An assessment of potential pesticide transmission, considering the combined impact of soil texture and pesticide properties: A meta-analysis

Title	An assessment of potential pesticide transmission, considering the combined impact of soil texture and pesticide properties: A meta-analysis
Author(s)	McGinley, John;Harmon O'Driscoll, Jenny;Healy, Mark G.;Ryan, Paraic C.;Mellander, Per Eric;Morrison, Liam;Callery, Oisin;Siggins, Alma
Publication Date	2022-02-22
Publisher	Wiley

Published as: McGinley, J., Harmon O'Driscoll, J., Healy, M.G., Ryan, P., Mellander, P.E., Morrison, L., Callery, O., Siggins, A. 2022. An assessment of potential pesticide transmission, considering the combined impact of soil texture and pesticide properties: a meta-analysis. Soil Use and Management 38(2): 1162-1171. 10.1111/sum.12794

An assessment of potential pesticide transmission, considering the combined impact of soil texture and pesticide properties: A meta-analysis

J. McGinley[1], J. Harmon O'Driscoll[2], M. G. Healy[1], P. Ryan[2], P.-E. Mellander[3], L. Morrison[4], O. Callery[4], A. Siggins[1,3,*].

[1] Civil Engineering and Ryan Institute, National University of Ireland Galway, Galway, Ireland.

[2] Civil and Environmental Engineering, University College Cork, Cork, Ireland.

[3] Teagasc Environmental Research Centre, Johnstown Castle, Co. Wexford, Ireland.

[4] Earth and Ocean Sciences, School of Natural Sciences and Ryan Institute, National University of Ireland Galway, Galway, Ireland.

[*] Corresponding author.

Abstract

Pesticides are widely employed as a cost-effective means of reducing the impacts of undesirable plants and animals. The aim of this paper is to develop a risk ranking of transmission of key pesticides through soil to waterways, taking into account physiochemical properties of the pesticides (soil half-life, and water solubility), soil permeability, and the relationship between adsorption of pesticides and soil texture. This may be used as a screening tool for land managers, as it allows assessment of the potential transmission risks associated with the use of specified pesticides across a spectrum of soil textures. The twenty eight pesticides examined were differentiated into three groups: herbicides, fungicides and insecticides. The highest risk of pesticide transmission through soils to waterways is associated with soils containing <20% clay or >45% sand. In a small number of cases, the resulting transmission risk is not influenced by soil texture alone. For example, for Phenmedipham, the transmission risk is higher for clay soils than for silt loam. The data generated in this paper may also be used in the identification of critical area sources, which have a high likelihood of pesticide transmission to waterways. Furthermore, they have the potential to be applied to GIS mapping, where the potential transmission risk values of the pesticides can be layered directly onto various soil textures.

Keywords: Adsorption; Freundlich; half-life; pesticides; soil texture.

1. Introduction

A pesticide is any substance, plant protection product or biocide, that is used to repel, control or kill organisms that are considered to be pests (DAFM, 2017). The umbrella term “pesticides” includes herbicides, fungicides, insecticides, molluscicides, bactericides and rodenticides (Mojiri et al., 2020). In Europe, total annual pesticide sales during the period 2011 to 2016 rose from 386,400 to 439,400 tonnes of active ingredients, with France, Spain, Italy and Germany collectively accounting for 80% of the European market (Peña, 2020). In line with increases in global population, the use of pesticides in agriculture has increased to improve crop yields and production rates (Gavrilescu, 2005; Morillo and Villaverde, 2017). While this intensified pesticide application has been beneficial in preventing hazardous diseases in agricultural crops (Maggi et al., 2020), it has also amplified the contact of these compounds with soil (Morillo and Villaverde, 2017), air (Raherison et al., 2019) and aquatic environments (Burri et al., 2019), and increased the risk of subsequent human exposure. This has resulted in human health issues, such as neurological, respiratory and carcinogenic effects (Van Maele-Fabry et al., 2017; Ye et al., 2017; Pouchieu et al., 2018). In 2007, globally, there was an estimated 258,000 deaths from pesticide self-poisoning (WHO, 2016).

It has been suggested that, under "worst case" scenarios, such as improper handling and unfavourable weather condition, as little as 1% of applied pesticides may reach their target organism, with the remainder entering soil and water environments (Ali et al., 2019), *via* direct losses, runoff, spray drift, or leaching (Álvarez-Martín et al., 2017; Cosgrove et al., 2019; Haddad et al., 2019; Mojiri et al., 2020), resulting in contamination of surface water or groundwater (Rojas et al., 2014). The European Environment Agency (EEA) reported that, of the 73,510 natural water bodies with known chemical and ecological status in the European Union (EU), 25,108 failed to achieve good chemical status (EEA, 2018), due to hydromorphological pressures, diffuse water pollution from agricultural practises, waste water treatment plants and sewage systems, as well as high inflow of nutrients and chemical contaminants including pesticides leading to accelerated loss of biodiversity (EEA, 2016).

Mathematical models are now widely used to predict the fate and transport of pesticides in the environment (Hartz et al., 2017; Bach et al., 2017; Rumschlag et al., 2019; D'Andrea et al., 2020). Modelling presents an appealing alternative to environmental monitoring, which is costly and time-consuming. Modelling is fast, cost effective and can predict how soil and climate conditions may affect, for example, the environmental fate of pesticides (Bach et al., 2017; McGrath et al., 2019). The main factors influencing the transport of pesticides to receptors are soil half-life (DT_{50}; Fantke et al., 2014), adsorption and desorption to and from soil particles (Paszko and Jankowska, 2018), and physico-chemical properties of soil (Boivin et al., 2005). The adsorption of pesticides on the soil surface determines how pesticides are either transported or degraded, which ultimately determines the concentration of pesticides in both soil and soil solution (Gondar et al., 2013). Adsorption is predominantly influenced by the properties and chemical composition of the soil, which is a complex mixture of inorganic materials and organic matter (Leovac et al., 2015), and the physicochemical properties of the pesticide (Kodešová et al., 2011). The relationship between the organic content of the soil and pesticide adsorption has been well examined in the literature (Rojas et al., 2013; Wei et al., 2015; Wu et al., 2018). However, the organic content of soil changes with time (Smith, 2004), meaning that it may not be a reliable metric for determining areas of high risk of pesticide loss in agricultural land management. The organic content of soil is also difficult to map, as it depends on soil and crop management practises. Conversely, the texture of the soil will remain more or less constant over time (Brouwer et al., 1985). A database of existing studies quantifying the relationship between adsorption of pesticides and the texture of the soil, using adsorption isotherm coefficients as a metric, could be a valuable tool in screening and in decision management protocols for the safe use of pesticides on certain soil textures. Although many soil factors have been investigated with regard to pesticide adsorption, including pH (Kodešová et al., 2011; Gondar et al., 2013), organic content (Boivin et al., 2005; Conde-Cid et al., 2019), pore size (Siek and Paszko, 2019), and cation exchange capacity (Kodešová et al., 2011), to date no study has conducted a meta-analysis of the literature that investigates the relationship between pesticide adsorption and soil texture.

Pesticide transport models used for national pesticide registration and licensing in the European Union, such as the FOCUS group’s PRZM modelling approach, are highly complex models which take hours to run for a single pesticide (FOCUS website; PRZM_SW website). Complex and data-hungry pesticide transport modelling software, as is used for pesticide licensing and registration in the EU, is not realistic or suitable for use by small-scale pesticide users or localised pesticide management projects. Instead a quick and easily applied screening tool, such as that which is outlined in this paper, is proposed as a more practical tool for pesticide users in this case.

Therefore, the aim of this paper is to conduct a meta-analysis of literature that has assessed pesticide adsorption and soil texture data, and integrate this with pesticide properties such as soil half-life and solubility, in order to determine if a relationship exists that could guide future modelling and decision-making protocols regarding the safe use of pesticides. This information may be used in the identification of critical source areas, which would have a high likelihood of pesticide transmission to groundwater, or as an application in GIS mapping where the potential groundwater transmission risk values of the pesticides can be layered directly onto the various soil textures.

2. Materials and Methods

2.1 Literature review methodology, pesticide selection and grouping

A detailed literature search was undertaken by searching key words including: pesticide, soil, adsorption, sorption, adsorption isotherm, and soil texture triangle. The search was limited to peer-reviewed papers published, in English, since 2000 that included data on adsorption isotherm parameters and soil texture. Several reports were found in languages other than English (see, for example, Regitano et al., 2002; Rocha et al., 2013) but, as these did not met the criteria outlined above, they were not included. No geographical limitations were employed. Search engines used included databases such as Scopus, as well as publisher-specific search engines including ScienceDirect, the American Chemical Society, and the

Royal Society of Chemistry. References from several papers found in these searches were also examined for relevant information. Research papers were selected based on the relevance to the review, with a target on the most commonly used pesticides in articles. A total of 1212 articles and a small number of book chapters and reports were reviewed.

Following this, the pesticides were ranked according to the number of studies in which they were investigated and they also had to be currently approved for use by the EU. This resulted in a short-list of 54 publications, reporting on the 28 most commonly studied pesticides, which are still available for use and are not banned in the EU or elsewhere. These 28 pesticides were grouped into herbicides, fungicides and insecticides, with no molluscicides, bactericides or rodenticides present in that group.

2.1.1 *Herbicide group*

Herbicides are chemical agents which are used to kill or inhibit unwanted plants or weeds (Thiour-Mauprivex et al., 2019; Oliveira et al., 2020). They can act as contact herbicides, which kill only the plant parts contacted by the chemical agent, or as systemic herbicides, which are absorbed through the roots or leaves of the plant and then moved to a different location within the plant. Furthermore, herbicide activity can be selective or non-selective. Selective herbicides kill unwanted plants without critical damage to the preferred plants. On the other hand, non-selective herbicides kill or injure all plants present. This study assessed seventeen different herbicides, employed to protect a range of crops, by targeting different weed species (Table 1).

Table 1. Applications, target pests, and physicochemical properties of selected pesticides.[a]

	Pesticide	Crop/Site	Target Pest	MW	S_W	Log K_{OW}	DT_{50} lab
Herbicide	2,4-D	Cereals, grass, amenity use	Broad-leaved weeds	221.04	24300	-0.82	4.4
	Bensulfuron-methyl	Cereals	Weeds, sedges	410.4	67	0.79	77
	Bentazone	Cereals, vegetables	Annual weeds	240.3	7112	-0.46	20
	Chlorotoluron	Cereals, vegetables, fruit	Broad-leaved weeds, grasses	212.68	74	2.5	45
	Dimethenamid-P	Vegetables, vineyards	Broad-leaved weeds, grasses	275.8	1499	1.89	12.1
	Ethofumesate	Beet, vegetables	Broad-leaved weeds, grasses	286.34	50	2.7	21.6
	Glyphosate	Agriculture, horticulture, amenity use	Broad-leaved weeds, grasses	169.1	10500	-3.2	15
	Isoxaflutole	Crops	Broad-leaved weeds, grasses	359.32	6.2	2.34	0.9
	Lenacil	Beet, vegetables, fruit	Broad-leaved weeds, grasses	234.29	2.9	1.69	49.7
	MCPA	Cereals, grass	Broad-leaved weeds, rushes	200.62	29390	-0.81	24
	Mecoprop-P	Cereals, grass, amenity use	Broad-leaved weeds	214.65	250000	-0.19	5.24
	Metamitron	Beet crops	Broad-leaved weeds, grasses	202.21	1770	0.85	19
	Metribuzin	Cereals, vegetables	Broad-leaved weeds, grasses	214.29	10700	1.75	7.03
	Metsulfuron-methyl	Cereals, land removed from production	Broad-leaved weeds	381.36	2790	-1.87	23.2
	Pendimethalin	Cereals, vegetables, vineyards	Broad-leaved weeds, grasses	281.31	0.33	5.4	182.3
	Phenmedipham	Beet, vegetables	Broad-leaved weeds	300.31	1.8	2.7	12
	Terbuthylazine	Cereals, vegetables, non-crop sites	Broad-leaved weeds, grasses, slime-forming algae	229.71	6.6	3.4	72
Fungicide	Azoxystrobin	Cereals, vegetables	Broad-spectrum	403.4	6.7	2.5	84.5
	Metalaxyl	Many agricultural crops	Air- and soil-borne *Peronosporales*	279.33	8400	1.75	7.1
	Metalaxyl-M	Potatoes, vegetables	Air- and soil-borne pathogens	279.33	26000	1.71	6.5
	Myclobutanil	Perennial and annual crops, fruit, vines	Ascomycetes, Fungi Imperfecti and Basidiomycetes	288.78	132	2.89	365
	Penconazole	Vines, fruit, vegetables	Fungal pathogens	284.18	73	3.72	117.2
	Pyrimethanil	Fruit, vegetables, nuts	Fungal pathogens	199.28	110	2.84	50.9
	Tebuconazole	Cereals, vegetables, vines	Foliar diseases	307.82	36	3.7	365
	Thiabendazole	Cereals, fruit, vegetables	Post-harvest fungicide	201.25	30	2.39	1000
Insecticide	Abamectin	Fruit, vegetables	Selective acaricide, nematicide and insecticide	866.6	0.02	4.4	25.3
	α-Cypermethrin	Cereals, vegetables, beet, fruit, grassland	Broad spectrum	416.3	0.009	5.55	22.1
	Deltamethrin	Cereals, fruit, vegetables, public and industrial buildings	Wide range of sucking and chewing pests	505.2	0.0002	4.6	28.2

[a]: Pesticide properties database online (http://sitem.herts.ac.uk/areu/ppdb/en/index.htm). MW, Molecular weight (g mol^{-1}); S_W, water solubility (20°C, mg l^{-1}); K_{OW}, Octanol-water partition coefficient at pH 7, 20°C; DT_{50} lab, 50% dissipation time under laboratory conditions (days).

2.1.2 *Fungicide group*

Fungicides can work preventatively or curatively, by either preventing the fungus from infecting the plant, or by partially or entirely treating an existing fungal infestation (Tleuova et al., 2020; Zhang et al., 2020). Like herbicides, they can act as contact fungicides, preventing the fungus from entering the plant, or as systemic fungicides, which are internalised by the plant and are then moved to a different site within the plant. This study assessed the transmission risk of eight different fungicides (Table 1).

2.1.3 *Insecticide group*

Chemical insecticides are employed to control harmful insects, as a result of either killing the insect or preventing it from doing destructive damage to plants. During the 1950s, the majority of insecticides operated from four different chemical groups (DDT and analogues, Organophosphates, Carbamates and Cyclodienes) using three modes of action (Sparks et al., 2019). These modes of action were inhibition of the acetylcholinesterase, modulation of the voltage-gated sodium channel and blockage of the *gamma*-aminobutyric acid-gated chloride channel (Sparks et al., 2019). By 2019, this number had increased to 25 different modes of action based on 55 different chemical classes (Swale, 2019). The current study assessed the transmission risk of three insecticides (Table 1). The number of insecticide studies included in our meta-analysis is low due to the small number of studies that fulfilled our criteria of (i) including an approved insecticide and (ii) reporting soil texture data.

2.2 Adsorption modelling

The manuscripts that fulfilled the selection criteria of this study (Supporting Information Excel file) modelled their experimental data using the Freundlich adsorption isotherm, with some also reporting the parameters of the Langmuir adsorption isotherm. The main assumption of the Langmuir adsorption isotherm model is monolayer adsorption, so all potential adsorption sites are treated equivalently (Langmuir, 1918). The Freundlich adsorption model can better describe adsorption on a heterogeneous surface (Freundlich, 1907) and is commonly used to describe pesticide adsorption in soil (Hiller et al., 2012; Papadopoulou et al., 2016; Wang et al., 2020), implying that monolayer adsorption is not representative of pesticide adsorption in soil. To facilitate comparative analysis within this paper, only the Freundlich model was used for determination of the adsorption isotherm coefficients. The Freundlich isotherm model is:

$$q_{\mathrm{e}} = K_F C_{\mathrm{e}}^{1/n} \qquad (1)$$

where q_{e} is the amount of adsorbate adsorbed at the equilibrium (mg.g^{-1}) and C_{e} is the concentration of the adsorbate at the equilibrium (mg.L^{-1}); $\mathrm{K_F}$ is the Freundlich sorption capacity coefficient (mg.g^{-1}(mg.L^{-1})$^{-1/n}$) and the exponent n is the Freundlich exponent (dimensionless) (Lima et al., 2015). The adsorption of pesticides on soils can be described using the linear form of the Freundlich equation (Papazlatani et al., 2019):

$$\log q_{\mathrm{e}} = \log \mathrm{K_F} + 1/\mathrm{n}*\log C_{\mathrm{e}} \qquad (2)$$

The Freundlich sorption capacity coefficient $\mathrm{K_F}$ (mg.g^{-1}(mg.L^{-1})$^{-1/n}$) represents the pesticide affinity for soil, with a high $\mathrm{K_F}$ value indicating a stronger adsorption for the pesticide and also suggesting a lower mobility of the pesticide in the soil (Wang et al., 2020).

2.3 Pesticide transport potential ranking

The movement of pesticides from the target crop through the soil and to the water receptor is a function of soil permeability (m.s^{-1}), the adsorption capacity of each soil texture for the investigated pesticide (g.m^{-3}), soil half-life of the pesticide ($\mathrm{DT_{50}}$, days) and the pesticide solubility in water ($\mathrm{S_w}$; mg.L^{-1}). In order to establish a soil texture-specific transport potential risk ranking for each of the pesticide groups examined in this study, a ranking system incorporating each of these parameters was developed with the highest value indicative of the greatest risk of transmission to receiving waters. The permeability of soils is well documented and was ranked according to soil texture (USDA, 2001). Soil adsorption values were generated from the median value for each pesticide/soil texture association reported in the literature (Supplementary Information, Excel file and Table S1). The water solubility and soil half-life values were obtained from the Pesticide Properties DataBase (Tables S2 and S3, respectively; Lewis et al., 2016). Using this rubric, each parameter was independently ranked from one to twelve, where twelve was considered to be the highest risk for pesticide mobility through soil to surface and groundwater bodies, i.e. high permeability soils, low pesticide adsorption capacity, high soil half-life and high water solubility. In this study, high permeability soils were considered to be most at risk for surface and groundwater pollution. If surface water processes were only considered, low permeability soils, which would have large surface runoff potential relative to surface flow, would be considered to be most at risk. Finally, these independent risk values were combined (with equal weighting) to give a final risk ranking for each pesticide across all soil textures, but also for all of the pesticides within an individual soil texture classification.

3. Results and Discussion

3.1 Variances in adsorption as a function of soil texture

Table 2 shows the potential pesticide transmission risks as a function of water solubility, soil half-life, adsorption by soil of the pesticide and also soil texture. The potential transmission risk can be quantified either on the basis of soil texture or pesticide type, with the highest score in each case being the most transmissible.

Table 2. Pesticide transmission risk rankings[a]

Category	Pesticide	Sand	Loamy Sand	Sandy Loam	Sandy Clay Loam	Loam	Sandy Clay	Silt Loam	Silt	Clay Loam	Silty Clay Loam	Silty Clay	Clay
Herbicide	2,4-D			30		26		25		24	22	22	20
	Bensulfuron-methyl					23					19	17	
	Bentazone			34		32		30		29	27	26	25
	Chlorotoluron	36	28	29	29	29		25		20	19	18	17
	Dimethenamid-P							28					
	Ethofumesate	28	29	29				22					17
	Glyphosate	28	26	27		23		22			18		16
	Isoxaflutole					20		24		22	21	13	
	Lenacil												22
	MCPA			35				33		31			23
	Mecoprop-P			34									
	Metamitron	34	34	35				32					24
	Metribuzin			34									
	Metsulfuron-methyl				35		33			30			27
	Pendimethalin			24		22		19					
	Phenmedipham	21	23	27				17					21
	Terbuthylazine	35	32	30		27		26			24		14
Fungicide	Azoxystrobin	32	29	27		25		22					
	Metalaxyl			38	36	33		26		25			23
	Metalaxyl-M			30	30	25				30			
	Myclobutanil			42									18
	Penconazole	33	33	31	28	28							
	Pyrimethanil							28					
	Tebuconazole	31		29									
	Thiabendazole									25			
Insecticide	Abamectin	21		18			15						9
	α-Cypermethrin							13					
	Deltamethrin		22							15			

[a]: Total transmission risk ranking = Risk rankings for Permeability + Adsorbency + Solubility + Half-life (Table S5, Supplementary Information). The higher the score, the higher the risk for transmission through soil to waterways. The colour of the ranking value indicates the likelihood of potential transmission risk, with red being most likely and green being least likely.

It is unfortunate that there are not complete adsorption isotherm data studies across the soil texture triangle for each of the selected herbicides, fungicides and insecticides. These data would facilitate a better understanding of the potential pesticide transmission risk across all soil textures. Given the current findings, it is impossible to assess the potential transmission risk of pesticides in silt or sandy clay, as no data are available for silt and only limited data are available for silty clay textures.

The highest potential transmission risk ranking for each individual pesticide across all herbicides, fungicides and insecticides shows that the soil textures resulting in highest transmission risks are sandy loam and sand, with nineteen of the highest rankings being in one of these two soil textures (Table 2). These two soil textures have low clay content (<20%), implying that a high clay content is important in the retention of pesticides within the soil, as previously reported (Vitoratos et al., 2016; Ren et al., 2018; García-Delgado et al., 2020). This is in agreement with Komárek et al. (2010), who highlighted that the possible factors influencing pesticide adsorption were physico-chemical properties of the pesticides and soil properties, such as particle size, soil organic matter and clay content. Komárek et al. (2010) also states that generalising the behaviour of fungicides in soil is difficult to predict, given the different sorption, mobility and toxicity properties each will have, which is inferred from their different chemical structures. ElGouzi et al. (2012) showed, in their work on adsorption of phenylurea pesticides by Mediterranean soils, that soils with relatively high clay content were better at pesticide retention. García-Delgado et al., (2020) suggest that the addition of organic amendments to soils, such as spent mushroom substrate, compost, manure or sewage sludge, is an effective method of immobilising pesticides in the soil as a result of increasing the organic content of the soil. Furthermore, both of these soil textures have a high sand content (>45%), which would suggest that soil textures having a high sand content are also susceptible to high potential transmission risk of pesticides.

The potential risk ranking values (Table 2) for the herbicide group range from 36 (for Chlorotoluron in sand) to 13 (for Isoxaflutole in silty clay). The majority of high values (>30), shown in red and orange, reside in the left hand side of Table 2. The soil textures in this group of sand, loamy sand, sandy loam, sandy clay loam, loam and sandy clay all have a sand content of ≥ 50%, except for the loam texture where the sand content is 25%. This would imply that there is a high risk of herbicide transmission if the soil contains a high sand content. Although limited adsorption data are available in the literature for the three herbicides with the highest solubility (Mecoprop-P, MCPA and 2,4-D), the trends observed for other pesticides indicate that it is likely that these herbicides would pose a high transmission risk in either sand or loamy sand textured soils.

There are two different ways that the data in Table 2 can be interpreted. The data can be viewed from the point of view of the pesticide. Considering the herbicide chlorotoluron, for example, the potential risk ranking varies from 36 in sand to 17 in clay. Therefore, the soil textures most likely to transmit chlorotoluron may be identified. Alternatively, the data may be examined considering only soil texture. Within sandy loam soils, for example, MCPA, Mecoprop-P, Bentazone, Metamitron and Metribuzin are some of the highest risk herbicides, with ranking values of 35, 34, 34, 35 and 34, respectively (Table 2). As Pendimethalin, also used for the removal of broad-leaved weeds from cereals (Table 1), has a much lower transmission ranking value in sandy loam soils (24, Table 2), it might be more appropriate for selection when applying to this soil texture. In a similar manner, the choice of Terbuthylazine (14, Table 2) would be appropriate, when considering removing broad-leaved weeds and grasses from cereal and vegetable crops in clay soil, than any of the other herbicides in this study (16-27, Table 2).

In the case of the selected fungicides, the majority of high values (>30) reside in the left hand side of Table 2, Indeed, Metalaxyl-M has equally high potential transmission risk rankings across the range of soil textures. Furthermore, transmission risks are available for most fungicides for sandy loam soils (Table 2). As the transmission risk of Azoxystrobin was deemed to be the lowest of the eight fungicides (Table 2), then the selection of Azoxystrobin for application on sandy loam soils could be proposed as a management tool to minimise the risk of fungicide transmission through soil to waterways. Specifically, Tebuconazole (27, Table 2) could be a suitable alternative to Metalaxyl or Metalaxyl-M (38 and 30, Table 2) for the control of air-borne pathogens of vegetables grown in sandy loam soil (Table 1).

Of the three insecticides, Deltamethrin has the higher transmission risk rankings across all textures (Table 2). The transmission risk for Abamectin was much greater in sandy soils (21, Table 2) than in clay soils (9, Table 2), again demonstrating the potential for applying the proposed transmission risk ranking scheme to pesticide selection and management. Consideration of the reported transmission risk ranking, based on soil texture, crop and target pest, will contribute to decision making practices for safer pesticide use.

4. Conclusions

Using soil texture-specific adsorption isotherm data for several groups of pesticides, their solubility in water, soil half-life and soil permeability, a transmission risk ranking was developed in this study. This is designed as a decision making support tool for agricultural land management, as it allows the agricultural sector to assess, either by soil texture or pesticide type, the risk of loss of pesticides to receptors. Whilst this is a simple decision making support tool, rather than the more complicated and complex PRZM modelling approach (PRZM_SW website), it offers a manageable choice for the end user. It is also useful for modelling the loss of pesticides to water and for identification of critical source areas for better land management. The risk ranking index demonstrated specific examples of support for decision making, such as that pendimethalin is a lower transmission risk option than MCPA, Mecoprop-P, Bentazone, Metamitron and Metribuzin in the removal of broad-leaved weeds from cereal crops. It has also illustrated that the fungicide, Azoxystrobin, is a lower transmission risk alternative to either Metalaxyl or Metalaxyl-M in sandy loam soil.

The risk ranking index indicated that there is a high risk of transmission of pesticides from soils containing <20% clay. Furthermore, the data suggest that, if the soil content contains more than 45% sand, then there is a much higher risk of potential pesticide transmission. There are several reports in the literature discussing the movement of pesticides through soil. However, the aim of this paper was to develop a tool that the farmer could easily access to see if the pesticide of choice for the required job was environmentally friendly or if there was a potential threat to the environment through its use. Further analysis should be undertaken to examine potential transmission risk rankings of pesticides not selected in this review, across all soil textures.

Acknowledgements

This project is funded under the Irish EPA Research Programme 2014-2020 (Project reference number 2019-HW-LS-3). The EPA Research Programme is a Government of Ireland initiative funded by the Department of Communications, Climate Action and Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research. DISCLAIMER: Although every effort has been made to ensure the accuracy of the material contained in this journal paper, complete accuracy cannot be guaranteed. Neither the Environmental Protection Agency nor the authors accept any responsibility whatsoever for loss or damage occasioned or claimed to have been occasioned, in part or in full, as a consequence of any person acting or refraining from acting, as a result of a matter contained in this journal paper.

References

Ali, I., Alharbi, O. M. L., Othman, Z. A., Al-Mohaimeed, A. M., & Alwarthan, A., (2019). Modeling of fenuron pesticide adsorption on CNTs for mechanistic insight and removal in water. *Chemosphere, 170*, 389-397. https://doi.org/10.1016/j.envres.2018.12.066

Álvarez-Martín, A., Sánchez-Martín, M. J., Ordax, J. M., Marín-Benito, J. M., & Rodríguez-Cruz, M. S., (2017). Leaching of two fungicides in spent mushroom substrate amended soil: Influence of amendment rate, fungicide ageing and flow condition. *Sci. Total Environ., 584-585*, 828-837. http://dx.doi.org/10.1016/j.scitotenv.2017.01.126

Bach, M., Diesner, M., Großmann, D., Guerniche, D., Hommen, U., Klein, M., Kubiak, R., Müller, A., Preuss, T. G., Priegnitz, J., Reichenberger, S., Kai, T., & Trapp, M., (2017). Pesticide exposure assessment for surface waters in the EU. Part 2: determination of statistically based run-off and drainage scenarios for Germany. *Pest Manag. Sci., 73*, 852–861. DOI 10.1002/ps.4519

Boivin, A., Cherrier, R., & Schiavon, M., (2005). A comparison of five pesticides adsorption and desorption processes in thirteen contrasting field soils. *Chemosphere, 61*, 668-676. doi:10.1016/j.chemosphere.2005.03.024

Brouwer, C., Goffeau, A., & Heibloem, M., (1985) Irrigation Water Management – Training Manual No. 1, Introduction to Irrigation, Chapter 2 Soil and Water, Food and Agricultural Organisation of the United Nations, Italy.

Burri, N. M., Weatherl, R., Moeck, C., & Schirmer, M., (2019). A review of threats to groundwater quality in the anthropocene. *Sci. Total Environ., 684*, 136-154. https://doi.org/10.1016/j.scitotenv.2019.05.236

Conde-Cid, M., Santás-Miguel, V., Campillo-Cora, C., Pérez-Novo, C., & Fernández-Calviño, D., (2019). Retention of propiconazole and terbutryn on acid sandy-loam soils with different organic matter and Cu concentrations. *J. Environ. Manage., 248*, 109346-109353. https://doi.org/10.1016/j.jenvman.2019.109346

Cosgrove, S., Jefferson, B., & Jarvis, P., (2019). Pesticide removal from drinking water sources by adsorption: a review. *Environ. Technol. Rev., 8*, 1-24. https://doi.org/10.1080/21622515.2019.1593514

D'Andrea, M. F., Letourneau, G., Rousseau, A. N., & Brodeur, J. C., (2020). Sensitivity analysis of the pesticide in water calculator model for applications in the Pampa region of Argentina. *Sci. Total Environ., 698*, 134232-134244. https://doi.org/10.1016/j.scitotenv.2019.134232

Department of Agriculture, Food and the Marine (DAFM), (2017). Pesticide Usage in Ireland, Grassland and Fodder Crops Survey Report.

ElGouzi, S., Mingorance, M. D., Draoui, K., Chtoun, E. H., & Peña, A., (2012). Assessment of phenylurea herbicides sorption on various Mediterranean soils affected by irrigation with wastewater. *Chemosphere, 89*, 334-339. http://dx.doi.org/10.1016/j.chemosphere.2012.04.051

European Environment Agency (EEA), (2016). European water policies and human health. Combining reported environmental information. doi:10.2800/821091

European Environment Agency (EEA), (2018). Chemicals in european waters. Knowledge developments. doi:10.2800/265080

Fankte, P., Gillespie, B. W., Juraske, R., & Jolliet, O., (2014). Estimating half-lives for pesticide dissipation from plants. *Environ. Sci. Technol., 48*, 8588-8602. dx.doi.org/10.1021/es500434p

FOCUS DG SANTE - ESDAC - European Commission (europa.eu)

Freundlich, H., (1907). Over the adsorption in solution. *Z. Phys. Chem., 57*, 385-470.

García-Delgado, C., Marín-Benito, J. M., Sánchez-Martín, M. J., & Rodríguez-Cruz, M. S., (2020). Organic carbon nature determines the capacity of organic amendments to adsorb pesticides in soil. *J. Hazard. Mater., 390*, 122162-122170. https://doi.org/10.1016/j.jhazmat.2020.122162

Gavrilescu, M., (2005). Fate of pesticides in the environment and its bioremediation. *Eng. Life Sci., 5*, 497–526. doi: 10.1002/elsc.200520098

Gondar, D., López, R., Antelo, J., Fiol, S., & Arce, F., (2013). Effect of organic matter and pH on the adsorption of metalaxyl and penconazole by soils. *J. Hazard. Mater., 260*, 627-633. http://dx.doi.org/10.1016/j.jhazmat.2013.06.018

Haddad, K., Gheid, A., Haddad, D., & Oulmi, K., (2019). Experimental and numerical study on the leaching of pesticides into the groundwater through a porous medium: Effects of transport parameters. *Environ. Technol. Innovation, 13*, 244-256. https://doi.org/10.1016/j.eti.2018.12.009

Hartz, K. E. H., Edwards, T. M., & Lydy, M. J., (2017). Fate and transport of furrow-applied granular tefluthrin and seed-coated clothianidin insecticides: comparison of field-scale observations and model estimates. *Ecotoxicology, 26*, 876–888. doi:10.1007/s10646-017-1818-z

Hiller, E., Tatarková, V., Šimonovičová, A., & Bartal, M., (2012). Sorption, desorption, and degradation of (4-chloro-2-methylphenoxy)acetic acid in representative soils of the Danubian Lowland, Slovakia. *Chemosphere, 87*, 437-444. doi:10.1016/j.chemosphere.2011.12.021

Kodešová, R., Kočárek, M., Kodeš, V., Drábek, O., Kozák, J., & Hejtmánková, K., (2011). Pesticide adsorption in relation to soil properties and soil type distribution in regional scale. *J. Hazard. Mater., 186*, 540-550. doi:10.1016/j.jhazmat.2010.11.040

Komárek, M., Čadková, E., Chrastný, V., Bordas, F., & Bollinger, J.-C., (2010). Contamination of vineyard soils with fungicides: A review of environmental and toxicological aspects. *Environ. Int., 36*, 138-151. doi:10.1016/j.envint.2009.10.005

Langmuir, I., (1918). The adsorption of gases on plane surfaces of glass, mica, and platinum. *J. Am. Chem. Soc., 40*, 1361-1403.

Leovac, A., Vasyukova, E., Ivančev-Tumbas, I., Uhl, W., Kragulj, M., Tričković, J., Kerkez, Đ., & Dalmacija, B., (2015). Sorption of atrazine, alachlor and trifluralin from water onto different geosorbents. *RSC Adv., 5*, 8122-8133. doi: 10.1039/c4ra03886j

Lewis, K. A., Tzilivakis, J., Warner, D., & Green, A., (2016). An international database for pesticide risk assessments and management. *Human and Ecological Risk Assessment: An International Journal, 22*, 1050-1064. doi: 10.1080/10807039.2015.1133242

Lima, E. C., Adebayo, M. A., & Machado, F. M., Chapter 3 Kinetic and Equilibrium Models of Adsorption *in* Carbon Nanomaterials as Adsorbents for Environmental and Biological Applications, Bergmann, C. P., Machado, F. M., editors, Springer 2015, 33-69. doi: 10.1007/978-3-319-18875-1_3

Maggi, F., la Cecilia, D., Tang, F. H. M., & McBratney, A., (2020). The global environmental hazard of glyphosate use. *Sci. Total Environ., 717*, 137167-137178. https://doi.org/10.1016/j.scitotenv.2020.137167

McGrath, G., Rao, P. S. C., Mellander, P.-E., Kennedy, I., Rose, M., & van Zwieten, L., (2019). Real-time forecasting of pesticide concentrations in soil. *Sci. Total Environ., 663*, 709-717. https://doi.org/10.1016/j.scitotenv.2019.01.401

Mojiri, A., Zhou, J. L., Robinson, B., Ohashi, A., Ozaki, N., Kindaichi, T., Farraji, H., & Vakili, M., (2020). Pesticides in aquatic environments and their removal by adsorption methods. *Chemosphere, 253*, 126646-126669. https://doi.org/10.1016/j.chemosphere.2020.126646

Morillo, E., & Villaverde, J., (2017). Advanced technologies for the remediation of pesticide-contaminated soils. *Sci. Total Environ., 586*, 576-597. http://dx.doi.org/10.1016/j.scitotenv.2017.02.020

Oliveira, M. C., Osipitan, O. A., Begcy, K., & Werle, R., (2020). Cover crops, hormones and herbicides: Priming an integrated weed management strategy. *Plant Sci., 301*, 110550-110554. https://doi.org/10.1016/j.plantsci.2020.110550

Papadopoulou, E. S., Karas, P. A., Nikolaki, S., Storck, V., Ferrari, F., Trevisan, M., Tsiamis, G., Martin-Laurent, F., & Karpouzas, D. G., (2016). Dissipation and adsorption of isoproturon, tebuconazole, chlorpyrifos and their main transformation products under laboratory and field conditions. *Sci. Total Environ., 569-570*, 86-96. http://dx.doi.org/10.1016/j.scitotenv.2016.06.133

Papazlatani, C. V., Karas, P. A., Tucat, G., & Karpouzas, D. G., (2019). Expanding the use of biobeds: Degradation and adsorption of pesticides contained in effluents from seed-coating, bulb disinfestation and fruit-packaging activities. *J. Environ. Manage., 248*, 109221-109230. https://doi.org/10.1016/j.jenvman.2019.06.122

Paszko, T., & Jankowska, M., (2018). Modeling the effect of adsorption on the degradation rate of propiconazole in profiles of Polish Luvisols. *Ecotoxicol. Environ. Saf., 161*, 584–593. https://doi.org/10.1016/j.ecoenv.2018.05.093

Pouchieu, C., Piel, C., Carles, C., Gruber, A., Helmer, C., Tual, S., Marcotullio, E., Lebailly, P., & Baldi, I., (2018). Pesticide use in agriculture and Parkinson's disease in the AGRICAN cohort study. *Int. J. Epidemiol., 47*, 299-310. doi: 10.1093/ije/dyx225

PRZM_SW - ESDAC - European Commission (europa.eu)

Raherison, C., Baldi, I., Pouquet, M., Berteaud, E., Moesch, C., Bouvier, G., & Canal-Raffin, M., (2019). Pesticides exposure by air in vineyard rural area and respiratory health in children: a pilot study. *Environ. Res., 169*, 189-195. https://doi.org/10.1016/j.envres.2018.11.002

Regitano, J. B., Prata, F., Dias, N. M. P., Lavorenti, A., & Tornisielo V. L., (2002). Sorção-dessorção do fungicida clorotalonil em solos com diferentes teores de matéria orgânica. *R. Bras. Ci. Solo, 26*, 267-274.

Ren, X., Zeng, G., Tang, L., Wang, J., Wan, J., Liu, Y., Yu, J., Yi, H., Ye, S., & Deng, R., (2018). Sorption, transport and biodegradation – an insight into bioavailability of persistent organic pollutants in soil. *Sci. Total Environ., 610-611*, 1154-1163. http://dx.doi.org/10.1016/j.scitotenv.2017.08.089

Rocha, P. R. R., Faria, A. T., Borges, L. G. F. C., Silva, L. O. C., Silva, A. A., & Ferreira, E. A., (2013). Sorção e dessorção do diuron em quarto latossolos brasileiros. *Planta Daninha, 31*, 231-238.

Rojas, R., Morillo, J., Usero, J., Delgado-Moreno, L., & Gan, J., (2013). Enhancing soil sorption capacity of an agricultural soil by addition of three different organic wastes. *Sci. Total Environ., 458-460*, 614-623. http://dx.doi.org/10.1016/j.scitotenv.2013.04.032

Rojas, R.,Vanderlinden, E., Morillo, J., Usero, J., & El Bakouri, H., (2014). Characterization of sorption processes for the development of low-cost pesticide decontamination techniques. *Sci. Total Environ., 488-489*, 124-135. http://dx.doi.org/10.1016/j.scitotenv.2014.04.079

Rumschlag, S. L., Bessler, S. M., & Rohr, J. R., (2019). Evaluating improvements to exposure estimates from fate and transport models by incorporating environmental sampling effort and contaminant use. *Water Res., 156*, 372–382. https://doi.org/10.1016/j.watres.2019.03.038

Siek, M., & Paszko, T., (2019). Factors affecting coupled degradation and time-dependent sorption processes of tebuconazole in mineral soil profiles. *Sci. Total Environ., 690*, 1035-1047. https://doi.org/10.1016/j.scitotenv.2019.06.409

Smith, P., (2004). How long before a change in soil organic carbon can be detected? *Global Change Biol., 10*, 1878-1883. doi: 10.1111/j.1365-2486.2004.00854.x

Sparks, T. C., Wessels, F. J., Lorsbach, B. A., Nugent, B. M., & Watson, G. B., (2019). The new age of insecticide discovery-the crop protection industry and the impact of natural products. *Pestic. Biochem. Physiol., 161*, 12-22. https://doi.org/10.1016/j.pestbp.2019.09.002

Swale, D. R., (2019). Perspectives on new strategies for the identification and development of insecticide targets. *Pestic. Biochem. Physiol., 161*, 23-32. https://doi.org/10.1016/j.pestbp.2019.07.001

Thiour-Mauprivez, C., Martin-Laurent, F., Calvayrac, C., & Barthelmebs, L., (2019). Effects of herbicide on non-target microorganisms: Towards a new class of biomarkers? *Sci. Total Environ., 684*, 314-325. https://doi.org/10.1016/j.scitotenv.2019.05.230

Tleuova, A. B., Wielogorska, E., Talluri, V. S. S. L. P., Štěpánek, F., Elliott, C. T., & Grigoriev, D. O., (2020). Recent advances and remaining barriers to producing novel formulations of fungicides for safe and sustainable agriculture. *J. Controlled Release, 326*, 468-481. https://doi.org/10.1016/j.jconrel.2020.07.035

USDA NRCS, Soil Quality Test Kit Guide, July 2001.

Van Maele-Fabry, G., Gamet-Payrastre, L., & Lison, D., (2017). Residential exposure to pesticides as risk factor for childhood and young adult brain tumors: A systematic review and meta-analysis. *Environ. Int., 106*, 69-90. http://dx.doi.org/10.1016/j.envint.2017.05.018

Vitoratos, A., Fois, C., Danias, P., & Likudis, Z., (2016). Investigation of the soil sorption of neutral and basic pesticides. *Water Air Soil Pollut., 227*, 397. doi:10.1007/s11270-016-3076-8

Wang, X. Q., Liu, J., Zhang, N., & Yang, H., (2020). Adsorption, mobility, biotic and abiotic metabolism and degradation of pesticide exianliumi in three types of farmland. *Chemosphere, 254*, 126741-126752. https://doi.org/10.1016/j.chemosphere.2020.126741

Wei, T., Guizhen, L., Mei, B., Min, Y., Jinhui, P., Barrow, C. J., Wenrong, Y., & Hongbin, W., (2015). The study of adsorption mechanism of mixed pesticides prometryn-acetochlor in the soil-water system. *Int. Biodeterior. Biodegrad., 102*, 281-285. http://dx.doi.org/10.1016/j.ibiod.2015.04.005

World Health Organisation, (2016). Safer access to pesticides for suicide prevention.

Wu, D., Yun, Y., Jiang, L., & Wu, C., (2018). Influence of dissolved organic matter on sorption and desorption of MCPA in ferralsol. *Sci. Total Environ., 616-617*, 1449-1456. https://doi.org/10.1016/j.scitotenv.2017.10.169

Ye, M., Beach, J., Martin, J. W., & Senthilselvan, A., (2017). Pesticide exposures and respiratory health in general populations. *J. Environ. Sci., 51*, 361-370. http://dx.doi.org/10.1016/j.jes.2016.11.012

Zhang, C., Zhou, T., Xu, Y., Du, Z., Li, B., Wang, J., Wang, J., & Zhu, L., (2020). Ecotoxicology of strobilurin fungicides. *Sci. Total Environ., 742*, 140611-140618. https://doi.org/10.1016/j.scitotenv.2020.140611