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Long-term experiments to investigate irreversibility in sorption of pesticides to soil

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HIGHLIGHTS

- Isotope exchange method is extended to study sorption over periods up to 9 months.
- Three pesticides in three soils took ca. 4 months to approach sorption equilibrium.
- Release of sorbed pesticide after exchange approximated ideal behaviour.
- Sorption processes under abiotic conditions were overwhelmingly reversible.

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ABSTRACT

Experiments investigated irreversibility in pesticide sorption to soil. Sorption behaviour under abiotic conditions was quantified for chlorotoluron, prometryn and hexaconazole in three soils over periods of up to 274 days. An isotope-exchange procedure was used whereby sorption of ^{12}C- and ^{14}C-pesticide isotopes in shaken suspensions of three soils (56–168 days shaking) was followed by substitution of the isotopes in the liquid phase and a 14-day exchange phase. This was followed by forced isotope exchange where the sorbed ^{14}C material was exchanged by adding an excess of non-radiolabelled compound. Experiments were concluded with solvent extraction and soil combustion to determine remaining radioactivity. Under conditions of continuous shaking, the pesticide-soil systems took around four months to approach sorption equilibrium, resulting in strong asymmetry between the profiles of exchange for isotopes of all three compounds. Physically entrapped residues were released back into solution under the steep concentration gradient of forced isotope exchange and small amounts of radioactivity were still being released at the termination of the experiment. The profiles of exchange did not deviate markedly from ideal behaviour based on the assumption that sorption is fully reversible. Whilst the timescales for release of sorbed residues back into solution were very long, soil combustion at study termination only yielded <1–2% of applied radioactivity; this confirms that sorption processes under abiotic soil conditions were overwhelmingly reversible for this set of compounds and soils.

1. Introduction

Sorption is a key process controlling the fate of a pesticide in soil as it determines the distribution between soil solid phase and soil water phase. Sorption (both adsorption and absorption) and desorption can be kinetically-controlled, typically involving multiple domains of sorption kinetics ranging from instantaneous to very slow with true equilibrium approached over months or years (Altfelder and Streck, 2006). Pesticide sorption to soils is often reported to be only partially reversible, with a fraction of the sorbed pesticide apparently resistant to desorption at the tails of kinetically-controlled release (Chen et al., 2004). The formation of non-extractable (bound) residues is important for the fate and transport of organic contaminants in environmental systems as it

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limits the bioavailability of pesticides in surface soil systems and has potential to reduce pesticide mobility in the environment (Barriuso et al., 2008).

Physical entrapment within the soil solid phase and covalent bonding to soil organic matter are two processes known to give rise to bound residues (Dec et al., 1997; Kan et al., 2000). Some parent compounds will be directly subject to covalent bonding (Bollag et al., 1992; Senesi, 1992), but in many cases, the formation of bound residues has been found to arise as a result of biodegradation of the parent compound to one or more metabolites that are prone to covalent bonding to organic matter. Several studies have demonstrated a large reduction in formation of bound residues in sterile soil where biodegradation to metabolites is inhibited (Rice et al., 2002). Recent work has demonstrated that biodegradation of parent compound can also be followed by assimilation into biogenic material by soil microorganisms (*e.g.* as fatty acids and amino acids) (Nowak et al., 2010). Such biogenic material is excluded from conventional definitions of bound residues, but is indistinguishable in studies based solely on recovery of radiolabelled chemical from treated soil. Whilst the formation of bound residues effectively reduces bioavailability and transport of pesticide in soil, questions have been raised about long-term reversibility and possible implications for human and ecosystem health. In this context, the parent compound is generally most toxicologically active and thus of greatest concern (Sinclair and Boxall, 2003). For chemicals that are not prone to covalent bonding to soil organic matter, bound residues of the parent compound will be most frequently associated with physical entrapment. The current paper investigates whether or not there is an irreversibly bound fraction for pesticide residues sorbed to soil over extended periods of time.

Experimental approaches and instrumental methods used to characterise bound residues in soil were reviewed by Northcott and Jones (2000). Classical extraction procedures aimed to recover as much of the pesticide as possible using exhaustive extraction techniques (Gevao et al., 2005). A modification to the IUPAC definition of bound residues by Führ et al. (1998) stipulated that "the extraction method must not substantially change the compounds themselves or the structure of the matrix", meaning that bound residues now typically refer to those residues that cannot be extracted from soil by an organic solvent and without alteration to the chemical structure of the compound.

Celis and Koskinen (1999a, 1999b) presented an isotope exchange technique using ^{14}C to characterise pesticide exchange kinetics. The principle of the approach is pre-equilibration of duplicate tubes with soil-water slurry and dosed with either ^{12}C- or ^{14}C-pesticide; the tubes are centrifuged and the supernatants switched to allow characterisation of the kinetics of pesticide exchange and estimation of amounts of sorbed pesticide that do not participate in the exchange. The authors proposed that their method eliminated inherent experimental artefacts of other approaches such as the specific effectiveness of the extracting method and changes to the soil solid phase. Despite the promise of the approach, it is unlikely that true irreversible sorption could be measured during Celis and Koskinen (1999a, 1999b) three-day tests. Sander and Pignatello (2005, 2009) used equilibration times of up to 140 days with the objective of ensuring sorption equilibrium in their forward isotope exchange experiment with the persistent hydrocarbons naphthalene and 1,4-dichlorobenzene. Therefore, sorption and desorption periods should be extended to widen the scope and environmental applicability of isotope exchange studies.

An isotope exchange study was carried out using three test compounds in three soils to characterise irreversibility in pesticide sorption-desorption to soils over time and to determine whether any irreversibly bound fraction of pesticide changes over time and/or differs for differing pesticides and soil types. The three pesticides were selected to have a range in sorption properties; they comprised chlorotoluron [*N*′-(3-Chloro-4-methylphenyl)-*N*,*N*-dimethylurea], prometryn [*N*,*N*′-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine], and hexaconazole [α-butyl-α-(2,4-dichlorophenyl)-1*H*-1,2,4-triazole-1-ethanol].

2. Materials and methods

2.1. Soils

Three soils from the UK with differing physico-chemical properties were selected for study. Fresh soils from 0 to 15 cm depth of a Blackwood loamy sand, Andover clay loam and Salop sandy clay loam were collected, air-dried and passed through a 2-mm sieve (sampling sites and dates are given in Table 1). Soil characterisation was carried out by NRM Laboratories Ltd (Bracknell, UK; Table 1). Soils were gamma irradiated at 35.40 kGy by Isotron Ltd (Bradford, UK) to sterilise and thus inhibit microbial degradation. Irradiated soils were subsequently stored under sterile conditions (at 4 °C in darkness) until use. It is assumed throughout that any impact of irradiation on the soil constituents did not materially influence pesticide sorption behaviour.

2.2. Chemicals

Analytical-grade ^{12}C-pesticides were purchased from Sigma-Aldrich Ltd (Dorset, UK). All ^{14}C-pesticides were supplied by Syngenta Ltd (Jealott's Hill International Research Centre, Bracknell, UK). Details of purity and specific activity are given in Table S1 in the Supporting Information. Preliminary batch-slurry experiments with ^{12}C-pesticides quantified sorption isotherms in the three soils after 24-h shaking and for seven initial concentrations of each pesticide. All chemicals were either received sterile or sterilised prior to use by autoclave.

2.3. Isotope exchange

Experiments comprised a sequence of adsorption (periods from 7 to 168 d), isotope exchange and re-equilibration over 14 days, forced isotope exchange (periods from 145 to 204 days), then finally solvent extraction, analysis for metabolites and soil combustion. These different procedures are described in turn below and any differences in methodology for experiments with the three pesticides are given in Table S1 in the Supporting Information. Long-term experiments commenced with the isotope exchange technique based on the method described by Celis and Koskinen (1999a, 1999b), but longer timescales were used here. The experiment involved independent application of two isotopes of pesticide (^{12}C and ^{14}C) to the three study soils. The study was performed in triplicate and over four sorption periods (7, 14, 28 and 56 d for chlorotoluron; 28, 56, 112 and 168 days for prometryn and hexaconazole). Soil was irradiated and all materials were sterilised prior to use in order to inhibit microbial degradation, but no additional sterility controls were applied during subsequent experimental manipulations.

Preliminary experiments determined that the optimal soil:solution ratio (*i.e.* giving 30–70% sorption over 96 h) varied between 1:4 (chlorotoluron) and 1:50 (hexaconazole). Test vessels were 50 mL Teflon® centrifuge tubes, irradiated to sterilise for 20 min prior to use in a CL-1000 ultraviolet cross-linker (UVP Ltd, CA, USA). Tubes had screw-topped lids and we assumed negligible losses of liquid via evaporation between experimental steps. Soils were weighed into vessels to give the appropriate soil:solution ratio on an oven-dry basis (Supporting Information Table S1) and then

Table 1
Characterisation of the three study soils.

Soil type	Texture	Sample location (OS grid ref.)	Date collected	pH (in $CaCl_2$)	Content (% w/w)			
					Sand	Silt	Clay	Organic matter
Blackwood	Loamy sand	SE50917051	29/05/2009	5.6	83	8	9	5.6
Andover	Clay loam	SE99105892	28/05/2009	6.9	49	32	19	5.1
Salop	Clay loamy sand	SP26616611	28/05/2009	5.8	54	26	20	5.2

19.0 mL of sterile 0.01 M $CaCl_2$ was added (24.0 mL for hexaconazole). The experiment was performed in the dark in an incubator at 4 °C (Sanyo Fitotron RS232 incubator) to minimise degradation, with continuous shaking at 150 rpm (HS 501 Digital IKA®-Werke reciprocal shaker). Soil suspensions were pre-equilibrated by shaking overnight. Sterile pesticide treatment solutions (^{12}C and ^{14}C) were prepared in 0.01 M $CaCl_2$, ensuring equivalence in concentration. This was applied (1.0 mL) to the pre-equilibrated soils to give 20 mL total pesticide solution (25 mL for hexaconazole) with an initial concentration of 0.70, 0.78 and 0.77 μg mL^{-1} for chlorotoluron, prometryn and hexaconazole, respectively. For each soil-pesticide combination, half of the samples contained only ^{12}C-pesticide and half contained only ^{14}C-pesticide.

After the respective sorption period, samples were centrifuged at 3500 rpm for 10 min (Hermle Z513K, LaborTechnik, Bench Top Centrifuge). The supernatant from each sample was removed by weight (Supporting Information Table S1) using a Pasteur pipette, taking care not to disturb the soil. A 200-μL aliquot was taken from each ^{12}C supernatant to determine percentage sorption by HPLC analysis. The same sample volume was also removed from each ^{14}C supernatant but instead mixed with 10 mL of EcoScint A for quantification by LSC. Supernatants were then exchanged between corresponding tubes, with initially ^{12}C samples receiving the parallel ^{14}C supernatant and vice versa. This substitution did not disturb sorption equilibrium when expressed for the combination of the two isotopes as the same sorption equilibrium was reached in both tubes prior to the exchange, only with different carbon isotopes. Samples were then shaken for a further 14 days for isotope exchange to occur and sampled during this time on days 1, 3, 7 and 14 (centrifuged and a 200-μL aliquot of supernatant removed for LSC quantification) to measure exchange between ^{12}C- and ^{14}C-pesticide isotopes over time.

2.4. Forced isotope exchange

A forced isotope exchange procedure involving the addition of a high-concentration ^{12}C-pesticide solution in 0.01 M $CaCl_2$ was carried out following the 14-day isotope exchange phase. Repeated influx of high-concentration ^{12}C-pesticide over time ensures that competition for sorption to soil between ^{12}C- and ^{14}C-pesticide is increasingly biased towards the former; supply of ^{12}C-pesticide to the soil solid phase surfaces to take part in sorption is essentially instantaneous with exchange with ^{14}C-pesticide the rate-limiting step. Thus, as ^{12}C-pesticide occupies all available sorption sites by out-competing any available ^{14}C-pesticide, it is possible to identify, through measurement of ^{14}C-pesticide in solution, the proportion of sorbed ^{14}C-pesticide available for desorption and hence the proportion of ^{14}C-pesticide not taking part in the sorption-desorption process.

Only initially ^{14}C samples (three soils, three replicates) adsorbed for 56 days (all pesticides) or for 112 and 168 days (prometryn and hexaconazole) were used in this part of the study as these had the greatest mass of ^{14}C-pesticide sorbed to soil after the 14-day exchange phase. There were 12–17 sampling points over periods of 145–204 days (Supporting Information Table S1). Samples were shaken between sampling points (150 rpm, 4 °C). At each sampling point, samples were centrifuged and the supernatant was removed by weight (Table S1). A 250-μL aliquot was taken for quantification by LSC to measure release of ^{14}C from soil over time. The supernatant that was removed was then replaced with fresh, high-concentration (Table S1) ^{12}C-pesticide solution to maintain the competition for sorption sites.

At the end of forced isotope exchange, soils were extracted with acidified methanol (0.1% H_3PO_4) to determine whether the ^{14}C-pesticide residue remaining sorbed to the soil was available by harsher extraction. Extractions involved addition of 20 mL of methanol acidified with 0.1% H_3PO_4 before shaking at 250 rpm for 24 h at room temperature. The process was repeated until further removal of ^{14}C-pesticide was insignificant (<1% of initial-applied). Supernatants and soil extracts were analysed by radio-HPLC for parent compound and metabolites, and soils were finally combusted to complete the mass balance.

2.5. Theoretical development for isotope exchange and forced exchange

Theoretical development is provided for treatments with initially ^{14}C-pesticide as these were taken through the full procedure of isotope exchange followed by forced exchange. Equivalent relationships (equations (1)–(3)) for isotope exchange of treatments with initially ^{12}C-pesticide can be obtained by reversing the isotope nomenclature. At the end of the equilibration phase prior to isotope exchange and for tubes with initially ^{14}C-pesticide, the partition coefficient (K_d, mL g^{-1}) can be defined as:

$$K_d = \frac{^{14}C_s}{^{14}C_e} = \frac{^{14}M_s}{^{14}M_e} \cdot \frac{V}{S} \quad (1)$$

where $^{14}C_s$ and $^{14}C_e$ are the concentration of ^{14}C-pesticide in soil and solution (μg g^{-1} and μg mL^{-1}), respectively; $^{14}M_s$ and $^{14}M_e$ are the mass of ^{14}C-pesticide in soil and solution (μg), respectively; V is the volume of solution (mL); and S is the mass of soil (g). At this point, the supernatants are exchanged between initially ^{14}C and initially ^{12}C tubes. The total mass of ^{14}C-pesticide present in the initially ^{14}C tube after exchange is now $^{14}M_s$ and all of this will be sorbed at the point of exchange. We can define the quantity of ^{12}C-pesticide as $^{12}M_e$ which will be numerically equivalent to $^{14}M_e$ and will be wholly in the solution phase at the point of exchange.

It is assumed that sorbed and equilibrium pesticide concentrations are identical for tubes with the same treatment and differing only in having initially ^{14}C- or initially ^{12}C-pesticide and that the sorption equilibrium is maintained after isotope exchange when expressed on the basis of the total pesticide (*i.e.* ^{14}C and ^{12}C) in the system. This assumption is supported by the research of Sander and Pignatello (2009) who showed complete reversibility of sorption at low concentrations in their long-term isotope exchange experiments. In this circumstance and assuming that all sorbed ^{14}C-pesticide is available for exchange, the K_d will be maintained at the pre-exchange value and there will be a net transfer of ^{12}C-pesticide

out of solution into the sorbed phase and a numerically equivalent net transfer of ^{14}C-pesticide in the opposite direction. Theoretically, these net fluxes will continue until the point where the two isotopes each attain the characterising equilibrium (nomenclature as previously, with equilibrium for each individual isotope designated with prime symbols (′)):

$$K_d = \frac{^{12}M'_s}{^{12}M'_e} \cdot \frac{V}{S} = \frac{^{14}M'_s}{^{14}M'_e} \cdot \frac{V}{S} \quad (2)$$

The amount of ^{14}C-pesticide released into solution following isotope exchange is given by $^{14}M'_e$. As it is assumed that K_d is constant throughout the exchange process and no degradation occurs, and as $^{14}M'_s$ is given by ($^{14}M_s - ^{14}M'_e$):

$$^{14}M'_e = \left(^{14}M_s - ^{14}M'_e\right) \cdot \left(\frac{^{14}M_e}{^{14}M_s}\right)$$

which can be rearranged to:

$$^{14}M'_e = \frac{^{14}M_s \cdot ^{14}M_e}{(^{14}M_s + ^{14}M_e)} \quad (3)$$

For the condition where there is no irreversible sorption, we can thus calculate theoretical values for $^{14}M'_e$ as a function of the partitioning measured immediately prior to isotope exchange. This relationship is plotted as the dashed line in Fig. 3.

The sorption equilibrium is completely changed during forced exchange due to the addition of concentrated ^{12}C-pesticide solution. At this point in the experiment, we are interested in how much of the ^{14}C-pesticide that is still sorbed after isotope exchange is participating in reversible sorption equilibrium. Assuming zero irreversible sorption, all of the ^{14}C-pesticide should be released back into solution over successive exchange steps due to the huge imbalance in presence of the two isotopes. The ^{14}C released during forced exchange is thus defined as:

$$^{14}M''_s = \left(^{14}M_s - ^{14}M'_e\right) \quad (4)$$

For the condition where there is no irreversible sorption, we can thus calculate theoretical values for $^{14}M''_e$ as a function of the partitioning measured immediately prior to isotope exchange. This relationship is plotted as the solid line in Fig. 3.

2.6. Testing for degradation

Degradation was measured in parallel to the isotope exchange studies. The three soils were treated with ^{12}C-pesticide (chlorotoluron) or ^{14}C-pesticide (prometryn and hexaconazole); there were again three replicates, but this time with five sorption periods (7, 14, 28, 56 and 70 days for chlorotoluron; 28, 56, 112, 168 and 182 days for prometryn and hexaconazole) to include the isotope exchange period. Soil suspensions were prepared and shaken exactly as in the main study using the same soil:solution ratio and initial mass of pesticide. After each sorption period, samples were centrifuged, the supernatant was removed by weight (Supporting Information Table S1) and a 1-mL aliquot was taken for analysis by HPLC or radio-HPLC. The soils were then extracted with solvent by adding 20 mL methanol (acidified with 0.1% H_3PO_4) and shaking at 250 rpm for 1 h at room temperature. After centrifuging to separate the soil extract, a 1-mL aliquot was taken for analysis by HPLC or radio-HPLC to derive the mass balance and assess presence/absence of any degradation products. Supernatants and soil extracts taken from chlorotoluron experiments at 28, 56 and 70 days were analysed by LC-TOF-MS to confirm that mass balances were solely attributable to parent compound and not to any degradation products. This step was not necessary for the other two compounds due to use of radio-HPLC.

2.7. Chemical analysis

All ^{12}C-pesticide samples in solution were analysed by HPLC (Agilent 1100 Series, Agilent Technologies UK Ltd); full details are given in Table S2 in the Supporting Information. ^{14}C-pesticide samples in solution were analysed by LSC (LS 6500 Beckman Coulter Inc., Fullerton, USA). The LSC method counted each sample three times for a total of 15 min (5 min each). Duplicate blanks were used to account for the background radioactivity and results were corrected for quench and luminescence. Limits of quantification were 0.00011, 0.00012 and 0.00022 Bq mL^{-1} for chlorotoluron, prometryn and hexaconazole, respectively. Radio-HPLC analysis was carried out using a Hewlett Packard 1100 Series HPLC with Perkin-Elmer Radiomatic 625 TR Flow Scintillation Analyser (see Table S3 in the Supporting Information for details).

To prepare soil samples for combustion, soils were air-dried (7 days) and then ground using a pestle and mortar. Approximately 200 mg of dry, ground soil was weighed into a combustion cone sandwiched between two combustion caps. Soil samples were then oxidised in a Perkin-Elmer Oximate 80, Model 370 and finally analysed by LSC (Perkin-Elmer Tri-Carb 2810 TR Liquid Scintillation Analyser). Limit of quantification was 2.5 Bq g^{-1} sample.

LC-TOF-MS analysis of supernatants and soil extracts containing chlorotoluron was performed using an Agilent 1200 Series LC with G120 Time of Flight Mass Spectrometer (Santa Clara, CA, USA). LC was performed using a Waters Acquity BEH C_{18} (2.1 × 50 mm, 1.7 μm) column (at 35.0 °C) with 0.2 μm in-line filter. Mobile phases were 5 mM ammonium acetate in water (Channel A) and methanol (Channel B). A gradient method and flow rate of 0.6 mL min^{-1} was used. The initial ratio of ammonium acetate:methanol was 98:2, changing to 2:98 over 5 min, held for 3.1 min before then returning to original conditions after 8.1 min (total run time 9 min). Retention time of parent chlorotoluron was 3.01 min. Injection volume was 3 μL in acetonitrile. TOF-MS analysis was carried out in positive or negative mode electrospray with a nebulizer pressure of 45 psi, capillary of 4000 V, gas temperature of 450 °C, drying gas flow at 15 L min^{-1}, skimmer of 60 V, fragmentor of 150 V and octopole RF voltage of 250 V. The mass range measured was 100–1100 m/z with resolving power of 5000. Total ion chromatographs were generated using Agilent Masshunter.

3. Results and discussion

3.1. Degradation and 24-h sorption isotherms

LC-TOF-MS analysis did not identify chlorotoluron metabolites in any supernatants or soil extracts analysed following 28, 56 or 70 days of sorption; ^{12}C-chlorotoluron samples did not differ (except for chlorotoluron peak) from the blank supernatants and soil extracts. Hence, it was assumed that negligible degradation of chlorotoluron occurred during the 70-day experiment. Radio-HPLC analysis confirmed that there was no quantifiable degradation of hexaconazole over the 182 days investigated. Small amounts of degradation of prometryn occurred with the proportion of radioactivity attributable to parent decreasing from 97 ± 0.3%, 97 ± 0.1% and 98 ± 1.9% after 56 days to 92, 94 and 97% after 182 days in the Blackwood, Andover and Salop soils, respectively; there were no replicates at the latter date due to combination and concentration of supernatants. Table S4 in the Supporting Information characterises sorption isotherms for 24-h batch-slurry experiments with all pesticide-soil combinations to act as a reference point for data

from long-term sorption experiments. These batch values are in line with ranges reported in regulatory databases (*e.g.* www.sitem.herts.ac.uk/aeru/ppdb).

3.2. Isotope exchange

Fig. 1 characterises isotope exchange in the study soils during the 14-day exchange phase for the three compounds subjected to 56 days of sorption. This sorption period is discussed in detail as it was common for all pesticides; corresponding results for other sorption periods are shown in Figs. S1–S3 in the Supporting Information. For initially ^{12}C samples, Fig. 1 shows a significant reduction of ^{14}C-pesticide in solution over the first day after exchange. Meanwhile, for the initially ^{14}C samples, a significant increase of ^{14}C-pesticide in solution is evident during the same period. The influx of ^{12}C- (initially ^{14}C sample) or ^{14}C- (initially ^{12}C sample) pesticide at 0 days (supernatant exchange) gave large differences between the ratios of the two isotopes in the soil and solution in both tubes. Thus, rapid sorption (initially ^{12}C sample) and release (initially ^{14}C sample) of ^{14}C-pesticide in one direction dominates as the system responds to accommodate for the new conditions.

The remainder of the isotope exchange phase (between 1 and 14 days) sees any further net exchange between ^{12}C- and ^{14}C-pesticide become much slower. For both initially ^{12}C and ^{14}C samples, the disparity in isotope concentration has lessened as the majority of isotope exchange has already occurred. For initially ^{12}C samples, there is an overall decrease of ^{14}C-pesticide in solution over time as this sorbs to the soil, displacing ^{12}C-pesticide. For initially ^{14}C samples, the anticipated increase in ^{14}C-pesticide in solution over time is short-lived. After the initial (0–1 day) increase due to release of sorbed material, there is a net decrease (chlorotoluron) or relatively constant amounts (prometryn, hexaconazole) of ^{14}C-pesticide in solution between 1 and 14 days. Any decrease in concentration of ^{14}C-pesticide in solution is seen most strongly in those instances when the shaking period prior to isotope exchange was shorter (*e.g.* for shaking periods of 7–56 days; Supporting Information Figs. S1–S3). This phenomenon is likely the result of continued sorption, demonstrating that the system had not reached equilibrium at the point of supernatant exchange, even after 56 days (Fig. 1). None of the pairs of isotope exchange curves shown are symmetrical around a horizontal line, indicating that none of the systems reached true equilibrium during the experimental period, even where the sorption phase lasted 168 days for prometryn and hexaconazole (Supporting Information Figs. S1–S3). There is no trend of different behaviour for the

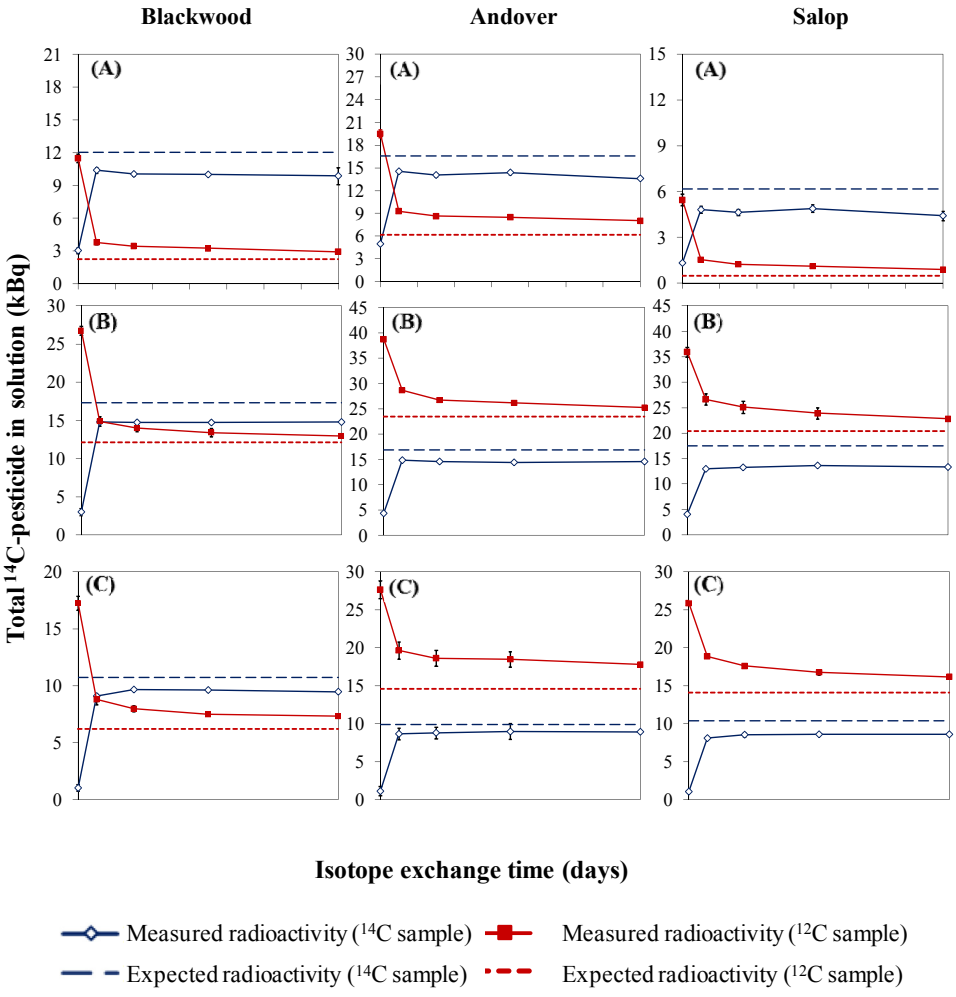

Fig. 1. Pesticide isotope exchange over time following 56 days of sorption. The solid lines show the measured change in total ^{14}C-pesticide in solution over 14 days for the Blackwood, Andover and Salop soils for (A) chlorotoluron; (B) prometryn; and (C) hexaconazole. Diamonds represent the initially ^{14}C-pesticide samples, squares represent the initially ^{12}C-pesticide samples. Data are shown as the mean value with standard deviation of three replicates included. The dotted lines represent the radioactivity in solution that the measured radioactivities are expected to reach if there is perfect exchange, *i.e.* if sorption is a fully reversible process.

different soils.

If sorption equilibrium had been reached and all pesticide was in exchange between the soil and solution, meaning sorption was a fully reversible process, then Fig. 1 would show the measured radioactivity in solution (solid lines) reach the expected radioactivity in solution (dashed lines) during the 14-day isotope exchange phase. Expected radioactivity lines were calculated based on the proportion of initial ^{14}C-pesticide in solution after the respective sorption period, so the same proportion of ^{14}C-pesticide was expected to be in solution after the 14-day exchange phase if all sorbed pesticide was participating in exchange. This is clearly not the case for the initially ^{14}C samples, as continued sorption of ^{14}C-pesticide that was released into solution immediately after supernatant exchange means the measured radioactivity in solution actually deviates further from that expected over time (Fig. 1).

Central to the explanation of Fig. 1 is that the sorption of pesticide to soil is time-dependent. Extent of sorption increased between 28 and 56 days for all pesticide and soil combinations except prometryn in the Blackwood and Andover soils (Supporting Information Table S5). There were no measurements of sorption of chlorotoluron beyond 56 days, but data for prometryn in the Salop soil and hexaconazole in all three soils show further increases in sorption between 56 and 112 days. All systems with prometryn and hexaconazole were apparently very close to true sorption equilibrium after 112 days as there was little or no increase in sorption through to 168 days (Supporting Information Table S5). Gao et al. (2007) also found chlorotoluron sorption to soil to be time-dependent and suggested that the time-range to reach equilibrium was likely to be months or years. In contrast, Celis and Koskinen (1999a, 1999b) considered that triadimefon and imidacloprid-guanidine had reached sorption equilibrium during their three-day isotope exchange tests. However, the authors observed asymmetry in the behaviour of initially ^{12}C and ^{14}C samples which was similar to that observed here and may suggest that true equilibrium was not attained (Suddaby et al., 2013). The fact that sorption was not at equilibrium at the point of isotope exchange meant that results from this phase of experimentation could not be used to calculate the irreversibly sorbed fraction of pesticide as proposed by Celis and Koskinen (1999a). This is because exchange patterns for the two isotopes should be symmetrical in Fig. 1.

Overall, the patterns of asymmetry exhibited in Fig. 1 and Figs. S1–S3 are relatively consistent between the different pesticides and across the three different soils. One exception is for chlorotoluron in the Salop soil for shorter equilibration periods (Fig. S1, 7- and 14-d equilibration) where the effect of continued increase in strength of sorption after isotope exchange is particularly marked. This indicates that sorption of chorotoluron was further from the equilibrium in Salop soil after 7–14 days than in the other two soils at the equivalent time; however, the reasons for this deviation are unclear.

3.3. Forced isotope exchange

Fig. 2 shows the result of the forced isotope exchange over time for samples sorbed for 56 days with ^{14}C-chlorotoluron then subjected to isotope exchange over 14 days (data for prometryn and hexaconazole showed a similar form and are given in the SI as Figs. S4 and S5). The bulk of total recoverable ^{14}C-chlorotoluron was extracted with the first addition of ^{12}C-chlorotoluron (average 25% Blackwood, 42% Andover and 21% Salop after 1 day; Fig. 2). This was followed by a gradual decline in ^{14}C-chlorotoluron recovery over time, which finally reached <1% recovery of initial for the Blackwood and Andover soils and 2% for the Salop soil between 161 and 204 days.

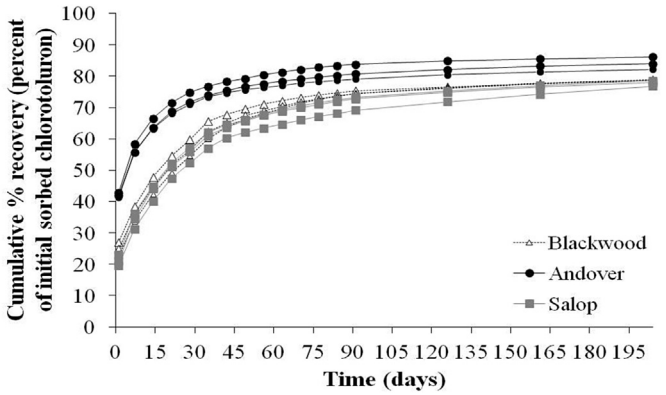

Fig. 2. Cumulative percentage recovery of ^{14}C-chlorotoluron during forced isotope exchange. Recovery is expressed as a percentage of the 14C-chlorotoluron that is sorbed at the start of the forced exchange procedure. Samples are initially ^{14}C with 56-days sorption and isotope exchange for 14-days (3 replicates per soil).

Although exposure to high concentrations of pesticide in solution is far from normal field conditions, the approach is anticipated to leave the soil solid phase essentially unchanged and thus may be a useful indication of long-term availability of residues to be biodegraded or leached in soils. Undoubtedly, there is some effect on the soil solid phase from shaking with aqueous solution over a protracted period (*e.g.* a possible increase in activity of the sorption sites) and this has not been quantified here.

The amount of ^{14}C-pesticide released into solution from the solid soil phase following both isotope exchange and forced exchange phases was 79–87%, 93–96% and 88–96% of that sorbed immediately prior to exchange for chlorotoluron, prometryn and hexaconazole, respectively. It should be noted that in each case the forced exchange was still releasing small amounts of ^{14}C-pesticide from the soil solid phase at the end of the process, albeit at very slow rates (Fig. 2; Figs. S4 and S5 in the Supporting Information).

3.4. Mass balance

The complete mass balance of the three ^{14}C-pesticides for an initial sorption period of 56 days is given in Table 2, whilst those for prometryn and hexaconazole sorbed for 112 and 168 days are given

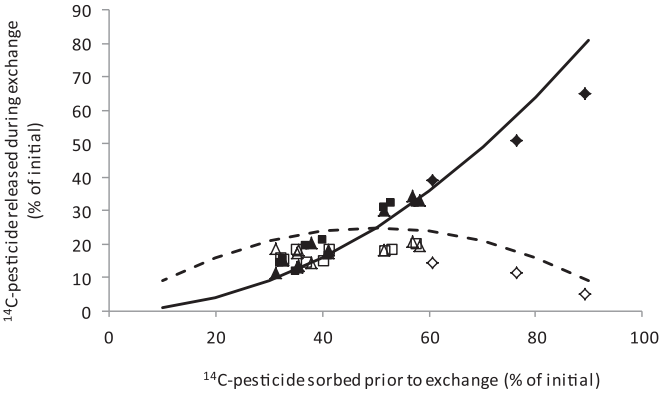

Fig. 3. Relationship between the amount of ^{14}C-pesticide sorbed immediately prior to isotope exchange (i.e. after 56, 112 or 168 d) and the amount of ^{14}C-pesticide released during subsequent phases of isotope exchange (open symbols) and forced exchange (solid symbols). Data are averages of triplicate measurements in three soils and for the three equilibration times for chlorotoluron (diamonds), prometryn (squares) and hexaconazole (triangles); standard deviations are given in Table 2 and Table S6. The lines show theoretical behaviour assuming ideal and fully reversible exchange for the isotope exchange (dashed line) and forced exchange (solid line), respectively.

Table 2
Mass balances for tubes containing initially ^{14}C-pesticide and with a 56-day sorption period (all values are % of initially applied radioactivity with one standard deviation in parentheses).

Pesticide	Soil	In solution after sorption	Released by isotope exchange	Released by forced exchange	Released by solvent extraction	Residue remaining	Degradation	Unaccounted for
Chlorotoluron	Blackwood	23.58 (1.05)	11.21 (1.04)	50.79 (1.68)	5.48 (0.66)	2.27 (0.36)	3.96 (1.60)	2.71 (0.93)
	Andover	39.23 (1.93)	14.19 (1.22)	38.98 (0.66)	2.03 (0.23)	1.07 (0.12)	3.90 (2.31)	0.60 (0.86)
	Salop	10.84 (0.71)	5.09 (0.37)	64.99 (0.72)	10.77 (0.73)	2.19 (0.22)	1.57 (1.49)	4.55 (0.09)
Prometryn	Blackwood	46.96 (0.95)	18.72 (0.35)	32.37 (0.99)	1.09 (0.06)	0.29 (0.10)	2.94 (0.32)	0.57 (0.39)
	Andover	67.92 (1.16)	16.19 (0.56)	14.60 (0.29)	0.56 (0.05)	0.33 (0.06)	2.76 (0.11)	0.40 (0.57)
	Salop	63.10 (1.11)	14.80 (0.28)	19.49 (0.34)	1.21 (0.11)	0.34 (0.01)	1.95 (1.93)	1.06 (0.44)
Hexaconazole	Blackwood	42.94 (1.70)	20.74 (0.39)	34.18 (1.70)	0.89 (0.04)	0.18 (0.03)	0 (–)	1.07 (0.72)
	Andover	68.64 (0.76)	18.44 (1.67)	11.47 (0.49)	0.45 (0.09)	0.14 (0.01)	0 (–)	0.87 (2.58)
	Salop	64.36 (0.60)	18.05 (0.31)	13.36 (0.48)	1.23 (0.11)	0.19 (0.02)	0 (–)	2.81 (0.58)

in the Supporting Information (Table S6). Repeated solvent extraction after the forced isotope exchange released small amounts of the initially applied ^{14}C-pesticide from the three soils (2–11%, 0.6–1.9% and 0.5–2.5% of initial radioactivity for chlorotoluron, prometryn and hexaconazole, respectively). Whilst this material had not been released by forced isotope exchange, it would not be included within a standard definition of bound residues (Führ et al., 1998). Radio-HPLC analysis of forced exchange solutions identified that a small proportion of the initial ^{14}C-chlorotoluron applied to the soils had degraded to transformation products during this phase of the study. The extent of degradation was 4.0 ± 1.6% (Blackwood), 3.9 ± 2.3% (Andover) and 1.6 ± 1.5% (Salop) of initial ^{14}C-chlorotoluron mass per sample. The half-life of chlorotoluron under laboratory conditions has been reported by Gao et al. (2007) to be 30 days, but soil sterilisation and experimental conditions of 4 °C in the dark effectively inhibited degradation despite the long duration of the study (274 days). Combustion of the extracted soils released radioactivity equivalent to 1.1–2.3%, 0.3–1.4% and 0.1–0.5% of initial radioactivity for chlorotoluron, prometryn and hexaconazole, respectively. These small fractions could not be identified, but fit with a classical definition of bound residues. It should be noted that these percentages would not reflect environmentally-relevant irreversible fractions, which are likely to be greater than those reported here; this is because these figures were obtained through alteration of the soil solid phase via solvent-extraction and because the microbial community was eliminated. Finally, 0.6–4.6%, 0.2–1.4% and 0.9–3.6% of initial radioactivity was unaccounted for chlorotoluron, prometryn and hexaconazole, respectively. This may result from mineralisation to $^{14}CO_2$, volatilisation or cumulative errors over the course of the experiment due to the multiple solute exchanges undertaken.

3.5. Comparison with ideal behaviour

Under conditions of ideal, fully reversible sorption of pesticides to soil, the fraction of ^{14}C-pesticide that is in the solid phase after the initial period of sorption will exchange completely with ^{12}C-pesticide and be released into solution by the combination of isotope exchange and forced exchange. Perfect isotope exchange will be maximal at 50% initial sorption where 25% of the initial ^{14}C-pesticide (*i.e.* 50% of that sorbed) should exchange with ^{12}C-pesticide and be released back into solution (Equation (3)); release of ^{14}C-pesticide will be a smaller proportion of initial radioactivity for both weaker and stronger sorption (dashed line in Fig. 3). In contrast, ^{14}C released by forced exchange will increase non-linearly with proportion of initial radioactivity sorbed (Equation (4); solid line in Fig. 3). Fig. 3 compares this ideal behaviour with measurements for the three pesticides in the three soils following 56-days sorption. The measurements closely mirror the expected form of relationships indicating that there is no major deviation from ideal behaviour. ^{14}C-pesticide released by isotope exchange is smaller than predicted in all cases and this can be attributed to continued increase in sorption during the exchange phase and/or some small component of sorbed pesticide that does not participate in exchange. Presence of dissolved organic carbon and/or colloidal material in solution is a potential confounding factor as in most sorption studies. Any such material would be directly exchanged during isotope exchange, whereas presence of dissolved organic carbon and colloids would be reduced during forced exchange due to repeated replacement of the soil solution.

In conclusion, study of the long-term fate of pesticide residues in soil provides complex experimental challenges. This study demonstrates that earlier proposals for use of isotope exchange are constrained by the extremely long timescales needed to approach true sorption equilibrium. Chlorotoluron and prometryn have typical degradation half-lives in soil in the range of one to a few months which is of the same order as the times needed to approach sorption equilibrium (Pignatello and Xing, 1996). Time-dependence in pesticide sorption changes the availability of residues for leaching over time and it is important that this effect is included within models used to characterise risks to the environment from pesticide use (Beulke et al., 2015). The steep concentration gradient established within the forced isotope exchange element of this study acted to accelerate release of sorbed pesticide from the soil solid phase. Nevertheless, pesticide was still being released from the soil solid phase after more than six months exposure to this process. The forced exchange procedure was intermediate in efficiency of releasing sorbed pesticide between field conditions, where desorption would occur more slowly (Renaud et al., 2004), and a conventional solvent extraction. This is confirmed by the release of further sorbed chlorotoluron on extraction with methanol. The accepted definition of pesticide bound residues excludes any fraction that can be extracted by a solvent (Führ et al., 1998). Thus, the radioactivity released by soil combustion at study termination provides the purest measure of truly irreversible sorption (1–2% of applied radioactivity). This implies that abiotic processes of bound residue formation are overwhelmingly reversible for the three compounds and the set of soils studied here.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.chemosphere.2016.07.062.

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