluded in his review that degradation of glyphosate correlate with general microbial activity of the soil.

Simulations

More frequently collected empirical data could have given more precise results on herbicide fate. However, we could clearly show that simulations compensate quite adequately for the lack of empirical data. There are several reasons why successful simulations were obtained for bare soil pots (group C). The simulated soil was homogenous, the climate conditions were controlled in the green house environment and the used PEARL 3.0 model included all relevant process descriptions. On the contrary, simulations of glyphosate concentrations in cropped pots after canopy application did not correspond to the observed values. This was expected because the model does not contain a description of herbicide transport via plant to soil. By combining the simulated and observed data, we could show that glyphosate concentrations in soil root zone, except for the uppermost 2 cm, are higher after foliage application than after bare soil applications (see Fig. 3). The simulation results support our hypothesis that glyphosate translocation from plants to soil constitutes detectable glyphosate residues in soil. This simulation results are also in agreement with the results of Neumann et al. (2006) and other observations (e.g. T. Yamada, Potafos, Sao Paulo State, Brazil).

Field-scale implications

Our earlier results from a field study (Laitinen and Rämö 2005) correspond well with the results obtained in this study. In the field study glyphosate was found in quackgrass roots (2.7 mg kg^{-1} of dry weight) 40 days after the application. At the same time glyphosate was detected in both 0–5 cm and 5–35 cm soil layers (0.17 and 0.07 mg kg^{-1} of dry weight). The present study clearly shows that it is very likely that part of glyphosate residues detected in the field study soils originate from roots. It is evident that the translocation process has a significant role in glyphosate fate in soil.

What implications could our results have in field scale? First, translocated amounts of glyphosate may vary significantly. In cultivated fields the quantitative ratio of canopy and roots varies and thus the amount of glyphosate translocated to roots compared to field area and soil volume varies as well from case to case. For instance, when grass and green set-aside land is

treated with glyphosate for close down the canopy coverage is very high and most of the herbicide remains on the leaves and is further translocated to roots. Whereas in glyphosate sprayings in the beginning of growing season, e.g. in case of grain and genetically modified herbicide tolerant crops, a much larger amount of the herbicide ends up directly on the soil surface.

Second, due to translocation glyphosate can end up to deeper layers or root zone quite rapidly compared to leaching. The environmental impact of translocation depends on the depth of the root zone that is determined by the dominant weed species and the hydraulic conditions of the field site. Rapid release via roots into the rhizosphere or root channels may result in fairly high concentrations of glyphosate. This can cause various negative effects in non-glyphosate resistant plants through root uptake (Rodrigues et al. 1982; Guldner et al. 2005; Neumann et al. 2006). Third, glyphosate may be further transported from root zone to tile drainage water or to the ground water via macropore flow and when water table reaches the root zone. The impacts of such water contamination must be assessed separately.

Conclusions

The translocation of glyphosate via the shoot to the roots is fairly rapid and will take place also in circumstances where no leaching/transport in soil occurs. Our results give a strong evidence on the significance of translocation on the detected soil residues. We strongly recommend that translocation process should be included both in leaching assessments and pesticide fate models. Moreover, the negative effects of glyphosate residues in soil to conventional, non-resistant cultivars should be taken into account.

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