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Pesticides residues in European agricultural soils

Results from LUCAS 2018 soil module

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Contents

Abstract

In the past 20 years, the use of pesticides in agricultural lands have been target of several European Union (EU) regulations. More recently, and in line with several EU sustainability goals, the use of pesticides has been targeted by relevant policy ambitions aiming to reduce their use and risk following health and environmental concerns. Nonetheless, the current knowledge on soil contamination by pesticides residues is limited, due to a lack of systematic soil monitoring studies addressing soil pollution, especially at EU scale.

To fulfil this knowledge gap, the EU Soil Observatory led a study targeting residues of active ingredients of pesticides used as crop protection products in soil samples collected from the 2018 LUCAS survey. This is the largest study providing a comprehensive characterisation on the extent of residues of active ingredients from pesticides in the soils of the EU. This work establishes an initial EU baseline, and project a future assessment of the effectiveness of EU policies and regulations targeting pesticides use and soil pollution. Moreover, this study provides the first steps on the development of risk indicators for soil, allowing to present the first temporal assessment of pesticides in EU soils following a pilot study with samples from 2015 LUCAS survey.

This study highlights that pesticide residues in soils are widespread in the European agricultural land (74.5% sites), whereas most of the sites (57.1%) present mixtures of substances (two or more). Additionally, an indicator of the ecotoxicological impact for soil organisms was developed. This indicator compared the concentration of these substances with the no effect concentration (NOEC) for soil organisms, identifying areas at higher risk (1.7% sites). But also, allowed to estimate an increase in ecotoxicological risk when compared with a previous assessment (2015-2018). Finally, among the substances found was also possible to identify banned and non-approved substances in soils (12%), according to the 2018 regulations (Regulation 1107/2009),

The current study brought by the EU Soil Observatory and LUCAS 2018 soil module provides a significant contribution to the status of current knowledge on soil pollution in the EU. The insights provided in this report may help identifying target policies in creating a toxic-free environment

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Authors

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1 Introduction

The use of plant protection products has been identified as a key factor contributing to the increased food production in the past decades not only in the European Union (EU) but also globally (Silva et al., 2019; FAO, 2022). Nonetheless, and despite the pressures on the agricultural sector caused by the steady increase of the global population (UN, 2019), several human-health and environmental concerns have been raised regarding the widespread use of such products (EFSA, 2019).These concerns have led to the development of a series of guidelines and codes of conduct (FAO, 2014), and international agreements such as the Rotterdam Convention (SRC, 2019). In the case of the EU, those concerns materialized in increasingly demanding legislation aimed at protecting human health and the environment from the potential adverse effects of pesticides, including the regulations on the placing on the market and use of plant protection products (Directive 2009/128) and of biocidal products (Regulation 528/2012), legislation on food safety (Guidance SANTE/12682), and on environmental media such as surface water (Directive 2000/60) or groundwater (Directive 2006/118).

Currently in the EU, there are approximately 450 active substances that are approved for use in plant protection products (EC, 2023a), with roughly 356,000 tons of pesticides being sold annually for the 2011- 2019 period among the EU Member States (Eurostat, 2021). Nonetheless, and despite the tight control over the sales of these substances, only a generic fate and behaviour profile is known which cannot capture the variability of factors influencing their distribution/application, transport and degradation through EU soils (Mottes et al., 2021; Didoné et al., 2021; Silva et al., 2018; Bento et al., 2016), also due to the lack of a systematic monitoring system of soil pesticides residues at the EU level (Sabzevari & Hofman, 2022; Silva et al., 2018).

Moreover, and regardless of the recognition that the greatest contribution to the knowledge involving the impact of pesticides to human-health and the environment is originated from research conducted in European countries (Sabzevari & Hofman, 2022), several research studies also identified that current regulation and monitoring efforts in the soils of the EU may not be sufficient given the problem at hands (van Bruggen et al., 2021; Geissen et al., 2021; Silva et al., 2021). Therefore, and to address such preeminent need, the LUCAS survey (Orgiazzi et al., 2017) has been used to test its suitability as a platform for such assessment given its geographical coverage, systematic sampling and laboratorial procedures across Member States. This report presents the first systematic assessment of the pesticide residues distribution at the EU level, allowing us to create a baseline of understanding regarding the status of pesticide residue in soils, but also effectively evaluate the progress of legally binding instruments regulating human-health and environmental risks in the EU.

The main aim of this study is to provide a comprehensive characterisation on the extent of residues of active ingredients from pesticides in the soils of the EU. In addition, the report aims to provide evidence as to whether current legislative instruments are efficient tools to address human-health and environmental concerns, but also future ambitions within the European Green Deal (EC, 2023b). To achieve this, a set of 3,300 soil samples collected within the 2018 LUCAS campaign were screened for the presence of 120 individual active ingredients and selected metabolites, and their concentrations determined. Resulting data included pesticide residues incidence, concentration and their spatial distribution, which were analysed against a set of independent variables and previous local pesticide residues exposure assessments. Moreover, pesticide residues concentrations were compared to ecotoxicological data collected by the European Food Safety Authority (EFSA) (Open FoodTox) and other sources, by means of a novel ecotoxicological indicator to characterise the potential risk to soil organisms and evaluate potential regulatory implications.

The results of this work allowed the development of a series of reflections and recommendations for further research and policy development, as also for the improvement of future monitoring programs focused on large scale pesticide residues assessment.

2 Materials and Methods

2.1 Soil Samples

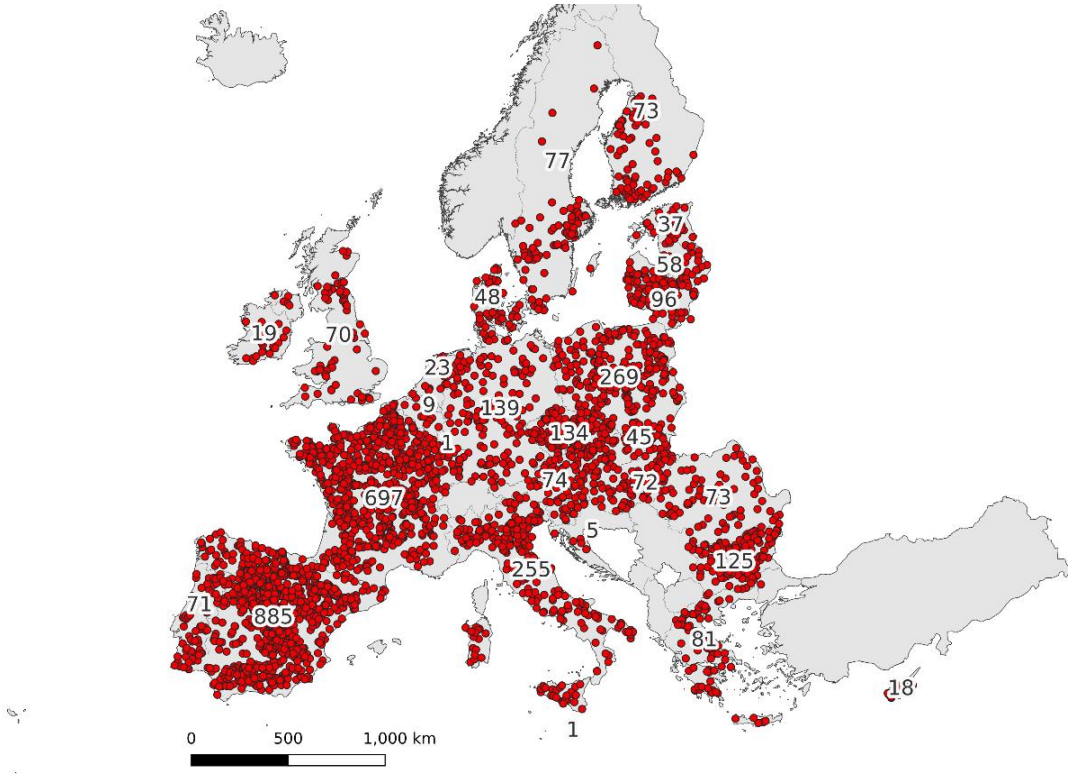
The soil assessment module of the LUCAS (Land Use and Cover Area Frame Survey) programme is the only mechanism for a harmonised monitoring (common sampling procedure and standard analysis methods), both in space and time, of topsoils in the European Union (EU).

The LUCAS Programme is a survey organised and managed by Eurostat (the Statistical Office of the EU) to monitor changes in land use (LU) and land cover (LC) over time across the EU. Since 2006, Eurostat has carried out LUCAS surveys every three years since 2006. The surveys are based on the visual assessment of environmental and structural elements of the landscape in georeferenced control points. The points belong to the intersections of a 2 x 2 km regular grid covering the territory of the EU. This results in around 1,000,000 georeferenced points. In every survey, a subsample of these points is selected for the collection of field-based information.

In LUCAS 2018, soil sampling was carried out in all EU Countries and the UK, using the same set of 25,947 locations that were targeted in 2015. In 65% of these locations, samples were to be taken following the standardised sampling procedure of previous surveys, in which a spade was used to collect a sample from a depth of 20 cm. In the remaining 35% of the locations (approximately 9,000 points), metallic rings were used to collect soil cores from a depth of 0-10 and 10-20 cm3.

Finally, in a subset of the locations a pilot study was developed with Wageningen Food Safety Research to assess the presence of a selected group of active ingredients of pesticides in soil (**Figure 1**). This analysis, of 118 substances (comprising neonicotinoids, conazoles, organochlorinated compounds, and organophosphorus compounds) and metabolites, was performed in soil samples originated from 3,473 sites, and collected between March and November of 2018 from agricultural land. The full list of compounds being analysed is presented in Annex 1.

Figure 1 – Spatial distribution of LUCAS 2018 sites used for pesticides residues assessment in the EU and the number of sites per country from a total of 3473.

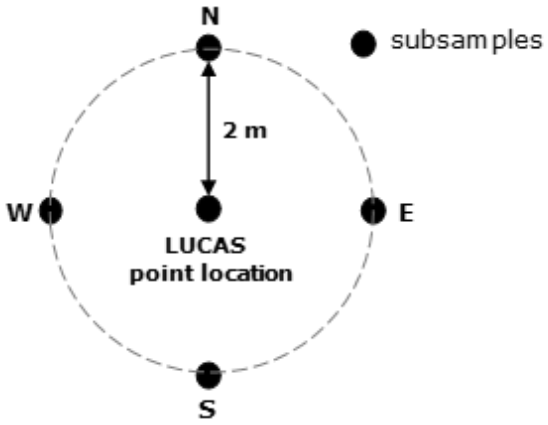


Source: Joint Research Centre.

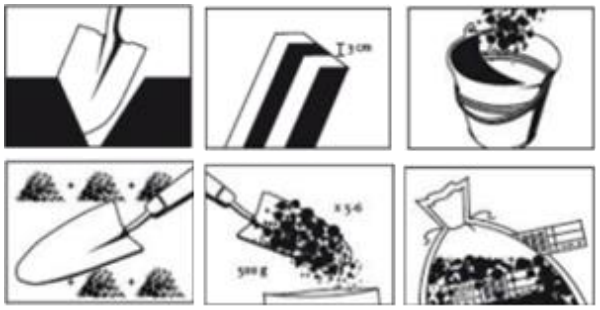
With the common sampling procedure, a composite sample of approximately 500 g was taken at each LUCAS point. The composite sample consisted of five subsamples taken with the help of a spade. The first subsample was taken at the geo-referenced point location; the other four subsamples were collected at a distance of 2 m following the cardinal directions (North, East, South and West) (Fig. 2a). Before taking the subsamples, stones (>6 cm) (FAO, 2006), vegetation residues, grass and litter were removed from soil surface by raking with the spade. As shown by **Figure 2**, a V-shaped hole was dug to a depth of 20 cm using the spade and a slice of soil (approximately 3-cm thick) was taken from the side of the hole with the spade. The slice was trimmed at the sides to give a 3-cm wide subsample. The subsample was placed in a bucket. The procedure was repeated at the other four subsample sites. Finally, the five subsamples in the bucket were mixed with a trowel. Vegetation residues and stones were removed. Approximately 500 g of the mixed soil was taken with a trowel from the bucket, placed in a plastic bag, and labelled to derive the composite sample. Soil samples were allowed to air dry before the bags were sealed (**Figure 2**).

Figure 2 – LUCAS soil sampling scheme.

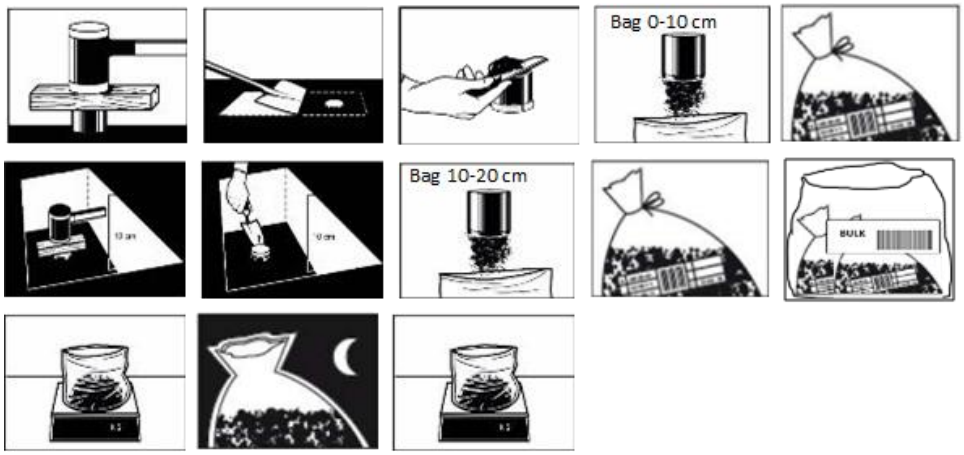
a)



b)



c)



Source: Joint Research Centre.

2.2 Active substances

The active substances from pesticides under analysis in this work are depicted in **Table 1**.

Table 1 – Active substances analysed within the LUCAS soil survey and corresponding limit of quantification (LOQ, mg Kg^{-1}).

Substances and LOQ (mg Kg^{-1})					
2,4-DB	0.01	Dimethomorph	0.001	Metalaxyl	0.001
Abamectin	0.01	Dimoxystrobin	0.001	Metamitron	0.005
Aldrin	0.005	Diuron	0.001	Metconazole	0.005
AMPA	0.01	Endosulfan,alpha-	0.005	Metolachlor	0.001
Atrazine	0.001	Endosulfan,beta-	0.005	Metrafenone	0.001
Atrazine-deisopropyl	0.005	Endosulfan,sulphate	0.005	Myclobutanil	0.001
Atrazine-desethyl	0.001	Endrin	0.005	Parathion	0.005
Azoxystrobin	0.001	Epoxiconazole	0.001	Parathion-methyl	0.005
Bentazone	0.005	Ethion	0.001	Penconazole	0.001
Bixafen	0.001	Fenbuconazole	0.005	Pendimethalin	0.001
Boscalid	0.001	Fenpropidin	0.001	Penflufen	0.001
Bromuconazole	0.005	Fenpropimorph	0.001	Pentachlorbenzene(PeCB)	0.01
Carbaryl	0.001	Fluazinam	0.001	Penthiopyrad	0.001
Carbendazim	0.001	Fludioxonil	0.005	Pinoxaden	0.005
Carbofuran	0.001	Flufenacet	0.001	Pirimicarb	0.001
Carbofuran,-3-hydroxy	0.001	Fluometuron	0.001	Pirimiphos-methyl	0.001
Carbofuran,-keto	0.001	Fluopicolide	0.001	Prochloraz	0.001
Chlordanecis-(alpha)	0.005	Fluopyram	0.001	Procymidone	0.005
Chlordanetrans-(gamma)	0.005	Fluoxastrobin	0.001	Promethryn	0.001
Chlordecone	0.01	Fluquinconazole	0.001	Propiconazole	0.001
Chlorfenvinphos	0.001	Fluroxypyr	0.01	prosulfocarb	0.001
Chloridazon	0.001	Folpet	0.01	Prothioconazoledesthio	0.005
Chlorpyrifos	0.001	Glyphosate	0.025	PTI	0.01
Chlorpyrifos-methyl	0.005	HCB	0.01	Pyraclostrobin	0.001
Clothianidin	0.001	HCH,alpha-	0.01	Pyriofenone	0.001
Cymoxanil	0.005	HCH,beta-	0.01	Quinoxyfen	0.001
Cyproconazole	0.005	HCH,gamma-	0.01	Simazine	0.001
Cyprodinil	0.001	Heptachlor	0.005	Tebuconazole	0.001
DDD,o,p'-(TDE)	0.005	Heptachlorendoepoxide(isoA)	0.005	Terbuthylazine	0.001
DDD,p,p'-(TDE)	0.005	Heptachlorepoxide(isoB)	0.005	Terbuthylazine-desethyl	0.001
DDE,o,p'-	0.005	Imazalil	0.001	Terbutryn	0.001
DDE,p,p'-	0.005	Imazamox	0.005	Thiabendazole	0.005
DDT,o,p'-	0.005	Imidacloprid	0.001	Thiamethoxam	0.001
DDT,p,p'-	0.005	Indoxacarb	0.001	Thiophanate-methyl	0.01
Deltamethrin	0.005	Isoproturon	0.001	Triadimenol	0.005
Diazinon	0.001	Isoxaben	0.001	Tri-allate	0.005
Dieldrin	0.01	Lenacil	0.005	Triclopyr	0.01
Difenoconazole	0.001	Linuron	0.001	Trifloxystrobin	0.001
Diflufenican	0.001	Malathion	0.001		
Dimethenamid	0.001	MCPA	0.005		

Source: Joint Research Centre.

2.3 Laboratory analysis

A set of multi-residue methods based on Gas Chromatography/Mass Spectrometry (GC-MS/MS) and Liquid chromatography–mass spectrometry (LC-MSMS) were developed and validated to analyse the presence and concentrations of 118 molecules of active substances and metabolites of selected pesticide residues. These are referenced under the Standard Operating procedures (SOP) from the European Food Safety Authority (EFSA, 2023) as follows:

Specifically:

- SOP-A-1347 - Soil - Pesticides – LC-MSMS
- SOP-A-1361 - Soil – Multimethod Pesticides – GC-MSMS
- SOP-A-1348 - Soil - Glyphosate and AMPA - LC-MSMS

Following these procedures, the limit of quantification (LOQ) was used for identification of presence or absence of a given substance in the sample. The LOQ for most of the substances was between 0.001 and 0.1 mg Kg^{-1}, while for glyphosate was set on 0.025 mg Kg^{-1}.

2.3.1 Multi-residue LC-MS/MS method

For the LC-MS/MS multi-residue method an extraction method referred to as 'QuEChERS' was applied using a methodology similar to the one described by Anastassiades et al. (2003) and Mol et al. (2008). With this method to a sub sample of 5.0 g homogenized soil, 5 ml of water was added. After adding 10 ml of acetonitrile/1% acetic acid the pesticides were extracted by mechanical shaking (end-over-end) for 30 min. By addition of 1 g sodium acetate and 4 g of magnesium sulphate a phase separation was induced with the pesticides of interest partitioning into the acetonitrile layer. After centrifugation an aliquot of the organic extract was diluted with Millipore water and after filtration analysed by LC-MS/MS using electrospray ionization in positive and negative mode. A high-end LC-MS/MS instrument (AB Sciex 6500+ triple quadrupole) was used to combine a wide scope screening while achieving LOQs that typically were in the range 0.001-0.01 mg/kg. At least two diagnostic transitions for each pesticide were measured to facilitate proper identification. Quantification of the pesticides was based on solvent standards (bracketing one-point). With each sequence, linearity of response was verified, and three QC samples were included: one negative control (blank QC-soil), two positive controls spiked at LOQ level (blank QC soil and one random soil sample from the batch).

2.3.2 Multi-residue GC-MS/MS method

For the GC-MS/MS method to a sub sample of 5.0 g homogenized soil, 5 ml of water was added. After adding 10 ml of ethyl acetate the pesticides were extracted using mechanical shaking (end-over-end) for 30 min. After centrifugation 500 µl of the clear supernatant followed by 500 µl ethyl acetate was transferred to a dispersive SPE tube containing 150 mg MgSO4 and 100 mg GCB. After homogenisation and centrifugation 200 µl of the cleaned and diluted extract was transferred to a GC vial with insert and acidified with 10 µl 1% acetic acid in ethyl acetate. This final extract was analysed by GC-MS/MS. A high-end GC-MS/MS instrument (Agilent 7010B) was used to combine a wide scope screening while achieving LOQs that typically were in the range 0.005-0.01 mg/kg. At least two diagnostic transitions for each pesticide were measured to facilitate proper identification. Internal standards were added for QC measures and correct quantification. Quantification of the pesticides was based on matrix-matched standards (bracketing one-point). With each sequence, linearity of

response was verified, and three QC samples were included: one negative control (blank QC-soil), two positive controls spiked at LOQ level (blank QC soil and one random soil sample from the batch).

2.3.3 Glyphosate/AMPA LC-MS/MS method

Glyphosate and AMPA were extracted from soil (2.0 g sub sample) with 10 ml of 0.6 M potassium hydroxide, after addition of isotope labelled internal standards for both glyphosate and AMPA, using mechanical shaking (end-over-end) for 60 min. After centrifugation 1.0 ml of the clear supernatant was transferred to a test tube and neutralized with 80 µl 6 M HCl. Glyphosate and AMPA were derivatised by 8 van 48 adding 500 µl 5% borate solution and 500 µl 6.5 mM FMOC-Cl solution in acetonitrile to the neutralized extract. After 30 minutes the derivatisation reaction was stopped by adding 50 µl formic acid, 100%, to the reaction mixture. Finally, 500 µl of the derivatised extract was transferred into a mini-uniprep PTFE filter vial (0.45 µm) and filtered. The extracts were analysed by LC-MS/MS under alkaline chromatographic conditions, using electrospray ionization in negative mode. An AB Sciex 6500+ triple quadrupole mass spectrometer was used for measurement. At least two diagnostic transitions for both glyphosate and AMPA and one transition for the isotope labelled internal standards were measured to facilitate proper identification. Potential losses during sample preparation and matrix effects in the LC-MS/MS measurement were accounted for by normalization of the response to the corresponding isotope labelled internal standards. Quantification of the glyphosate and AMPA was based on solvent standards (bracketing one-point). With each sequence, linearity of response was verified, and three QC samples were included: one negative control (blank QC-soil), two positive controls spiked at 0.05 mg Kg^{-1} level (blank QC soil and one random soil sample from the batch).

The validation and quality control quality control were done by inclusion of spiked samples in each batch of analysis. This was performed in line with Eurachem 2ed (2014), SANCO/825/00 rev. 8.1 (meanwhile superseded by SANTE/2020/12830), and SANTE/12682/2019 (Guidance document on analytical quality control and method validation procedures for pesticide residues and analysis in food and feed). During this initial validation the ion ratio, retention time, response stability, linearity, recovery, repeatability, bias, (provisional) within-laboratory reproducibility, (provisional) measurement uncertainty and matrix effects were assessed.

2.4 Data and Statistical analysis

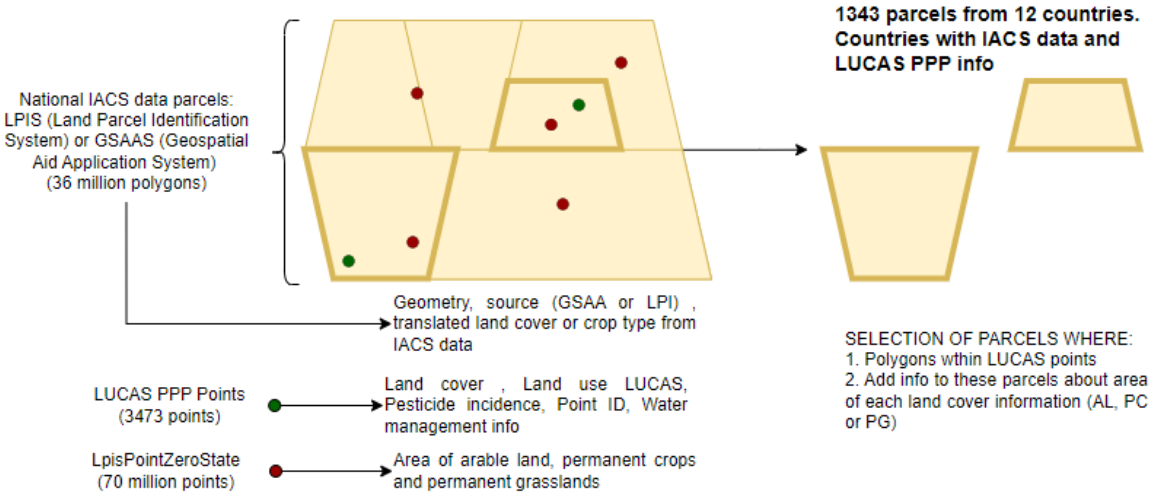
The LUCAS 2018 survey resulted in a database of concentrations of pesticides residues per individual sampling point, combined with additional attributes regarding land use and land cover, and crop type, as retrieved by the survey. For this work the pesticides residues results were aggregated in two main indicators adapted from Silva et al. (2019):

- **Incidence** – the number of substances found in each soil sample, reflecting the variability of substances found within each site, distributed by class (no substance, 1 substance, 2-5 substances, 5-10 substances , >10 substances);
- **Content** – maximum individual pesticide content determined in a soil sample, reflecting the order of magnitude of concentrations, distributed by class (<LOQ, LOQ-0.05 mg Kg^{-1}, 0.05-0.15 mg Kg^{-1}, 0.15-0.50 mg Kg^{-1}, 0.5-1 mg Kg^{-1}, >1 mg Kg^{-1}).

Besides the data obtained from the LUCAS survey, other complementary datasets were integrated into the studied database. These integrations allowed us to perform a more exhaustive quality assessment of the LUCAS survey, as also provided additional explanatory variables which allowed us to better understand the obtained results. Such databases include:

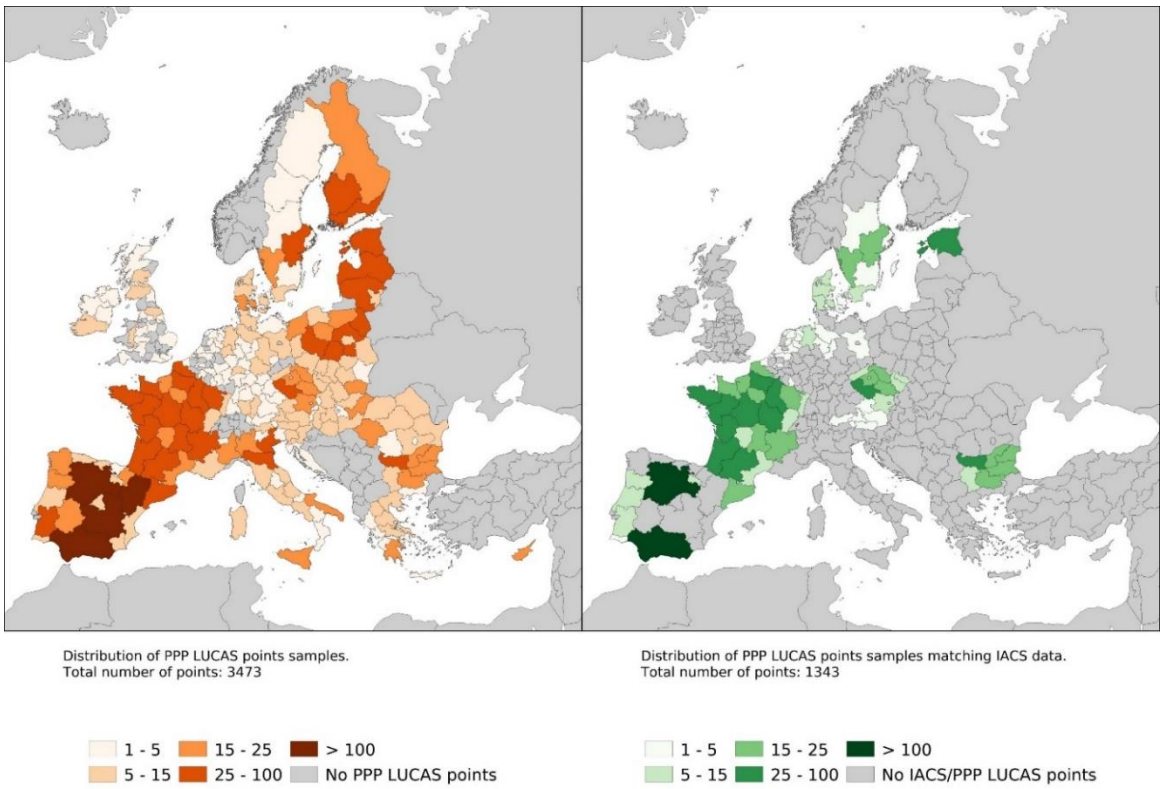
- European Statistical Office (Eurostat) – Data on the total pesticides sales in EU for the 2011-20219 period (Eurostat, 2021).
- Integrated Administration and Control System (IACS) - Available agricultural data from the Members States' Integrated Administration and Control System (IACS). Such data consist of the Land Parcel Identification System (LPIS), and the Geospatial Aid Application (GSA) datasets made available through the IACS Data Sharing process launched by EC DG AGRI and its stakeholders and accessible through the MS Geoportal (EC, 2023c). This included Land Cover Classification (arable land, permanent crop, permanent grassland) for an LPIS Reference Parcel where available for the concerned LUCAS Soil point with a soil sample that has been analysed, or a crop or crop group for a GSAA agricultural parcel where available (**Figure 3**, **Figure 4**).
- Meteorological data - E-OBS daily gridded meteorological data (Cornes et al., 2018) for Europe (based on the station network of the European Climate Assessment & Dataset (ECA&D) project), for the year 2018 and derived from in-situ observations, have been extracted at the geographical positions of the sample's measurements (Copernicus, 2020).

Figure 3 – Diagram of data integration between LUCAS survey points and IACS datasets.



Source: Joint Research Centre.

Figure 4 – Distribution of LUCAS points assessing pesticides residues and IACS data by NUTS-2 Regions.



Source: Joint Research Centre.

3 Results

3.1 Frequency of pesticides residues in topsoil samples

3.1.1 Overall

Only 25.5% of the samples analysed show no presence of pesticides residues (**Figure 5**). The majority of the samples (57.1% total) present at least two different residues, and of those, 29.8% total presented more than five different residues, while 11.1 % total presented more than 10 pesticides residues.

Additionally, from the entire universe of combinations between sites (n=3473) and substances under analysis (n=118), 14,106 positive quantifications (**Table 2**), 12% corresponded to non-approved substances according to the 2018 applicable regulations (Regulation 1107/2009). Under current list of approved and banned substances (May 2023), this would represent 36% of the identifications.

3.1.2 National perspectives

Austria, Cyprus, Greece, Spain, Croatia, Ireland, Italy, Lithuania, Latvia, Portugal, Romania, Slovenia, Slovakia, and United Kingdom presented lower incidence in pesticides residues when compared to the EU, varying from 25.7% to 63.2% of soil samples with no presence of pesticides residues. It should be noted that Malta presents no incidence in a single sample, and therefore was not considered in the former statistics.

Belgium, Czech Republic, Germany, Denmark, France, Hungary, Netherlands, Poland, Slovakia, and United Kingdom presented higher than EU average contribution of the extreme incidence class, varying from 11.1% to 44.4% of soil samples with more than 10 distinct pesticides residues.

3.2 Pesticide content in topsoil samples

3.2.1 Overall

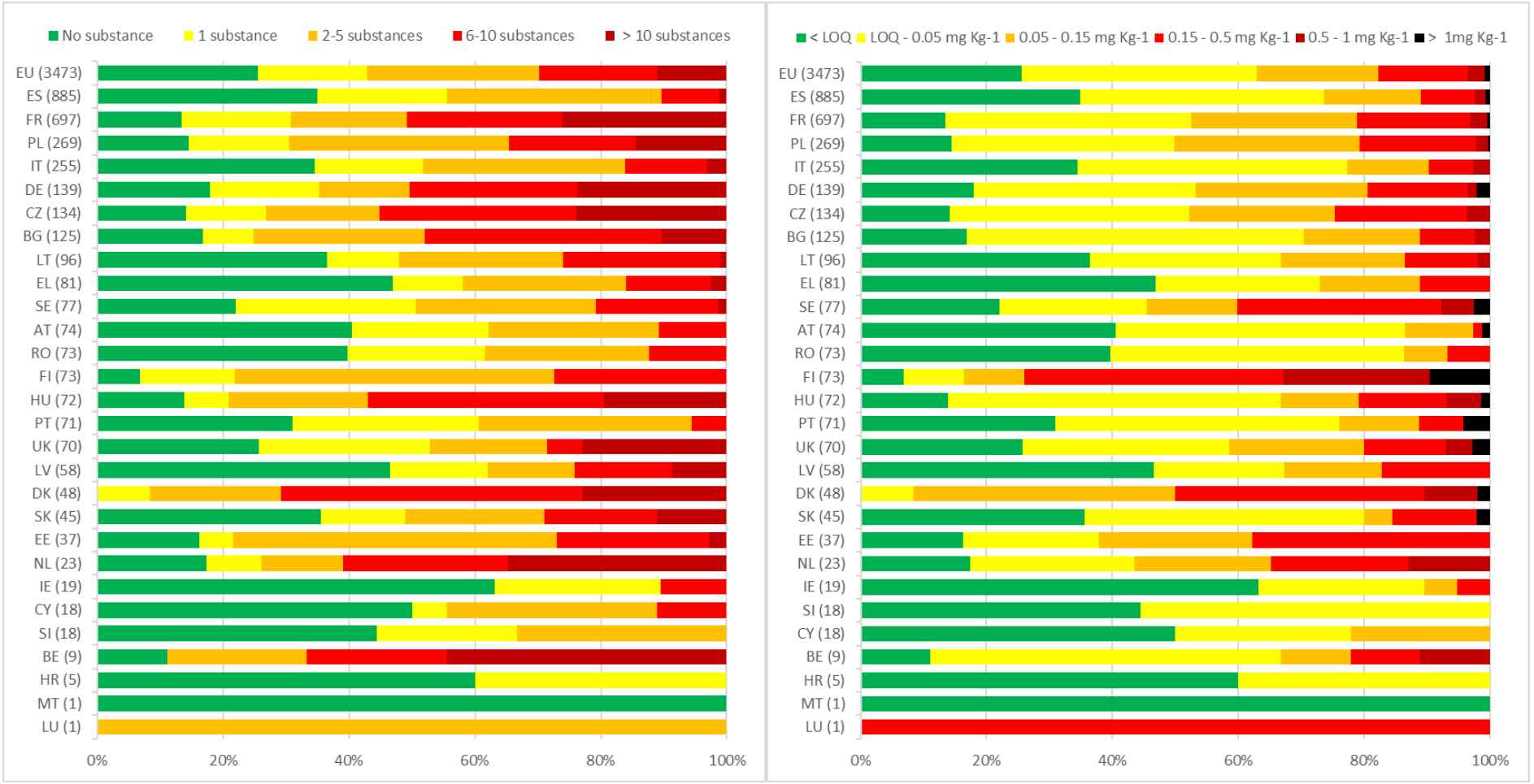
Most of soil samples (62.1% total) present concentrations levels classified as low to no detection (i.e. LOQ) (**Figure 5**), and from those, 37.8 % total presented concentrations above the quantification limit. On the other hand, 37.9 % total show pesticide residues concentrations above 0.05 mg Kg^{-1}, being 17.9% of the total above the 0.15 mg Kg threshold, and 3.6% total above the 0.5 mg Kg^{-1}.

3.2.2 National perspectives

Spain, Italy, Bulgaria, Lithuania, Greece, Hungary, Austria, Romania, Portugal, Latvia, Ireland, Cyprus, Belgium, Croatia and Malta presented higher distribution of sites with pesticides residues concentrations below 0.05 mg Kg, when compared to the EU reference, varying from 66.2% to 90.1%, and 100% for Croatia and Malta with five and a single sample, respectively.

On the other hand, France, Poland, Germany, Czech Republic, Finland, Denmark, Greece, Sweden, Netherlands and Luxembourg presented higher than EU average contribution regarding pesticide residues concentrations, varying between 47.3% to 91.7% of soil samples presenting maximum concentrations above 0.05 mg Kg^{-1}, and 100% for Luxembourg with a single sample.

Figure 5 – Pesticide incidence (left panel) and content (right panel) distribution (%) for all soil samples (EU) and by Country. Note number of soil samples in parenthesis.



Source: Joint Research Centre.

Table 2 – Status of EU approval in 2018 (Regulation 1107/2009), and positive quantification (P), for active substances analysed within the LUCAS 2018 soil survey. Note the codes, Y for yes, N for No, and Met. for Metabolites.

Substances	EU approved	P	Substances	EU approved	P	Substances	EU approved	P
2,4-DB	Y	N	Dimethomorph	Y	Y	Metalaxyl	Y	Y
Abamectin	Y	N	Dimoxystrobin	Y	Y	Metamitron	Y	Y
Aldrin	N	Y	Diuron	N	Y	Metconazole	Y	Y
AMPA	Y (Met.)	Y	Endosulfan,alpha-	N	Y	Metolachlor	N	Y
Atrazine	N	Y	Endosulfan,beta-	N	Y	Metrafenone	Y	Y
Atrazine-deisopropyl	N (Met.)	n	Endosulfan,sulphate	N	Y	Myclobutanil	Y	Y
Atrazine-desethyl	N (Met.)	Y	Endrin	N	N	Parathion	N	N
Azoxystrobin	Y	Y	Epoxiconazole	N	Y	Parathion-methyl	N	N
Bentazone	Y	Y	Ethion	N	N	Penconazole	Y	Y
Bixafen	Y	Y	Fenbuconazole	Y	Y	Pendimethalin	Y	Y
Boscalid	Y	Y	Fenpropidin	Y	Y	Penflufen	Y	Y
Bromuconazole	Y	Y	Fenpropimorph	N	Y	Pentachlorbenzene(PeCB)	N*	N
Carbaryl	N	N	Fluazinam	Y	Y	Penthiopyrad	Y	Y
Carbendazim	N	Y	Fludioxonil	Y	Y	Pinoxaden	Y	N
Carbofuran	N	N	Flufenacet	Y	Y	Pirimicarb	Y	Y
Carbofuran,-3-hydroxy	N (Met.)	N	Fluometuron	Y	Y	Pirimiphos-methyl	Y	N
Carbofuran,-keto	N (Met.)	N	Fluopicolide	Y	Y	Prochloraz	Y	Y
Chlordanecis-(alpha)	N	Y	Fluopyram	Y	Y	Procymidone	N	N
Chlordanetrans-(gamma)	N	Y	Fluoxastrobin	Y	Y	Promethryn	N	Y
Chlordecone	N	N	Fluquinconazole	Y	Y	Propiconazole	N	Y
Chlorfenvinphos	N	N	Fluroxypyr	Y	Y	Prosulfocarb	y	Y
Chloridazon	N	Y	Folpet	Y	N	Prothioconazoledesthio	Y (Met.)	Y
Chlorpyrifos	N	Y	Glyphosate	Y	Y	PTI	N*	Y
Chlorpyrifos-methyl	N	N	HCB	N	Y	Pyraclostrobin	Y	Y
Clothianidin	N	Y	HCH,alpha-	N	N	Pyriofenone	Y	Y
Cymoxanil	Y	Y	HCH,beta-	N	N	Quinoxyfen	N	Y
Cyproconazole	Y	Y	HCH,gamma-	N	Y	Simazine	N	Y
Cyprodinil	Y	Y	Heptachlor	N	N	Tebuconazole	Y	Y
DDD,o,p'-(TDE)	N	Y	Heptachlorendoepoxide(isoA)	N (Met.)	N	Terbuthylazine	Y	Y
DDD,p,p'-(TDE)	N	Y	Heptachlorepoxide(isoB)	N (Met.)	Y	Terbuthylazine-desethyl	Y (Met.)	Y
DDE,o,p'-	N	Y	Imazalil	Y	Y	Terbutryn	N	Y
DDE,p,p'-	N	Y	Imazamox	Y	Y	Thiabendazole	Y	Y
DDT,o,p'-	N	Y	Imidacloprid	Y	Y	Thiamethoxam	N	Y
DDT,p,p'-	N	Y	Indoxacarb	Y	Y	Thiophanate-methyl	N	N
Deltamethrin	Y	N	Isoproturon	N	Y	Triadimenol	N	Y
Diazinon	N	Y	Isoxaben	Y	Y	Tri-allate	Y	Y
Dieldrin	N	Y	Lenacil	y	Y	Triclopyr	Y	N
Difenoconazole	Y	Y	Linuron	N	Y	Trifloxystrobin	Y	Y
Diflufenican	Y	Y	Malathion	Y	N			
Dimethenamid	N	Y	MCPA	Y	Y			

* *Not referred in EU Pesticides Database (EC, 2023a)*

Source: Joint Research Centre.

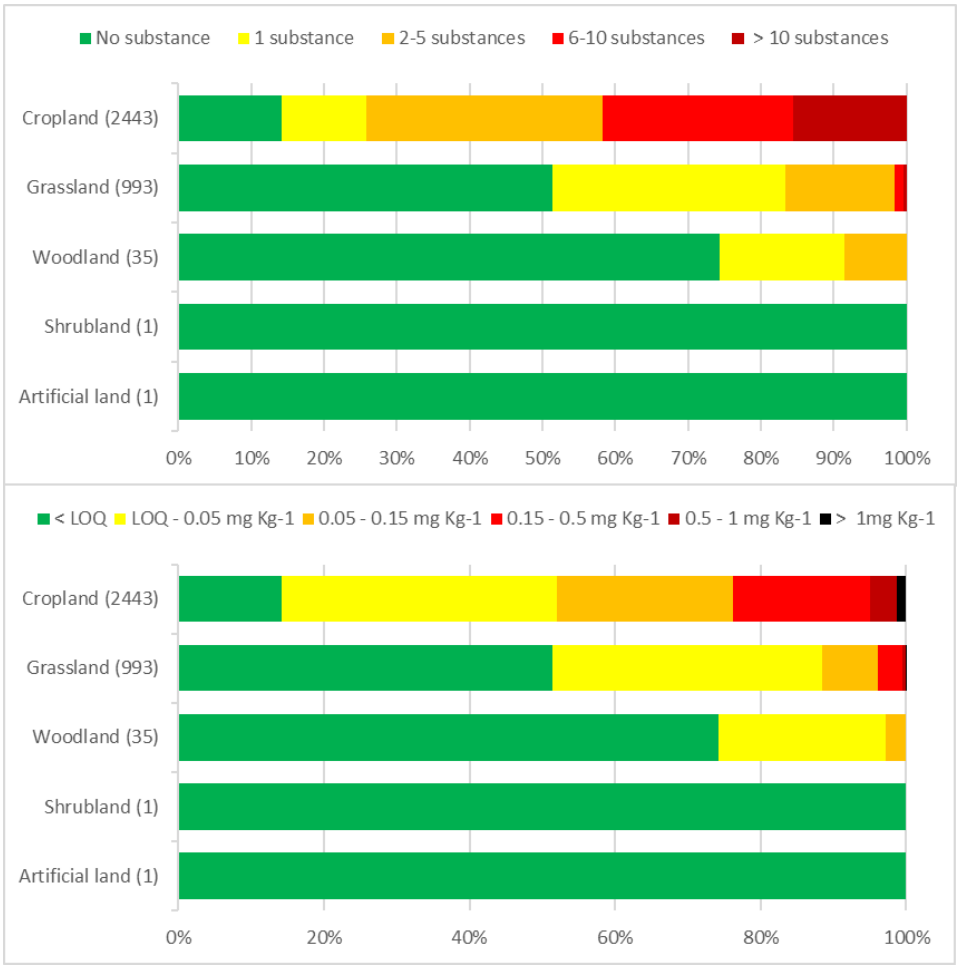
3.3 Land Cover and crop classes

As expected, areas with cropland present the highest incidence of pesticide residues with 85.8% of samples presenting at least one pesticide residue (**Figure 6**), while in grassland areas the no incidence class is more represented, whereas 48.0% of the samples present at least one pesticide residue.

On the pesticide residue content, more than half of the soil samples from cropland (52.4%) present maximum pesticide residues concentrations below 0.05 mg Kg^{-1}, but an important number of samples (22.9%) evidence concentration values above 0.15 mg Kg^{-1}.

The result obtained in the grassland areas for both incidence and pesticide content raise several questions, namely regarding the land cover classification (short vs. long-term grasslands), if some pesticide residues might present longer half-life than expected, but also about the possibility of pesticide residues transference from cropland areas into grasslands.

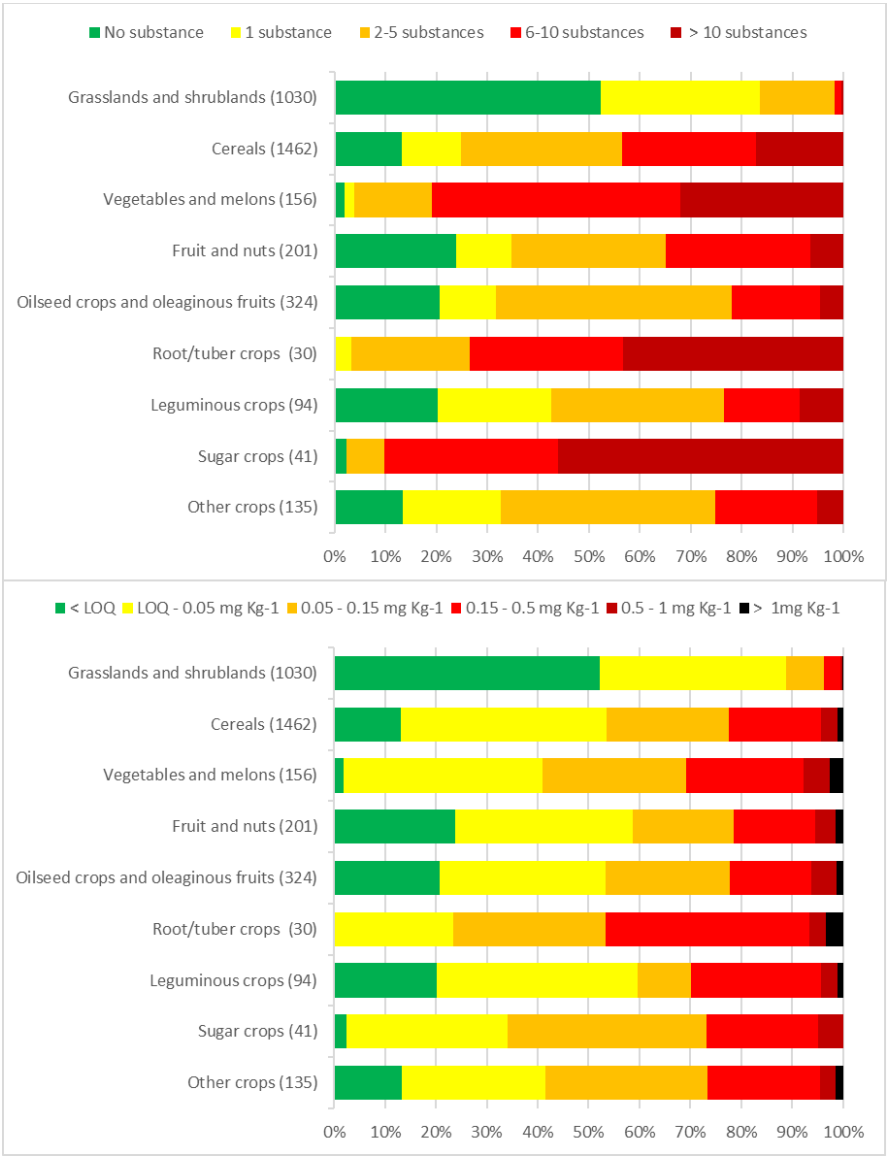
Figure 6 – Pesticide incidence (upper panel) and content (bottom panel) distribution (%) for land cover type. Note number of soil samples in parenthesis.



Source: Joint Research Centre.

When crop type is considered, the results show a higher incidence and pesticide content (**Figure 7**) among soils under vegetables and melons, root/tuber crops, and sugar crops classes, in which pesticides residues are found in most of the analysed samples (97.4 to 100 %). In addition, the soils associated with these crops also present a substantial contribution (32.2 to 55.3 %) on the extreme incidence class (more than 10 pesticides). The pesticide total concentration in most samples was found in the highest class (above 0.5 mg Kg^{-1}) only in 4.6% of the samples.

Figure 7 – Pesticide incidence (upper panel) and content (bottom panel) distribution (%) for crop type. Note number of soil samples in parenthesis.



Source: Joint Research Centre.

Given the fact that sites under Cereal crops were the most sampled within LUCAS 2018 survey, it is important to highlight that 86.9% of those investigated sites present at least one pesticide residue, and 45.9% of the site reveal maximum pesticides residues concentrations above 0.05 mg Kg^{-1}.

Following the observation of pesticides residues in 47.8% of the grassland areas, a quality assessment was performed by comparing land cover and use from LUCAS sampling points with the available IACS data for the same locations, when available (n=1301). Under this procedure it was possible to identify a potential mismatch in the classification of 2.3% of cropland areas, which were identified as grasslands according to IACS database. On the other side the sampling points located in grasslands (according to LUCAS) revealed a potential error of 14%, since in the IACS database these are classified as croplands (**Table 3**). As a result, further analysis by land cover and land use originated from this dataset included such uncertainty.

Table 3 – Land cover and use classification comparison between LUCAS and IACS databases (LPIS and GSA). Match between classes were identified as contributor to the classification confidence (**bold**), while mismatches were identified as contributor to the classification errors (i*talic*).

LUCAS Class	IACS class (LPIS and GSA combined for land cover and land use)	Match (%)	**Confidence**/ *Error*
Cropland *n=1037*	Arable land	45.9%	**97.7%**
	Wheat	13.8%	
	Maize	6.8%	
	Olives	6.3%	
	Barley	4.8%	
	Rape	3.4%	
	Beet	1.7%	
	Vineyards	1.4%	
	Dry fruit trees	1.3%	
	Sunflower	1.3%	
	Rye	0.9%	
	Triticale	0.9%	
	Temporary Crops	0.8%	
	Oat	0.7%	
	Lucerne	0.6%	
	Potatoes	0.5%	
	Fruit trees	0.5%	
	Bean	0.4%	
	Flax fibre	0.4%	
	Fodder	0.4%	
	Cereals	0.3%	
	Peas	0.3%	
	Suvioder	0.3%	
	Other mixtures	2.3%	
	Other (less representative)	1.9%	
	Temporary grassland	1.0%	*2.3%*
	Grassland	0.6%	
	Set-aside ≤5 years	0.4%	
	Permanent grassland	0.3%	
	Grass with clover/alfalfa	0.1%	

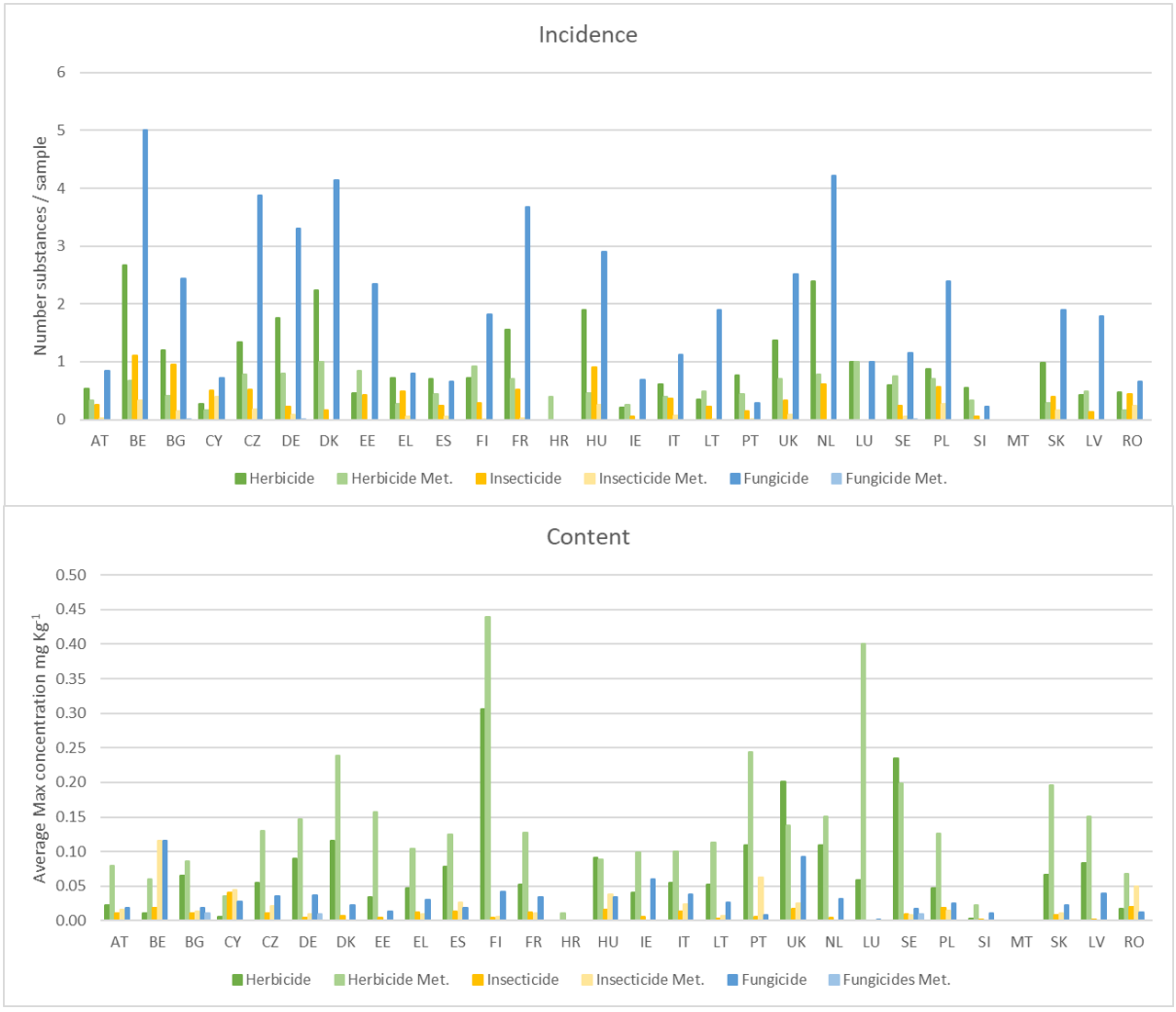
LUCAS Class	IACS class (LPIS and GSA combined for land cover and land use)	Match (%)	**Confidence**/ *Error*
Grassland *n=264*	Permanent grassland	61%	**86.0%**
	Grassland	12%	
	Pasture	6%	
	Pastures, grasslands & meadows	2%	
	Grazing	1%	
	Set-aside ≥6 years	1%	
	Forage area	1%	
	Herbaceous plants	1%	
	Permanent pasture	1%	
	Other mixtures	2%	
	Arable land	10%	*14.0%*
	Temporary Crops	1%	
	Rye	0%	
	Soya	0%	
	Vine	0%	
	Wheat	0%	

Source: Joint Research Centre.

3.4 Pesticide type

The main classes of pesticides residues used for this analysis correspond to Herbicides, Insecticides and Fungicides. The analysis of the LUCAS samples evidenced a higher incidence for fungicides among most of the MS, followed by the herbicides and their metabolites (**Figure 8**). Notwithstanding, when analysing in terms of pesticide content, herbicides and their metabolites presented the highest average maximum concentrations within the analysed soils. It is also important to notice that herbicide metabolites systematically present higher maximum concentrations than the original herbicide. On the other side, despite Fungicides residues evidence the highest incidences within Countries, their content is much lower in comparison to Herbicides, while the trace of Fungicide metabolites is almost inexistent.

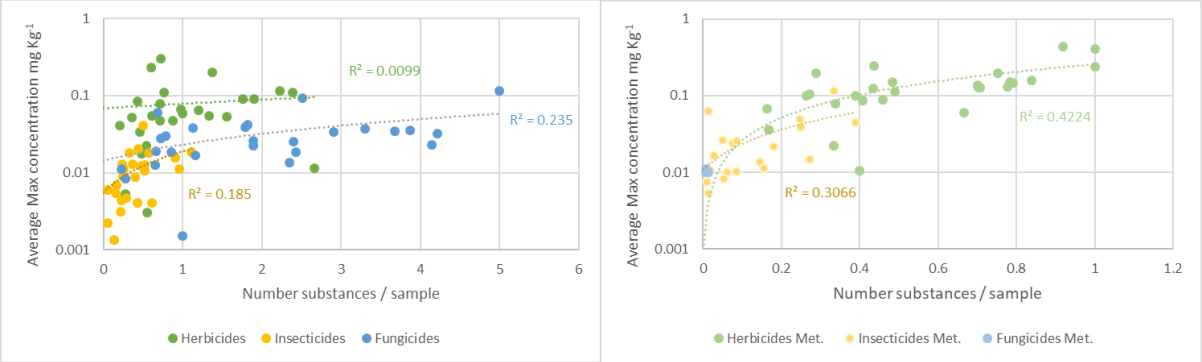
Figure 8 – Pesticide incidence (upper panel) and average maximum concentration (bottom panel) for each Country by class type (Herbicides, Insecticides, Fungicides) and their Metabolites (Met.).



Source: Joint Research Centre.

In an attempt to relate incidence and content within the obtained results (**Figure 9**), the best correlation found was for Herbicide metabolites, in which maximum concentrations found are systematically higher in comparison to their counterparts (**Figure 8**). This could evidence a possible effect of having longer half-life under the studied sites, but such analysis still requires further exploration.

Figure 9 – Pesticide average maximum concentration vs. incidence for each Country by class type (Herbicides, Insecticides, and Fungicides) and their Metabolites (Met.).



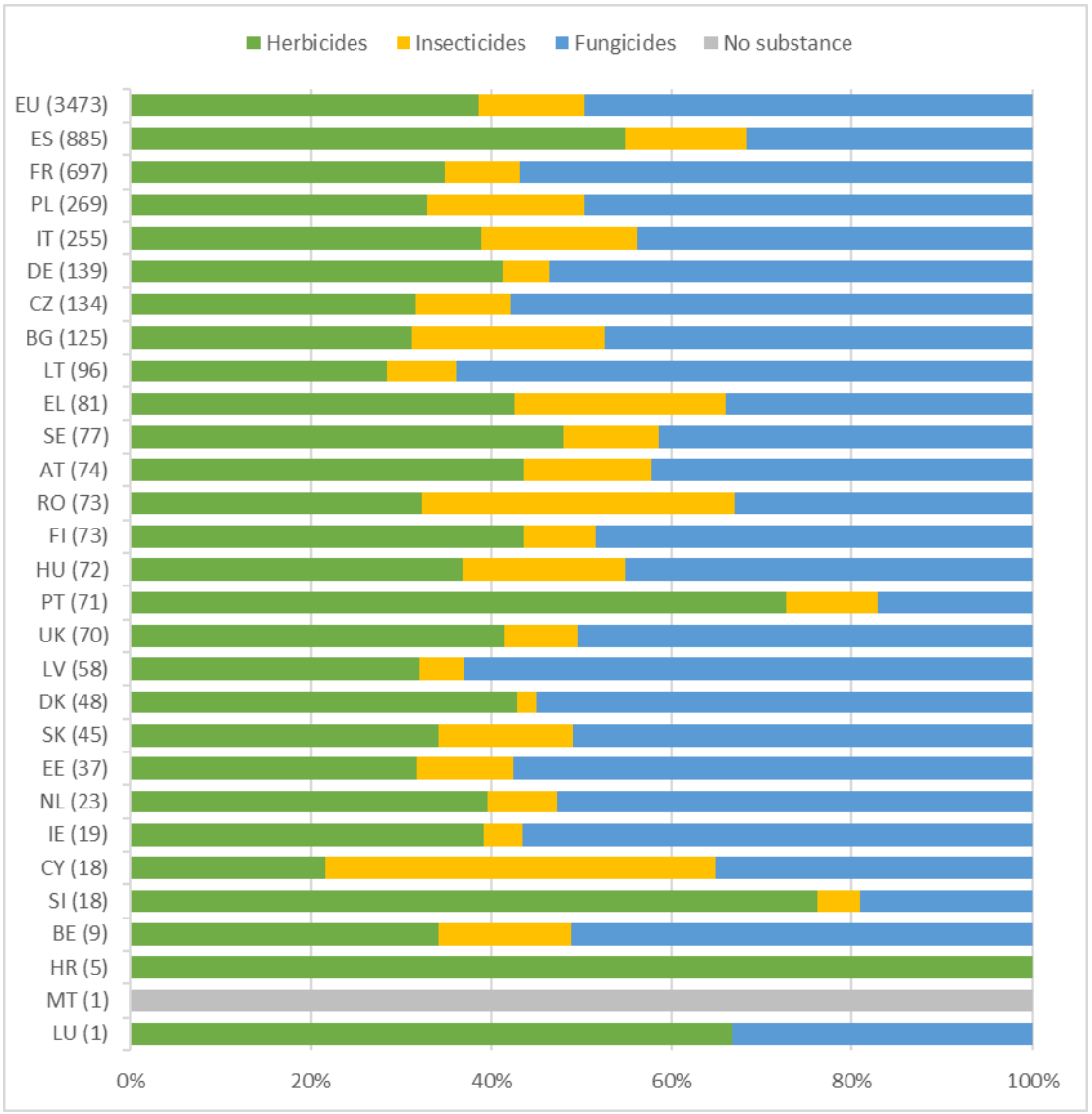
Source: Joint Research Centre.

3.5 Drivers of spatial distribution

3.5.1 Pesticide usage and needs

When analysing positive quantifications of pesticides by individual Countries, it is possible to recognize different needs in terms of class type, such as Herbicides, Insecticides, and Fungicides (**Figure 10**). Our analysis shows that most of the soil samples resulted in a higher incidence of Fungicides, followed by Herbicides and Insecticides. This trend was generally observed for most Countries, except for Spain, Greece, Portugal, Luxembourg and Croatia in which Herbicides present higher contribution, but also for Cyprus in which Insecticides incidence dominates the samples under analysis.

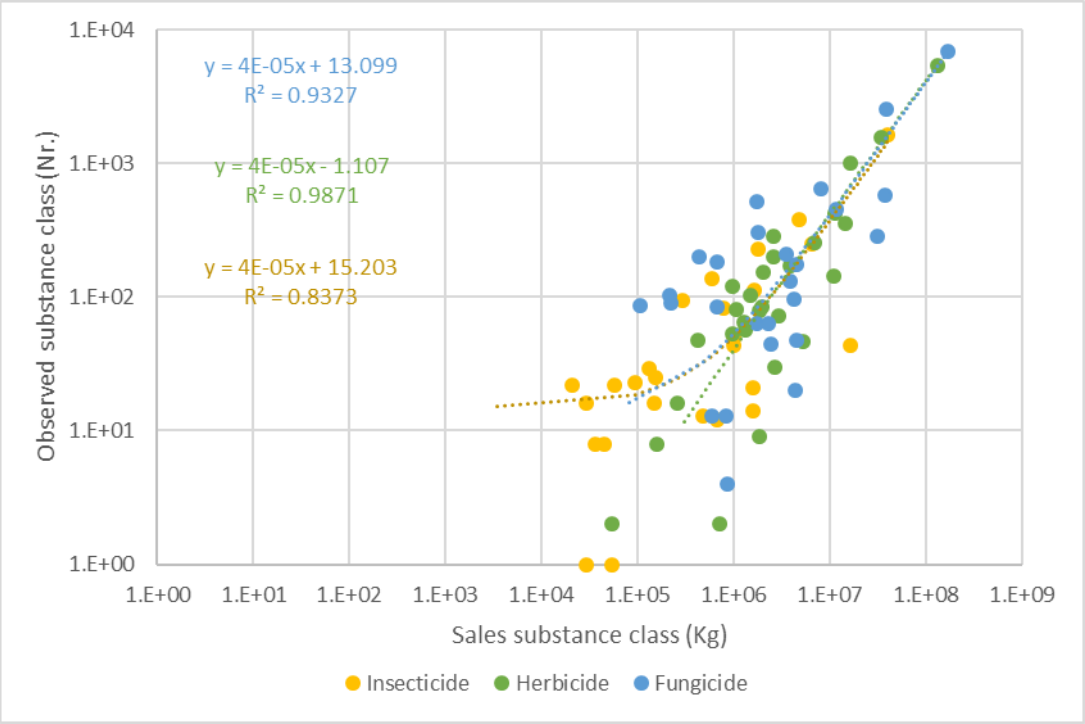
Figure 10 – Distribution of Pesticide class type (Herbicides, Insecticides, Fungicides) found in soil (%).Note number of soil samples in parenthesis.



Source: Joint Research Centre.

When this pesticide residues distribution from the LUCAS soil samples are compared against the distribution of annual sales (Kg) registered in the EU for 2018 (Eurostat, 2021) it is possible to conclude that an indicator based on sales can partially explain pesticide residues incidence magnitude in soils by countries (**Figure 11**).

Figure 11 – Comparison between sales of active substance for each Country and incidence found in LUCAS survey by class type (Herbicides, Insecticides, and Fungicides).



Source: Data from Eurostat and LUCAS survey, and visuals from Joint Research Centre.

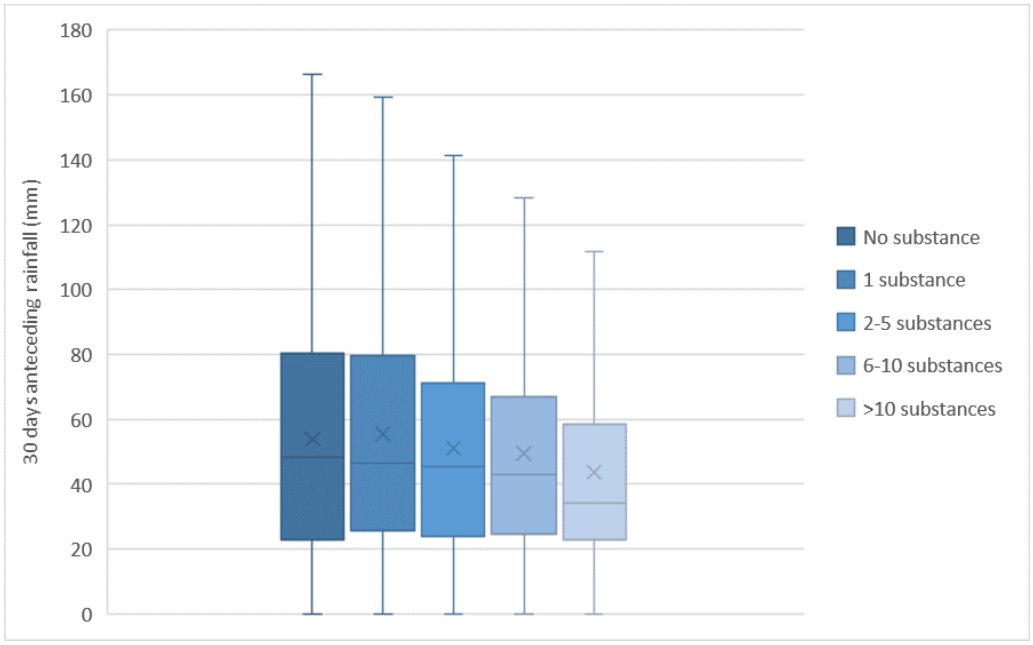
3.5.2 Climate variables affecting pesticide residues

In order to understand the influence of local meteorological conditions in each individual soil sample and their corresponding pesticide residues result, pesticide incidence for each individual LUCAS point was compared against accumulated rainfall (**Figure 12**), and mean air temperature (**Figure 13**), according to the closest meteorological station available (Climate Copernicus, 2022) for the 30 days preceding the sampling.

As expected, the results from these two climate variables evidence a potential reduction of pesticide incidence with increasing antecedent rainfall (**Figure 12**) as already evidenced by other studies (Bento et al., 2016; Abbasi et al.,2019). Our results also show a greater incidence of pesticides residues in areas with mild temperatures, under smaller thermic variability (**Figure 13**). Notwithstanding, no significant differences were found between incidence classes against antecedent rainfall and temperature data when combining all sample points.

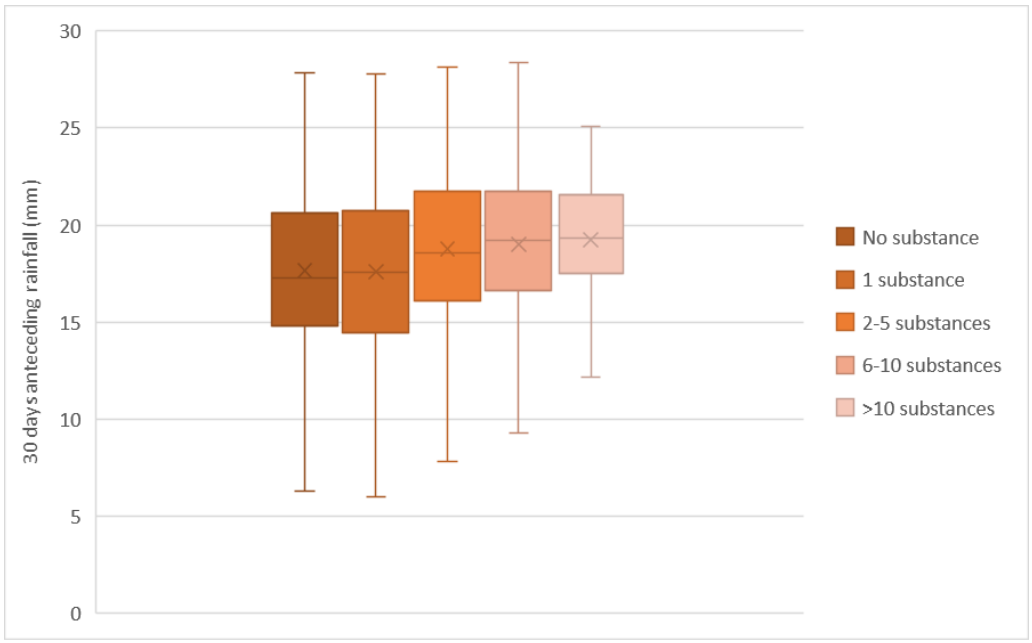
In what concerns the pesticides residues content, since there are significant uncertainties associated with the timing of pesticide residue application, namely the lack of knowledge if it occurred during the preceding 30 days or not, we restricted such analysis to pesticides residues incidence as a better translator of chemical pressure applied to such soils.

Figure 12 – Accumulated rainfall referred to the antecedent 30 days before the sampling date, grouped by incidence class.



Source: Joint Research Centre.

Figure 13 – Local mean temperature on the antecedent 30 days before the sampling date, grouped by incidence class

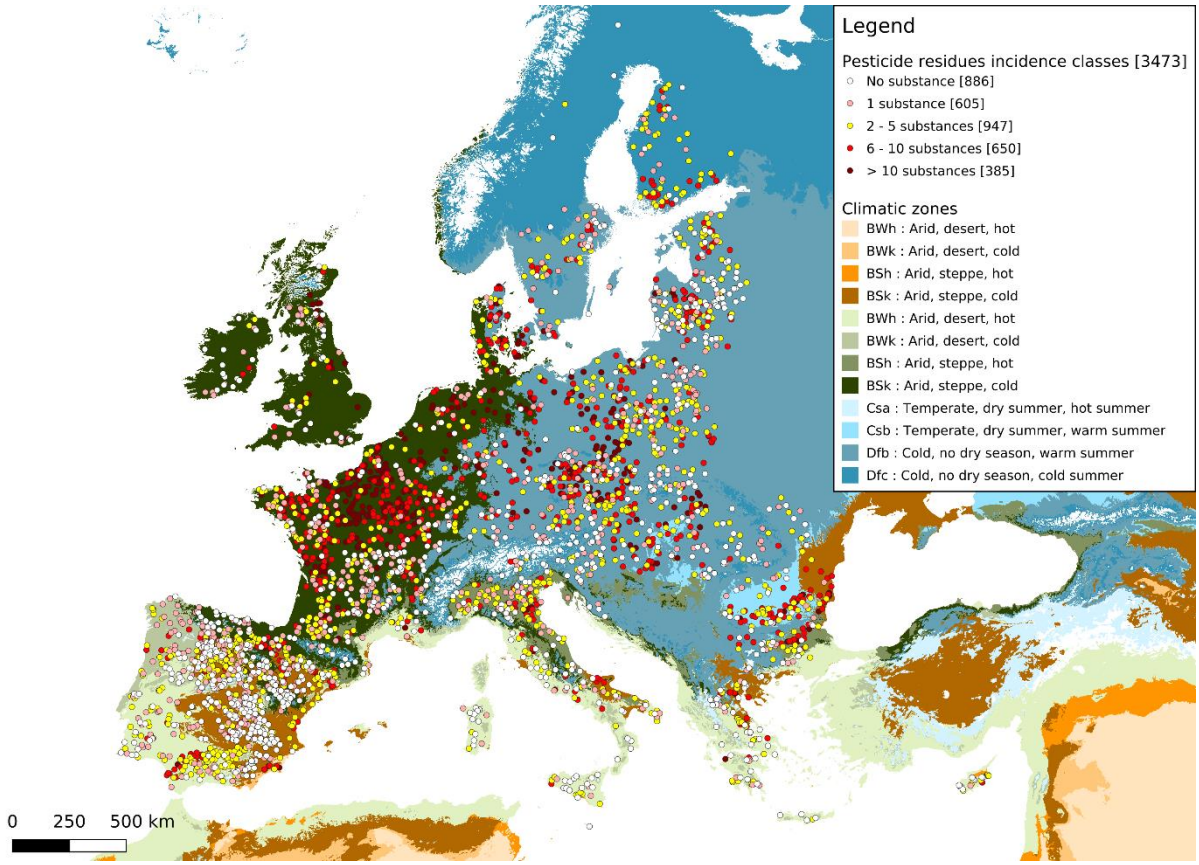


Source: Joint Research Centre.

Regarding the long term exposure of soils to pesticide residues application, the Koppen Climatic zones were thought to be a more appropriate indicator, since they can translate the climatic dynamics subjected to soils over an entire production year. In addition to that, such classification can also help identifying clusters of soils under higher pressures from pesticides residues, under specific climates, in a spatially explicit way.

Our results evidence a greater cluster of the highest incidence classes (**Figure 14**) over Cfb (Temperate, no dry season, warm summer) and Dfb climate zones (Cold, no dry season, warm summer). Despite the limitations of the single sampling analysis, these climate zones frequently evidence soils with more than 10 individual pesticide residues substances (**Figure 15**), possibly indicating a potential long-term exposure to pesticides, but also that such climate conditions might not be favourable for the degradation of such compounds. Should also be highlighted, that despite the class variability, Cfb and Dfb correspond to the most represented climate zones in the EU under this current survey, with 996 and 1100 sample points, respectively.

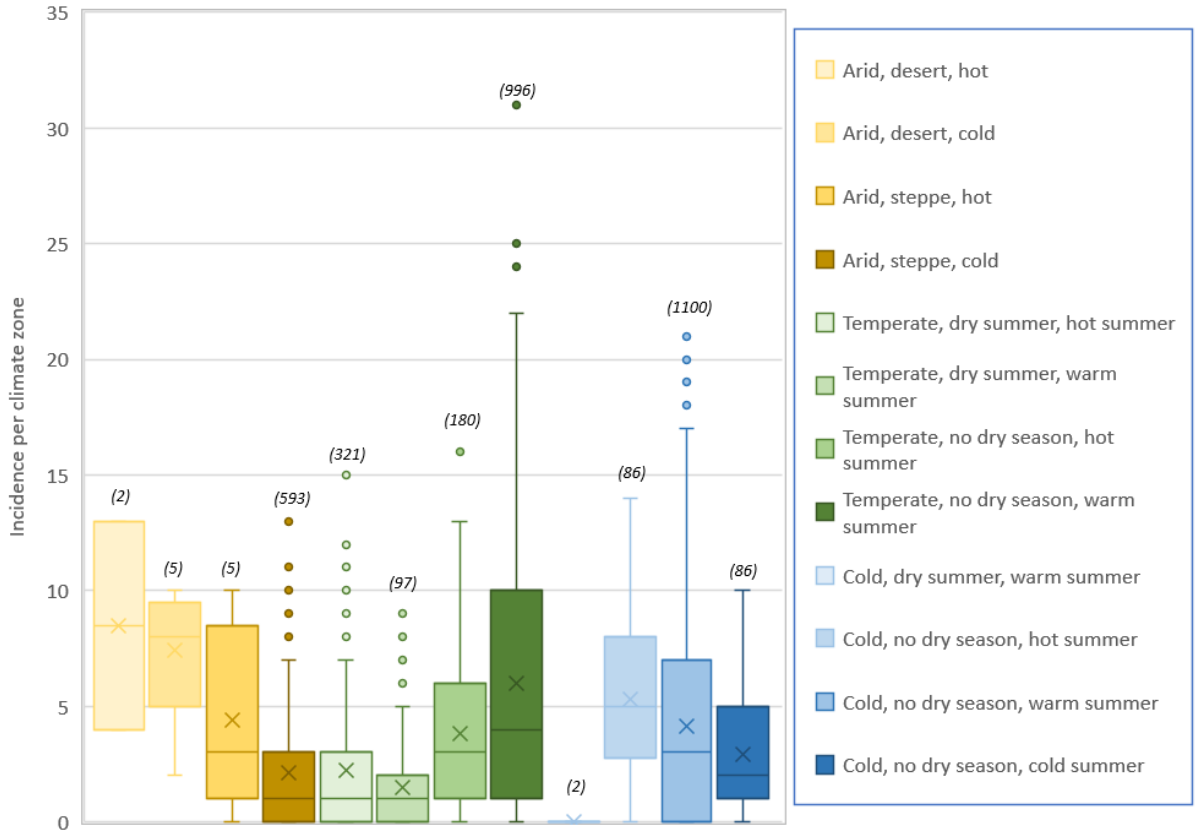
Figure 14 – Spatial distribution of pesticide residues incidence classes, from the 3473 sites under analysis, and spatial view of the climatic zones.



Source: Joint Research Centre.

On the other side, but still under a significant representation of sampling points (**Figure 14**, **Figure 15**), BSk (Arid, steppe, cold), Csa (Temperate, dry summer, hot summer), and Csb (Temperate, dry summer, warm summer), which correspond to the Mediterranean basin, present less extreme pesticides residues incidence in the sampling points, with median values under the five substances class.

Figure 15 – Incidence distribution for individual LUCAS points in function of the climatic zones. Note number of points for each class between parentheses.



Source: Joint Research Centre.

3.6 Ecological Risk Assessment

3.6.1 Objectives

All pesticides approved for agricultural use in Europe are assessed for their potential ecological risk before their approval. LUCAS soil concentration data can be used in a retrospective risk assessment and inform EU policy in various ways. Here, an ecological risk assessment in the form of a mixture risk indicator is presented. Such indicator can be used to:

- assess the effectiveness of EFSA regulatory framework to protect soil organisms from direct ecotoxicological effects of pesticide residues;
- develop a prototype indicator of ecological risk to soil organisms for potential use in monitoring the progress towards policy objectives (e.g. Farms to Fork 50% reduction of risks, indicators framework under the Chemicals Strategy for Sustainability);
- explore associations between pesticides risks and indicators of biodiversity.

3.6.2 Ecotoxicity dataset compilation and processing

Ecotoxicological data on the monitored pesticides exist in various datasets curated by regulatory and scientific institutions. Among these sources, experts from the JRC and EFSA identified four datasets based on their scientific and policy relevance:

- EFSA OpenFoodTox (EFSA, 2022)
- US EPA Ecotox database (EPA, 2023)
- The University of Hertfordshire Pesticides Properties Database (PPDB) (AERU, 2022)
- OECD eChemPortal (OECD, 2022)

Toxicity data were extracted from these datasets for the 118 substances of interest, identified by CAS number. The extraction targeted toxicity test results for in soil organisms expressed as No Observed Effect Concentrations (NOEC). Soil organisms include in soil macro-organisms that are consistent with the scope of risk assessment for the terrestrial compartment according to EFSA regulatory guidelines (EFSA 2002). NOEC are the highest concentration in a dose-response toxicity study at which no effect is observed.

Some harmonization steps were necessary to combine the datasets and enable further processing. Data fields that needed harmonization included substance identifiers (CAS), species names and units. Duplicate entries were identified based on identical CAS, endpoint name (NOEC), species, values and unit, and removed from the dataset. The OECD eChemPortal did not provide any additional entry compared to the other three. For those substances not covered in the dataset, and with at least one detection in the monitoring survey a targeted search of the scientific literature was performed. This brought the manual addition of AMPA and DDT p.p. (attributed to also to DDT o.p.)

The dataset of experimental records comprised 208 rows, covering 78 of the 118 substances in the list of pesticide residues monitored in LUCAS (Annex 2). For each of the 78 substances, NOEC values were available for between 1 and 9 species (median case = 2). The full list of species represented in the dataset include in the order of frequency: annelids (*Eisenia foetida*, *E.andrei*, *Aporrectodea caliginosa A.longa, Perionyx excavatus Allolobophora icterica, Lumbricus rubellus, L. terrestris, Enchytraeus albidus*), collembolans (F*olsomia candida, Heteromurus nitidus, F. fimetaria*) and mites (*Hypoaspis aculeifer*).

Experimental data gaps were filled with QSAR predicted data obtained using the earthworm NOEC model available in the VEGA QSAR platform (Benfenati et al., 2013)), excluding estimations flagged as "low reliability" and, in a subsequent step for the remaining data gaps, with extrapolations from short term (14 days) earthworm LC50 data retrieved from OpenFoodTox and PPDB, assuming an extrapolation factor of 10 (Frampton et al. 2009). At this point, soil NOEC was compiled for 94 substances.

The minimum and the median of the NOEC values were then calculated from the resulting combined dataset. Risk calculations were performed using NOECmin. Alternatives risk indicators using the median of soil NOECs as well as based on aquatic toxicity data (assuming partitioning equilibrium) have been developed (Franco et al, manuscript in preparation).

3.6.3 Mixture risk calculations

The overall toxic pressure of pesticide residues for a given biological endpoint is the result of the combined toxic contribution of each component of the mixture. The concentration addition or sum of risk quotients (RQs) is a commonly used model used in screening mixture risk assessment. This is simply calculated by adding the risk quotients obtained for each substance.

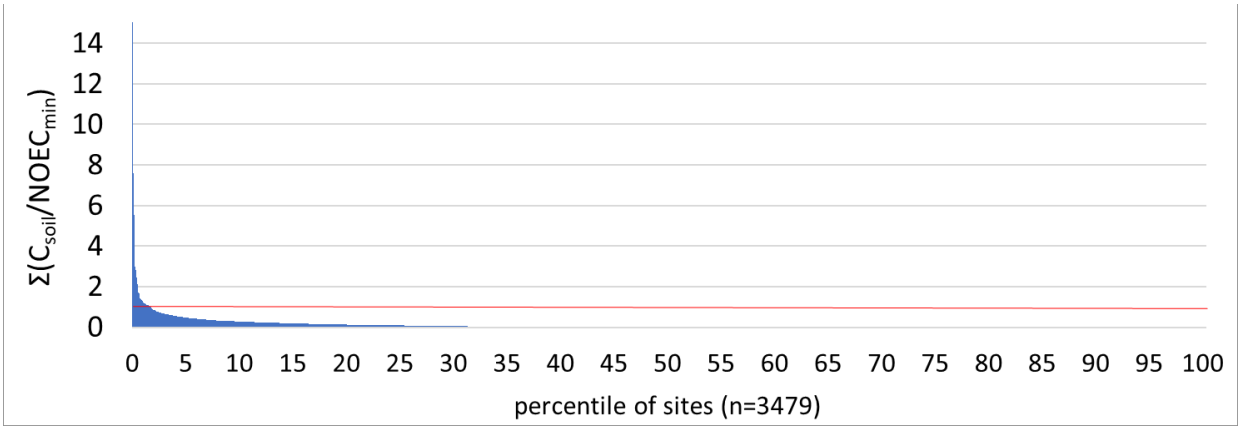
$$\sum RQs = \sum_{i=1}^{n} \frac{C_{soil,i}}{NOEC_{\min\_soil,i}}$$

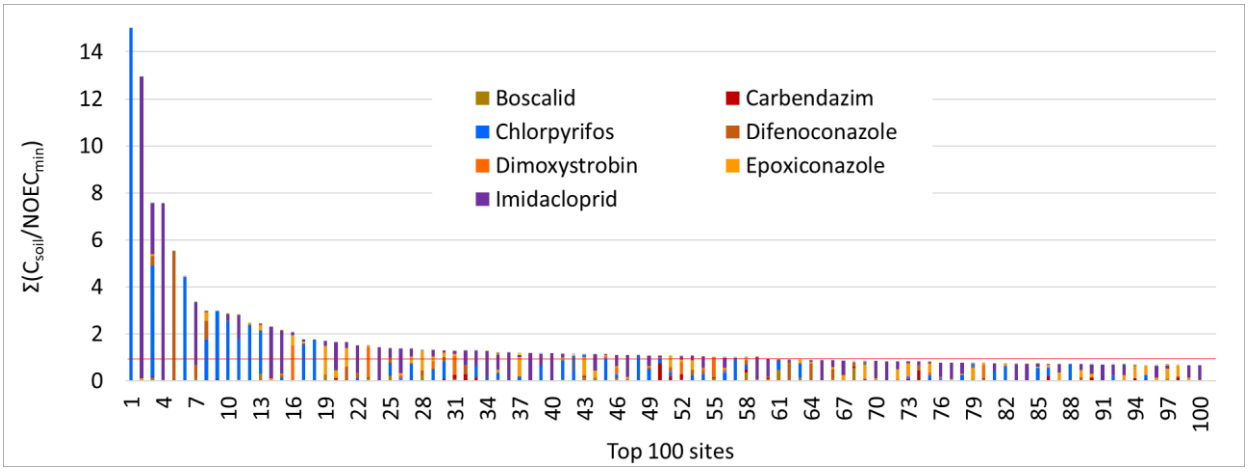
Where Csoil,i is the concentration of substance i of the mixture and NOECmin_soil,i is the minimum no observed effect concentration (NOEC) available for that substance. A sum of toxic units below 1 indicates no expected adverse effects on the most sensitive of the species tested. A sum of toxic units above 1 indicates a potential risk. These calculations do not include any assessment factors and are therefore not directly comparable to regulatory assessments.

3.6.4 Results

The sum of risk quotients calculated based on the NOECmin is shown in **Figure 16** for all sites (upper panel) and zoomed for the 100 sites with the highest risk (lower panel).

Figure 16 – Sum of soil risk quotients calculated for all sites (up) and for the top 100 high risk sites (low). The first and highest value, $\Sigma(C_{soil}/NOEC_{min}) = 54$ is cut at 15. Data labels in the lower panel are shown for substances with $\Sigma(C_{soil}/NOEC_{min}) > 0.5$ at any site. The horizontal red line represents $\Sigma(C_{soil}/NOEC_{min}) = 1$.



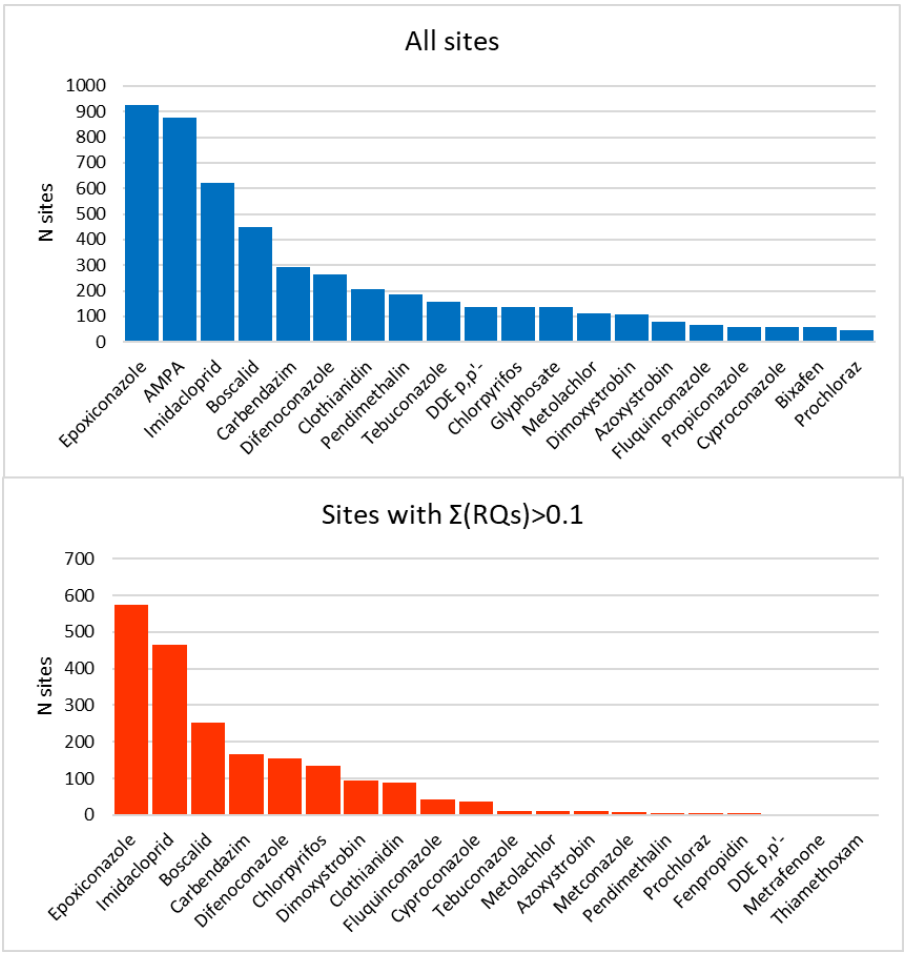


Source: Joint Research Centre.

This risk indicator exceeds 1 (potential risk) for 59 sites, representing 1.7% of all surveyed sites. The long tail of low-risk sites comprise 22% of those sites for which the sum of RQs ranges between 0.1 and 1 and 76% of those sites for which the sum of RQs are < 0.1. In the top 100 sites characterised by the highest risk, such risk is in most cases driven by a single substance. Based on risk quotients for individual substances, 30 sites exceed the RQ of 1. The insecticides imidacloprid and chlorpyriphos are the most recurrent toxicity drivers of the mixture, followed by the fungicides epoxiconazole, dimoxystrobin and difenoconazole and boscalid. Chlorpyriphos is also associated with the overall

highest risk site, with an RQ of 54 (cut at 15 in **Figure 16**). Overall, insecticides are the most frequent toxicity driver for soil dwelling organisms in the sites at highest risk, followed by fungicides. Herbicides, including glyphosate and its metabolite AMPA that are most frequently detected and present at the highest concentrations, do not pose a significant risk (highest RQs in the order of 10^{-3}). **Figure 17** shows how frequently each single substance contributes to more than 5% of the risk indicator across all sites (upper panel) and across all sites with sum of RQs exceeding 0.1 (lower panel). In both cases, epoxiconazole is the most frequent substance contributing to the risk indicator, indicating widespread use at risk-relevant levels. When considering all sites, AMPA is the second most frequent contributor, though mostly associated with low-risk sites. In fact, AMPA is in many sites the only substance detected. It does not appear among risk contributors looking at sites with appreciable risk (**Figure 17**, lower panel). In these sites, the most frequent risk contributors reflect more closely the toxicity drivers in the top 100 high-risk sites.

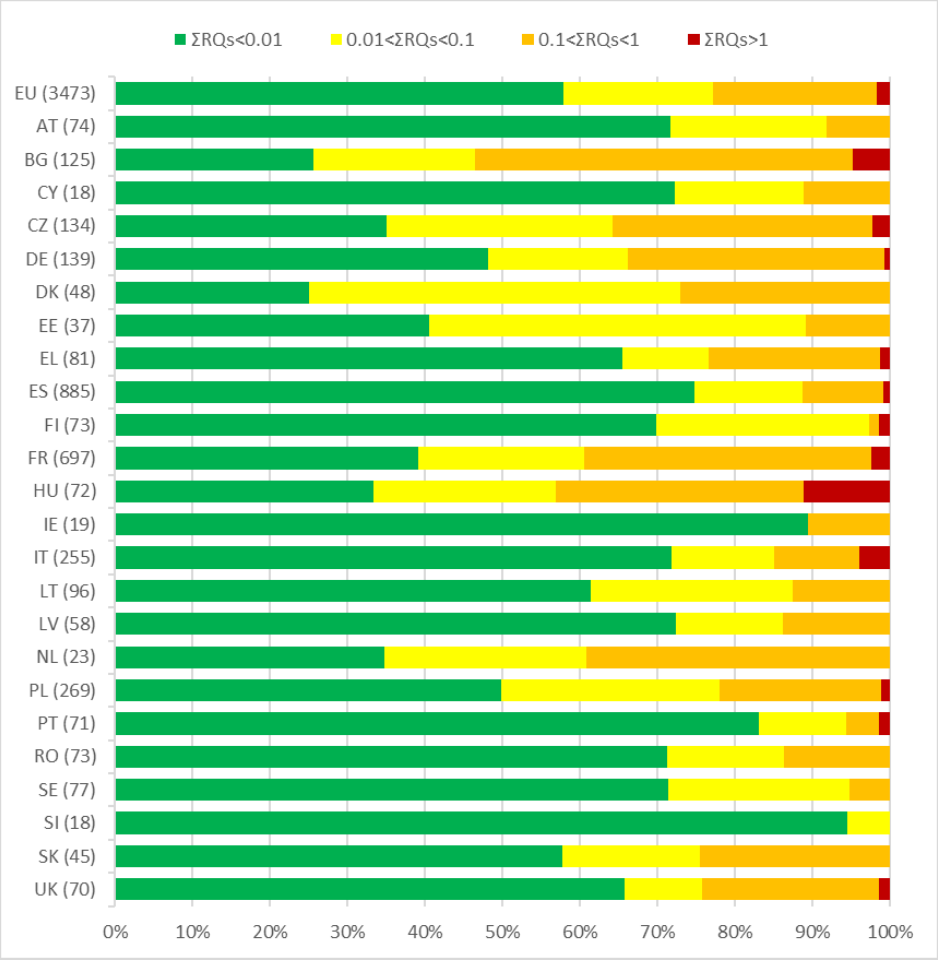
Figure 17 – Main pesticides contributing to toxicity: frequency of occurrence of substance contributing to more than 5% to the sum of risk indicator *$\Sigma(C_{soil}/NOEC_{min})$ across all sites (up) sites with $\Sigma(C_{soil}/NOEC_{min})>0.1$ (low).*



One or few substances, up to 3-5 at most, drive the overall risk for each site. These mixture combinations are mostly composed of the same substances mentioned above. They include insecticides and fungicides, (e.g., imidacloprid and epoxyconazole frequently found together at risk-relevant levels), but also include combinations of insecticides (e.g., chlorpyriphos with imidacloprid) and fungicides.

Aggregation by country shows differences across EU countries, though no clear geographical pattern emerge between macro-regions (**Figure 18**). The number or sites across countries is uneven and in some cases (Belgium, Croatia, Malta and Luxembourg) it is too small (n<10) to be reported in **Figure 18**. Aggregation at EU and possibly at country level provide suitable indicators to analyze temporal trends.

Figure 18– Distribution of mixture risk indicator across countries (in parenthesis number of sampling points), for Countries with more than 10 samples.

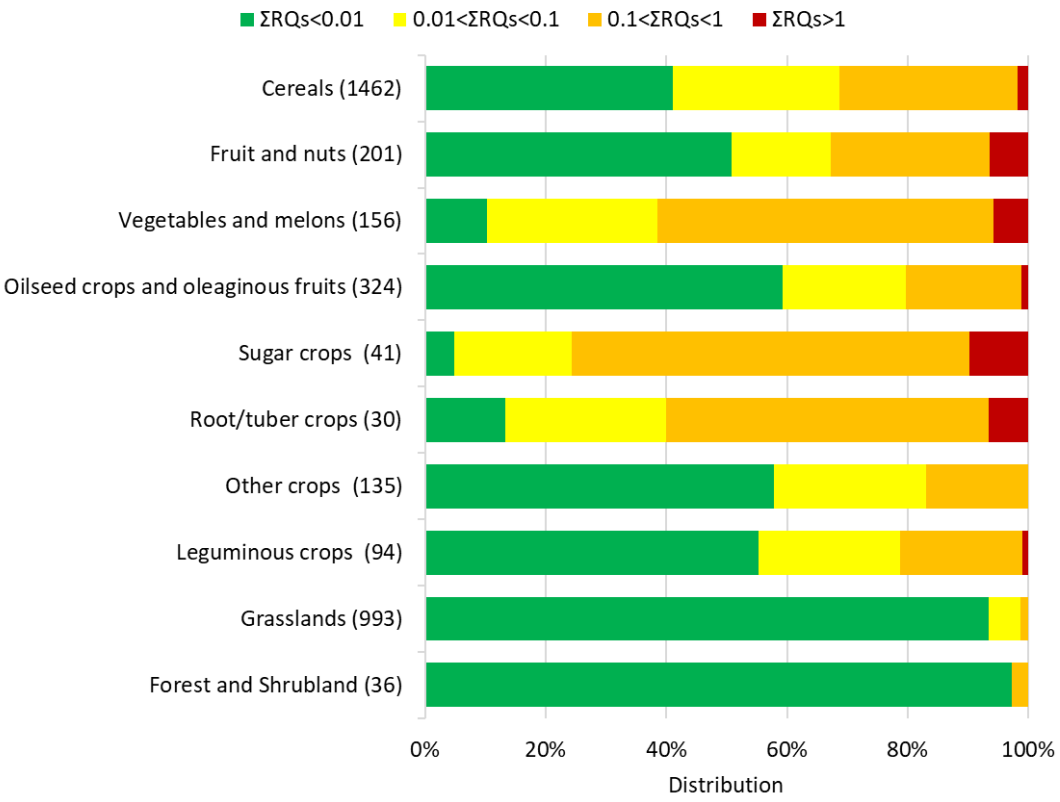


Source: Joint Research Centre.

When aggregated by crop types (**Figure 19**), higher soil risks occur in sugar crops, followed by vegetables and melons, root/tuber crops and fruits and nuts. Cereals, being the most abundant crop type surveyed (n=1462 sites), have the highest number of sites with sum of RQ > 1 in absolute terms, though the percentage of exceedances reflect a median risk scenario. As expected risks are lowest in grassland sites and in forest and scrubland.

In cereal crops, the risk is driven by both insecticides and fungicides. In fruits and nuts and in vegetables and melons, insecticides are the main toxicity driver, whereas fungicides drive the risk in sugar crops, oilseed crops and oleaginous fruits, root/tuber crops and potatoes.

Figure 19 – Soil risk indicator distribution by crop types (FAO) in the EU.



Source: Joint Research Centre.

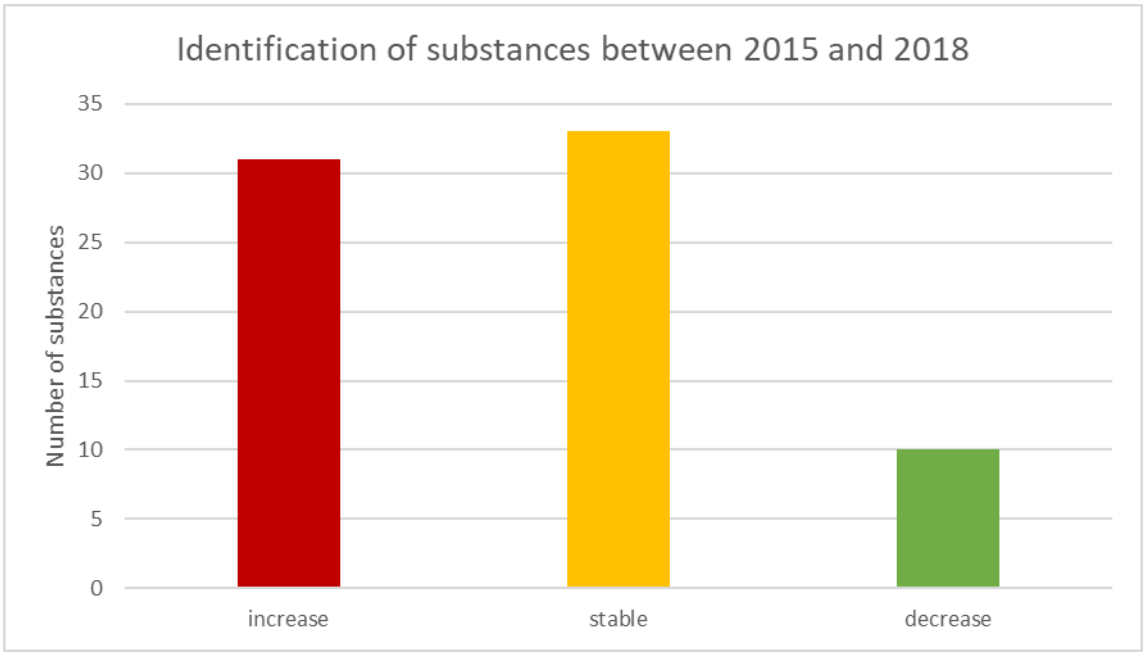
4 Discussion

4.1 Comparison with previous assessments

All substances monitored in the pilot study held in 2015 (Silva et al., 2019) were covered in the LUCAS 2018 soil module (Annex 2). The overlap of sampling sites is however limited to 73 sites. The sampling design including the time range of sampling was equivalent in both surveys, and carried out by the same laboratory. For this combination of substances and site, it was thus possible to compare results.

When comparing the results obtained in 2018 with the ones of 2015, it was possible to observe a substantial increase in incidence for 42% of the substances analysed, i.e. number of positive identifications in each soil sample, while only 14% of the substances revealed a decrease (**Figure 20**). Nevertheless, in what concerns the pesticide content, for every point with positive identification for pesticide in both years was observed an average reduction of 0.018 mg Kg^{-1}.

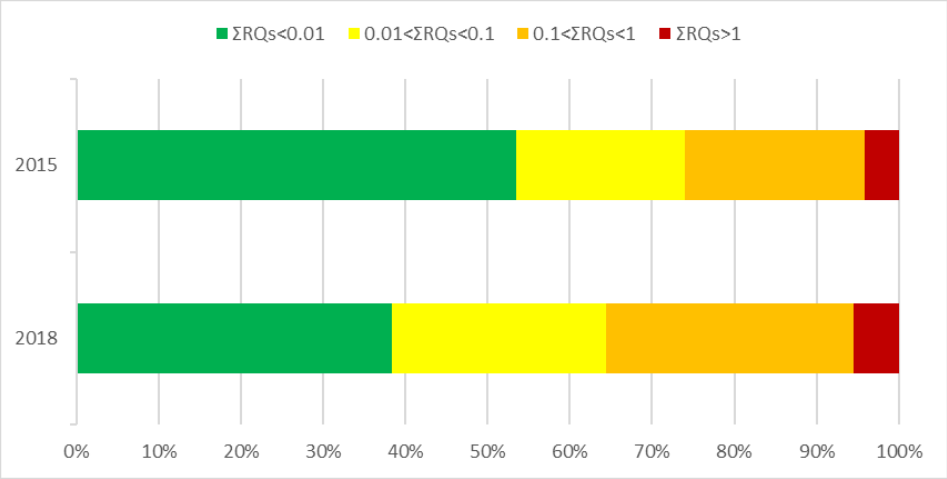
Figure 20 – Balance in the identification of active ingredients when comparing the 2015 pilot with the latest 2018 assessment, considering 73 common LUCAS points and 74 individual active ingredients (Annex 2.).



Source: Joint Research Centre.

A slight increase is also observed in the soil risk indicators (**Figure 21**). Although limited in scope, these results suggest no progress towards reduced pesticide risk levels between 2015 and 2018. The changes between 2015 and 2018 are not due to analytical improvements.

Figure 21 – Comparison of soil risk indicator, Σ(RQs) = Σ(C_{soil} / $NOEC_{soil,min}$), calculated for the same combination of substances and sites monitored in 2015 and 2018.



Source: Joint Research Centre.

The results of this study are difficult to compare with the other assessment on the pesticide residues in rivers, lakes and groundwater in Europe developed by EEA, for the 2013-2020 period (EEA, 2022). This report highlights a mean of 11-32% of exceedances for individual water bodies where one or more pesticides residues above threshold were detected, whereas no temporal trends were possible to be determined. This report also evidences difficulties assessing impacts since the application of pesticides may vary considerably between years, land cover, and weather, in combination with monitoring frequency, and methodological limitations.

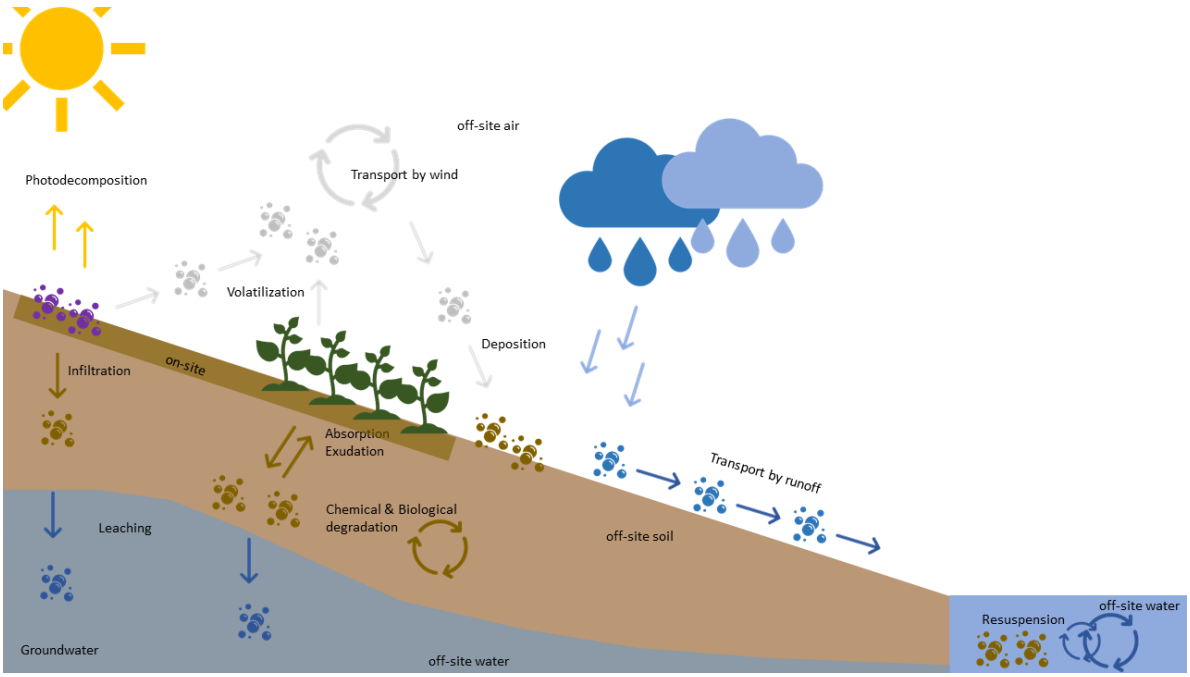
On the other hand, an EU modelling exercise performed for pesticides residues in stream networks (Pistocchi et al., 2023), provides similar proportions of EU stream sites at risk (Σ(RQs) >1 in >4% sites and about 30% exceeding 0.1 based on aquatic NOECs) throughout different countries. This shows some consistency in results with different methodologies, and more importantly, between soil and water media at similar scales. The comparison of the most frequent risk contributors identified in the present study with those found in the EU stream modelling work shows several commonalities (e.g. chlorpyriphos, imidachloprid, dimoxystrobin, boscalid) but also notable differences (Figure 3 in Pistocchi et al., 2023). Synthetic pyrethroids (i.e. deltamethrin, cypermethrin) are prominent risk contributors in EU streams but do not feature as such in the present study. The opposite can be concluded for some of the azole fungicides (e.g. epoxiconazole). Differences can be at least partly explained different emission and exposure profiles of substances between soil and streams and by differences in toxicity profiles between terrestrial and aquatic species.

4.2 Potential impact on soils

The impact of pesticides use in biodiversity has been one of the main concerns raised by the scientific community (Beaumelle et al., 2023, Sabzevari & Hofman, 2022, Aktar et al., 2009). With concerning claims that only a small portion (0.1%) of such chemicals targets the desired organisms (Pimentel, 1995), and the remaining are dispersed through the different environmental media (**Figure 22**) by transport, volatilization, wind erosion, surface runoff, leaching, and dispersion of sprayed pesticides (Didoné et al., 2021; Pérez et al., 2018; Villanneau et al., 2011).

The striking evidence that pesticide exposure negatively impacts soil invertebrates, has been identified in 70.5% of 2,842 tested parameters from 394 reviewed studies (Gunstone et al., 2021). The same study highlighted that pesticides of all types pose a clear hazard to soil invertebrates, with evident negative effects in both lab and field studies, across all studied pesticide classes, and in a wide variety of soil organisms and endpoints. Additionally, a recent meta-analysis assessing the pesticides effect on soil fauna of 54 studies and 294 observations (Beaumelle et al., 2023), verified that pesticides decrease abundance and diversity in soil fauna, with stronger effects on the latter. Moreover, the most harmful cases correspond to mixtures, broad-spectrum substances and insecticides which significantly decreased soil fauna diversity even at recommended rates.

Figure 22 – Scheme of the main degradation and transport processes associated to pesticide residues in soils.



Source: Joint Research Centre.

The result in loss of soil biodiversity and biomass, may also trigger a cascade effect leading to a decrease in organic matter and changes in nutrient inputs and cycling, affecting the productivity especially in croplands, leading to the overall loss of soil ecosystem services provision. Polluted soils, as the case of pesticides, can become a source of pollution for groundwater by leaching contaminants, and for fresh water and the marine environment, by transporting contaminants through wind and water erosion. As a result, ecosystems services provided such as water quality

provision ca be greatly impacted (Li and Fantke, 2022), and when these are combined with inadequate soil management practices, further pollutant dispersion can occur (Didoné et al., 2021).

So far, the results of this study provide an overall view of the extent of the diffuse pollution associated with pesticides use with focus on local (on-site) impacts. However, further studies are required combining on- and off-site impacts from pesticides at EU scale, across media (air, water and soil), and considering the interactions between mixtures of pesticides with other pollutants. Understanding the mechanism behind the transport of pesticides through air, water and soil is therefore fundamental to determine their concentration in receiving media (**Figure 22**), and the respective impact assessment. The mobilization potential of pesticides residues is function of the application rates and timing, biological and chemical degradation, vegetation cover, and climate dynamics following application. Given the uncertainties on the timing and active ingredients application, model simulations could be of assistance to provide spatiotemporal information on sediment and chemical transport by water and air.

4.3 Uncertainties

Despite the reduced sample size, the results from this report evidence a significant dissemination and extent on the use of pesticides within EU agricultural land. The high incidence of some of the samples indicates that the use of mixtures is also present in most of the investigated sites. Notwithstanding, there are several limitations on the method that can change the interpretation of these results.

Pesticides application and sampling timing – The sampling and analysis of pesticide residues was performed within the LUCAS survey protocol, which is not optimized for pesticides assessment neither consider the potential interference of land management operations. This is of relevance especially when addressing concentrations levels, since the analysis of such samples might be influenced by several anthropogenic or climatic variables (Sabzevari and Hofman, 2022, Bento et al., 2016). The application of pesticides or soil mobilization immediately before the sampling can potentially increase the concentration levels, while climatic variables such as high rainfall and temperatures preceding the sampling can dilute and reduce the pesticide residues concentrations.

Number and type of pesticide residues analysed – Currently more than 450 active substances are approved and available for application by 2018 (Eurostat, 2021) in the EU. However, in this study case, only 118 pesticides residues were assessed, with a greater focus given to substances presenting longer half-life, and not particularly for short-time and high-toxic impacts due to the unlikeliness of determining a representative extent of such substances. Notwithstanding, the investigation of additional active substances would likely increase these figures.

In what concerns the analysis of substances that have been banned by the Regulation 1107/2009, this work evidenced that the assessment of background pollution is important in order to follow up the efficiency of policies. However, this work does not allow to understand if the sources of pollution for banned and non-approved substances are originated by past applications, if they correspond to recent applications of substances that have been stored previous to the ban, or if such have been acquired outside the EU space.

Crop and climate diversity – The application of pesticides follow closely crop and land management needs, which in turn are highly influenced by climate. In this specific study case, our sampling resulted from more than 39 distinct crop profiles and highly variable climate dynamics within the EU space (**Figure 14**,**Figure 15**), increasing the complexity of the current analysis. The knowledge of general pesticide application periods for individual countries could already provide a significant help disentangling and understanding some of the figures obtained in this report, as also could provide further optimization of future sampling timings in order to optimize such assessment of pesticides residues in EU soils.

Furthermore, and following the LUCAS cover classification comparison against crop information from IACS data, further details about crop identification and their management would be useful to understand when assessing pesticides in non-targeted areas (e.g. grasslands). Thus, this could clarify if the observed pesticides residues concentrations correspond to recent local applications, if they could have been transported by water from nearby upstream areas, or if such result corresponds to background pollution from previous crop and land management.

Single annual sampling – Following the previously highlighted points, and given the variability in pesticides use, crops and climate dynamics, it is important to highlight that a single sampling in time might underrepresent the entire annual dynamics of pesticides residues in soils. Multiple sampling times in a year (eg. seasonal) could provide important insight on the periods in which some pesticides residues might be of greater concern and evaluate if the half-life of some substances follows the reference of literature, or if in reality their effects persist for longer than expected.

Therefore, such limitations were considered when analysing pesticides residues concentrations for this pilot study, and when developing recommendations to tackle such issues in the future.

4.4 Future projections on pesticides use and soil protection laws

The proposed Soil health law in the EU (EC, 2021) is expected to provide a basis for a more detailed assessment of soil health condition, especially in relation to soil contamination. The assessment of pesticides residues in soils should be made in parallel with other substances typically considered for diffuse pollution in soils such as heavy metals, pharmaceuticals, and - among others - micro plastics. Considering that these substances are a result of soil management practices, especially in agricultural lands, a shift towards more sustainable soil management practices pushed from the soil health law will expectably reduce soil contamination from all sources of pollutants.

Moreover, in relation to pesticides use alone, ongoing discussions on the Regulation on the Sustainable Use of Plant Protection Products (EC, 2023d) are expected to result in ambitious reductions on the use and risk of chemical pesticides by 2030, in line with the European Farm to Fork and Biodiversity strategies. The contribution of this study can bring light into the ongoing discussions, by providing the baseline, trends and ecotoxicological indicators.

However, the efficiency of present and future policies can only be properly assessed based on soil health monitoring and a quantification of the chemical releases to the environment.

5 Where do we stand

The results of this study highlight that pesticides residues are present in the majority (74.5%) of the soils assessed in the LUCAS 2018 survey. Moreover, and despite the highly regulated character of these substances, this study was able identify several substances in soil, that either have been banned prior to 2018, or never have been approved for sales according to the Regulation 1107/2009. Suggesting that, the Regulation 1107/2009 alone does not prevent soil contamination by pesticides residues pathways, the half-life of several pesticides residues might be longer than what was reported at the time of authorization, and that a more accurate control is required for the protection of soils and the habitats depending on soil health.

In addition, and despite the uncertainties, the development of an **ecotoxicological indicator for soil** contamination by pesticides can provide a practical way to assess risks to soil biodiversity which have been targeted as a very important pillar in the European Green Deal. This indicator used for soils corresponds to a first approach for a small number of organisms, whereas the integration of data relating pesticides residues and their impact in a wider number of species would benefit the robustness of the indicator and reduce the uncertainties thereof. However, thanks to this indicator was possible to assess that an increase in incidence of pesticides residues from 2015- to 2018 in fact reflected in an increase in the risk for soil organisms. Evidencing also its potential to assess the progress of EU policies towards the ambitions set by the Zero Pollution Action plan, Biodiversity, and Soil Strategy.

A more thorough quantification of the pesticide released to the environment is still required. Knowledge about active substances used, time of application, and rate are essential to reduce uncertainties on the current assessment, as also for the estimation of the ecotoxicological risk of such substances in the EU soils. Therefore, we suggest to increase this assessment from 3,473 soil samples in the EU to the total extent of LUCAS points for 2022 (~40,000), to increase the number of active substances under analysis, but also promote a better interaction with countries in order to understand key management practices to reduce uncertainties. The meaningful exchanges with IACS data in this context revealed to be the ideal platform for such purpose, especially considering the future ambitions from Common Agriculture Policy (CAP) Strategic Plans (EC, 2023e), to make a significant contribution to the ambitions of the European Green Deal, Farm to Fork Strategy and Biodiversity Strategy.

Soil pollution by pesticides is just one pathway for which pollutants can enter the soil. Despite the unprecedented contribution from the LUCAS 2018 soil module for the understanding of the drivers of soil pollution in the EU, the interaction between pesticides, mixtures of pesticides, soil constituents, and other soil pollutants needs to be further assessed. In this study we used an additive impact (Martin et al., 2021) by the different substances focused mostly on the incidence and in the ecotoxicological impact. However, Yang et al. (2017) and Hoesel et al. (2017) evidenced several harmful interactions for mixtures of pesticides residues, while Mishra et al. (2022) and Sun et al. (2021) evidenced a significantly enhanced the oxidative stress due to a combined effect from pesticides and microplastics. Therefore, in the end should be considered that environmental exposure to – pesticide - mixtures is the rule and not the exception (Gunstone et al., 2021; Silva et al., 2019), and that our current understanding of the response of soil biota to pesticide mixtures, and with other pollutants, is still inadequate (Tang and Maggi, 2021, Sun et al., 2021).

6 Conclusions & Recommendations

This study on the characterization and extent of pesticide residues originated from the LUCAS 2018 soil module on European agricultural soils, allowed to delineate the following conclusions:

- Pesticide use and residues in soils are widespread in the European agricultural soils (74.5%).
- Most of the assessed sites (57.1%) present mixtures of pesticides, and less often (11.1%) more than 10 different substances identified in a single site.
- An ecotoxicological mixture risk indicator of for soil organisms was developed, identifying sites at risk (1.7%, 59 sites), converging with other recent assessment on water.
- Comparison with past assessments under the same LUCAS points indicate higher incidence of pesticides residues, and an increased toxicity risk in 2018 when compared to 2015.
- Regulations on the sales of Pesticides, could not prevent the presence of banned and non-approved substances in EU soils.
- An increase in the number of active substances under study would likely increase these figures.

This study also allowed to delineate the following suggestions:

- A better understanding of the risk and extent of soil pollution from pesticides residues in EU soils is still required. We suggest to extend this analysis to screen all current LUCAS survey points and future assessments, and also to promote knowledge exchange with countries (e.g. IACS) in order to reduce current and future uncertainties.
- Several uncertainties regarding the methodologies used for this study were identified. We suggest to increase the number of active substances under analysis but also the frequency of soil sampling monitoring to seasonal intervals.
- The ecotoxicological risk indicator provides a complementary assessment of pesticides risk and can be used for assessing the progress of EU policies. However, its scope is limited to soil species that are tested for ecotoxicity under existing regulatory data requirements. A broader taxonomic representation would be needed to explore impacts on biodiversity.
- Increasing the understanding of transport and fate of pesticides in soil can be improved through modelling technologies. We recommend the use of simulations in order to anticipate the impacts of future policies, and also support pesticide users for a more efficient and sustainable use of these substances.

The current study brought by the EU Soil Observatory and LUCAS 2018 soil module provides a significant contribution to the status of current knowledge on soil pollution in the EU. The insights provided in this report may help identifying target policies in creating a toxic-free environment.

References

Abbasi, Y.; Mannaerts, C.M.; Makau, W. Modeling Pesticide and Sediment Transport in the Malewa River Basin (Kenya) Using SWAT. Water 2019, 11, 87. https://doi.org/10.3390/w11010087

Anastassiades, M., Lehotay, S.J., Štajnbaher, D., Schenck, F.J., 2003. Fast and Easy Multiresidue Method Employing Acetonitrile Extraction/Partitioning and "Dispersive Solid-Phase Extraction" for the Determination of Pesticide Residues in Produce, Journal of AOAC INTERNATIONAL, Volume 86, Issue 2, 1 March 2003, Pages 412–431, https://doi.org/10.1093/jaoac/86.2.412

Agriculture and Environment Research Unit (AERU), 2023. The University of Heartfordshire Pesticides Properties Database (PPDB). http://sitem.herts.ac.uk/aeru/ppdb/ (Accessed on 19-05-2023)

Benfenati, E., Manganaro, A., & Gini, G. C., 2013. VEGA-QSAR: AI inside a platform for predictive toxicology. *PAI@ AI* IA*, *1107*, 21-28. https://dblp.org/rec/conf/aiia/BenfenatiMG13.html

Bento, C.P.M., Yang, X., Gort, G., Xue, S., van Dam, R., Zomer, P., Mol, H.G.J., Ritsema, C.J., Geissen,V. 2016. Persistence of glyphosate and aminomethylphosphonic acid in loess soil under different combinations of temperature, soil moisture and light/darkness, Science of The Total Environment, 572. https://doi.org/10.1016/j.scitotenv.2016.07.215

van Bruggen AHC, Finckh MR, He M, Ritsema CJ, Harkes P, Knuth D and Geissen V (2021) Indirect Effects of the Herbicide Glyphosate on Plant, Animal and Human Health Through its Effects on Microbial Communities. Front. Environ. Sci. 9:763917. https://doi.org/10.3389/fenvs.2021.763917

Copernicus Climate Change Service (Copernicus), Climate Data Store, (2020): E-OBS daily gridded meteorological data for Europe from 1950 to present derived from in-situ observations. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.151d3ec6 (Accessed on 30-03-2022).

Cornes, R., van der Schrier, G., van den Besselaar, E.J.M., Jones, P., 2018: An Ensemble Version of the E-OBS Temperature and Precipitation Datasets, J. Geophys. Res. Atmos., 123. https://doi.org/10.1029/2017JD028200

Didoné, E.J., Minella, J.P.G., Tiecher, T. et al., 2021. Mobilization and transport of pesticides with runoff and suspended sediment during flooding events in an agricultural catchment of Southern Brazil. Environ Sci Pollut Res 28, 39370–39386. https://doi.org/10.1007/s11356-021-13303-z

Directive 2000/60. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. http://data.europa.eu/eli/dir/2000/60/2014-11-20

Directive 2006/118. Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. http://data.europa.eu/eli/dir/2006/118/oj

Directive 2009/128. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides. http://data.europa.eu/eli/dir/2009/128/2019-07-26

European Commission (EC), 2021. Soil health. https://environment.ec.europa.eu/topics/soil-and-land/soil-health_en (Accessed on 12-06-2023).

European Commission (EC), 2023a. EU Pesticides Database. https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/start/screen/active-substances (Accessed on 16-05-2023).

European Commission (EC), 2023b. A European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (Accessed on 19-05-2023).

European Commission (EC), 2023c. Member State Geoportals (including some IACS data). https://agridata.ec.europa.eu/extensions/iacs/iacs.html (Accessed on 19-05-2023).

European Commission (EC), 2023d. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the sustainable use of plant protection products and amending Regulation (EU) 2021/2115. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0305

European Commission (EC), 2023e. The common agricultural policy: 2023-27. https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27_en (Accessed on 19-05-2023).

European Environment Agency (EEA), 2022. Pesticides in rivers, lakes and groundwater in Europe. https://www.eea.europa.eu/ims/pesticides-in-rivers-lakes-and

European Food Safety Authority (EFSA), 2021. Carrasco Cabrera, L and Medina Pastor, P, 2021. The 2019 European Union report on pesticide residues in food. EFSA Journal 2021;19(4):6491, 89 pp. https://doi.org/10.2903/j.efsa.2021.6491

European Food Safety Authority (EFSA), 2022. Chemical Hazards Database (OpenFoodTox). https://doi.org/10.5281/zenodo.780543

European Food Safety Authority (EFSA), 2023. Guidelines on Active Substances and Plant Protection Products. (Accessed on 16-05-2023). https://food.ec.europa.eu/plants/pesticides/approval-active-substances/guidelines-active-substances-and-plant-protection-products_en

United States Environmental Protection Agency (EPA), 2023. US EPA Ecotox database.. https://cfpub.epa.gov/ecotox/ (Accessed on 19-05-2023)

Eurostat, 2021. Pesticide sales [aei_fm_salpest09]. https://ec.europa.eu/eurostat/web/products-datasets/-/aei_fm_salpest09 (Extracted 16-12--/2021).

Food and Agriculture Organization of the United Nations (FAO), 2014. The International Code of Conduct on Pesticide Management. https://www.fao.org/3/I3604E/i3604e.pdf (Accessed on 18-01-2022)

Frampton G. K., Jänsch S., Scott-Fordsmand J. J., Römbke J., van den Brink P. J. 2009. Effects of pesticides on soil invertebrates in laboratory studies: A review and analysis using species sensitivity distributions. Environ. Toxicol. 25(9), 2480-2489. https://setac.onlinelibrary.wiley.com/doi/10.1897/05-438R.1.

Franco A., Vieira D., Orgiazzi A., Labouyrie M., Koeninger J., Silva V., van Dam R., Dorne J.C.M., Carnesecchi E., Vuaille J., Vicente J.L., Jones A. 2023. Evaluation of the ecological risk of pesticides residues investigated in the European LUCAS soil monitoring 2018 survey. *Under preparation.*

Geissen, V., Silva, V., Lwanga, E. H., Beriot, N., Oostindie, K., Bin, Z., et al., 2021. Cocktails of pesticide residues in conventional and organic farming systems in Europe - Legacy of the past and turning point for the future. Environ. Pollut. 278, 116827. https://doi.org/10.1016/j.envpol.2021.116827

Guidance SANTE/12682. Guidance SANTE/12682/2019 – Guidance document on analytical quality control and method validation procedures for pesticides residues analysis in food and feed. https://www.eurl-pesticides.eu/docs/public/tmplt_article.asp?CntID=727

Gunstone T, Cornelisse T, Klein K, Dubey A and Donley N, 2021. Pesticides and Soil Invertebrates: A Hazard Assessment. Front. Environ. Sci. 9:643847. https://doi.org/10.3389/fenvs.2021.643847

van Hoesel W, Tiefenbacher A, König N, Dorn VM, Hagenguth JF, Prah U, Widhalm T, Wiklicky V, Koller R, Bonkowski M, Lagerlöf J, Ratzenböck A and Zaller JG, 2017. Single and Combined Effects of Pesticide Seed Dressings and Herbicides on Earthworms, Soil Microorganisms, and Litter Decomposition. Front. Plant Sci. 8:215. https://doi.org/10.3389/fpls.2017.00215

Li Z., and Fantke P. 2022. Toward harmonizing global pesticide regulations for surface freshwaters in support of protecting human health, Journal of Environmental Management, 113909. https://doi.org/10.1016/j.jenvman.2021.113909

Martin O., Scholze M., Ermler S., McPhie J., Bopp S.K., Kienzler A., Parissis N., Kortenkamp A., 2021. Ten years of research on synergisms and antagonisms in chemical mixtures: A systematic review and quantitative reappraisal of mixture studies, Environment International, 146, 106206. https://doi.org/10.1016/j.envint.2020.106206

Mishra, C.S.K.; Samal, S.; Samal, R.R.; Behera, B.P.; Pallavini, P.; Dash, P.; Brahma, S.; Moharana, T.; Pradhan, S.; Acharya, P., 2022. Polyvinylchloride and polypropylene as adsorbents of the pesticide monocrotophos enhance oxidative stress in Eudrillus eugeniae (Kinberg). Chemosphere 2022, 259, 133837. https://doi.org/10.1016/j.chemosphere.2022.133837

Mol, H.G., Plaza-Bolaños, P., Zomer, P., de Rijk, T.C., Stolker, A.A., Mulder, P.P., 2008. Toward a generic extraction method for simultaneous determination of pesticides, mycotoxins, plant toxins, and veterinary drugs in feed and food matrixes. Anal Chem. 15;80(24):9450-9. https://doi.org/10.1021/ac801557f

Mottes, C., Sabatier, P., Evrard, O. et al. Pesticide resurrection. Environ Chem Lett 20, 3357–3362 (2022). https://doi.org/10.1007/s10311-021-01347-z

Organisation for Economic Co-operation and Development (OECD), 2023. eChemPortal. https://www.echemportal.org/echemportal/ (Accessed on 19-05-2023)

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A. and Fernández-Ugalde, O. (2018), LUCAS Soil, the largest expandable soil dataset for Europe: a review. Eur J Soil Sci, 69: 140-153. https://doi.org/10.1111/ejss.12499

Pistocchi A, Dorati C, Galimberti F, Udias A, Bopp S, D'Andrimont R, Catarino R and Schaefer RB (2023) A screening study of the spatial distribution and cumulative toxicity of agricultural pesticides in the European Union's waters. Front. Environ. Sci. 11:1101316. https://doi.org/10.3389/fenvs.2023.1101316

Regulation 528/2012. Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products. http://data.europa.eu/eli/reg/2012/528/oj

Regulation 1107/2009. Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC

Sabzevari, S., Hofman, J., 2021. A worldwide review of currently used pesticides' monitoring in agricultural soils. Scie Total Environ 812, 15234. https://doi.org/10.1016/j.scitotenv.2021.152344

Secretariat of the Rotterdam Convention (SRC), 2019. ROTTERDAM CONVENTION. On the prior informed consent procedure for certain hazardous chemicals and pesticides in International trade. http://www.pic.int/Portals/5/download.aspx?d=UNEP-FAO-RC-CONVTEXT-2019.English.pdf

Silva, V., Montanarella, L., Jones, A., Fernández-Ugalde, O., Mol, H. G. J., Ritsema, C. J., et al., 2018. Distribution of glyphosate and aminomethylphosphonic acid (AMPA) in agricultural topsoils of the European Union. Sci. Total Environ. 621, 1352–1359. https://doi.org/10.1016/j.scitotenv.2017.10.093

Silva, V., Mol, H.G.J., Zomer, P., Tienstra, M., Ritsema, C.J., Geissen, V., 2019. Pesticide residues in european agricultural soils - a hidden reality unfolded. Sci. Total Environ. 653,1532–1545. https://doi.org/10.1016/j.scitotenv.2018.10.441

Silva V, Alaoui A, Schlünssen V, Vested A, Graumans M, van Dael M, et al., 2021. Collection of human and environmental data on pesticide use in Europe and Argentina: Field study protocol for the SPRINT project. PLoS ONE 16(11): e0259748. https://doi.org/10.1371/journal.pone.0259748

Sun, W.; Meng, Z.Y.; Li, R.S.; Zhang, R.K.; Jia, M.; Yan, S.; Tian, S.N.; Zhou, Z.Q.; Zhu, W.T. Joint effects of microplastic and dufulin on bioaccumulation, oxidative stress and metabolic profile of the earthworm (Eisenia fetida). Chemosphere 2021, 263, 128171. https://doi.org/10.1016/j.chemosphere.2020.128171

Tang F.H.M., and Maggi F., 2021. Pesticide mixtures in soil: a global outlook. Environ. Res. Lett. 16 044051. https://doi.org/10.1088/1748-9326/abe5d6

United Nations (UN), Department of Economic and Social Affairs, Population Division, 2019a. World Population Prospects 2019: Highlights (ST/ESA/SER.A/423). https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf

Yang G, Chen C, Wang Y, Peng Q, Zhao H, Guo D, Wang Q and Qian Y 2017 Mixture toxicity of four commonly used pesticides at different effect levels to the epigeic earthworm, Eisenia fetida Ecotoxicol. Environ. Saf. 142 29–39. https://doi.org/10.1016/j.ecoenv.2017.03.037

List of abbreviations and definitions

Active ingredients - Chemical, plant extract, pheromone or micro-organism (including viruses), that have an action against 'pests' or on plants, parts of plants or plant products.

Biocides - Chemical substance or microorganism intended to destroy, deter, render harmless, or exert a controlling effect on any harmful organism.

Content – maximum individual pesticide content determined in a soil sample, reflecting the order of magnitude of concentrations, distributed by class (<LOQ, LOQ-0.05 mg Kg^{-1}, 0.05-0.15 mg Kg^{-1}, 0.15-0.50 mg Kg^{-1}, 0.5^{-1} mg Kg^{-1}, >1 mg Kg^{-1}).

Incidence – the number of substances found in each soil sample, reflecting the variability of substances found within each site, distributed by class (no substance, 1 substance, 2-5 substances, 5-10 substances , >10 substances);

Metabolites - Intermediate or end products of biochemical reactions.

Pesticides - Substances that prevent, destroy, or control harmful organisms ('pest') or disease, or protect plants or plant products during production, storage and transport. They include herbicides, fungicides, insecticides, acaricides, nematicides, molluscicides, growth regulators, repellents, rodenticides and biocides (EU). For the purpose of this report, only pesticides applied to agricultural crops are discussed.

Pesticides residue - Substance or mixture of substances in or on food, agricultural and other types of commodities or animal feed as well as in environmental media including soil, air and water resulting from the use of a pesticide. The term includes any derivatives of a pesticide, such as conversion products, metabolites, breakdown products, reaction products and impurities considered to be of toxicological or ecotoxicological significance. The term includes residues from unknown or unavoidable sources (e.g. environmental contamination) as well as known, authorized uses of the chemical.

Plant protection products (PPP) - Chemical substances that are used to protect, preserve or influence the growth of desirable plants or to destroy or control the growth of unwanted plants or parts of plants. They include herbicides, fungicides, insecticides, acaricides, plant growth regulators, and repellents.

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Annex 1. FAO crop types and LUCAS land cover equivalence

FAO class	LUCAS LC1 class
Cereals	Barley
	Maize
	Oats
	Other cereals
	Mix of cereals
	Lucerne
	Rice
	Rye
	Triticale
	Common wheat
	Durum wheat
Vegetables and melons	Other root crops
	Other fresh vegetables
	Tomatoes
	Rape and turnip rape
Fruit and nuts	Apple fruit
	Strawberries
	Other fruit trees and berries
	Vineyards
	Nuts trees
	Oranges
	Cherry fruit
	Other citrus fruit
	Pear fruit
	Strawberries
Oilseed crops and oleaginous fruits	Olive groves
	Other fibre and oleaginous crops
	Soya
	Sunflower
Root/tuber crops with high starch or inulin content	Potatoes
Leguminous crops	Dry pulses
	Other Leguminous and mixtures for fodder
Sugar crops	Sugar beet
Other crops	Cotton
	Floriculture and ornamental plants
	Clovers
	Other non-permanent industrial crops
	Nurseries
	Permanent industrial crops
	Temporary crops (photointerpreted)
	Temporary grassland
	Tobacco

Annex 2. Ecotoxicological data complied for LUCAS 2018 pesticides and used for risk calculations: No Observed Effect Concentrations (NOEC) reported for soil dwelling organisms.

Substance	CAS	Species	Soil NOEC [mg/kg]	Source
2,4-DB	94826	Eisenia foetida	82.1	EFSA OpenFoodTox
Abamectin*	71751412	Eisenia foetida	0.72	PPDB
		Folsomia fimetaria	0.25	EPA ECOTOX
		Folsomia candida	0.25	EPA ECOTOX
		Eisenia foetida	0.25	EPA ECOTOX
		Folsomia fimetaria	0.5	EPA ECOTOX
		Folsomia candida	0.81	EPA ECOTOX
		Enchytraeus crypticus	0.81	EPA ECOTOX
		Eisenia andrei	0.88	EPA ECOTOX
		Eisenia andrei	1.4	EPA ECOTOX
		Folsomia candida	1.5	EPA ECOTOX
		Folsomia candida	2.5	EPA ECOTOX
		Eisenia foetida	5	EPA ECOTOX
		Enchytraeus crypticus	8	EPA ECOTOX
		Eisenia andrei	9.8	EPA ECOTOX
		Enchytraeus crypticus	10	EPA ECOTOX
		Enchytraeus crypticus	50	EPA ECOTOX
Aldrin*	309002			
AMPA*	1066519	Eisenia foetida	198.1	Von Merey et al 2016
		Hypoaspis aculeifer	320	Von Merey et al 2016
		Folsomia candida	315	Von Merey et al 2016
Atrazine*	1912249	Enchytraeus albidus	1	EPA ECOTOX
		Folsomia candida	36	EPA ECOTOX
		Folsomia candida	105	EPA ECOTOX
Atrazine-deisopropyl*	1007289			
Atrazine-desethyl*	6190654			
Azoxystrobin*	131860338	Eisenia foetida	3	EFSA OpenFoodTox
		Eisenia andrei	50	EPA ECOTOX
Bentazone	25057890			
Bixafen	581809463	Eisenia foetida	100	PPDB
		Folsomia candida	7.74	PPDB
Boscalid*	188425856	Eisenia foetida	1.2	PPDB
Bromuconazole	116255482	Eisenia foetida	37.2	EFSA OpenFoodTox
		Eisenia foetida	18.6	PPDB
Carbaryl*	63252	Eisenia andrei	20	EPA ECOTOX
		Eisenia andrei	40	EPA ECOTOX
Carbendazim	10605217	Eisenia foetida	1	EFSA OpenFoodTox
		Enchytraeus albidus	0.1	EPA ECOTOX
		Eisenia andrei	0.1	EPA ECOTOX

Carbofuran*	1563662	Eisenia andrei	0.6	EPA ECOTOX
		Eisenia andrei	1	EPA ECOTOX
		Eisenia andrei	1.9	EPA ECOTOX
		Eisenia foetida	31.6	EPA ECOTOX
		Folsomia candida	0.21	EFSA OpenFoodTox
		Hypoaspis aculeifer	10.4	EFSA OpenFoodTox
		Eisenia foetida	0.84	EFSA OpenFoodTox
		Eisenia foetida	16.8	EFSA OpenFoodTox
		Perionyx excavatus	0.5	EPA ECOTOX
		Eisenia andrei	0.5	EPA ECOTOX
		Eisenia andrei	1	EPA ECOTOX
		Perionyx excavatus	2	EPA ECOTOX
Carbofuran, -3-hydroxy*	16655826			
Carbofuran, -keto*	16709301			
Chlordane cis- (alpha)	12789036			
Chlordane trans- (gamma)*	5103742			
Chlordecone*	143500			
Chlorfenvinphos*	470906			
Chloridazon	1698608			
Chlorpyrifos*	2921882	Eisenia foetida	12.7	PPDB
		Folsomia candida	0.065	EPA ECOTOX
		Perionyx excavatus	1	EPA ECOTOX
		Eisenia andrei	1	EPA ECOTOX
		Aporrectodea caliginosa	4	EPA ECOTOX
		Lumbricus rubellus	4.6	EPA ECOTOX
		Eisenia foetida	5	EPA ECOTOX
		Perionyx excavatus	10	EPA ECOTOX
		Eisenia foetida	20	EPA ECOTOX
		Lumbricus rubellus	46	EPA ECOTOX
		Eisenia foetida	60	EPA ECOTOX
		Lumbricus rubellus	83	EPA ECOTOX
		Eisenia andrei	100	EPA ECOTOX
		Lumbricus rubellus	150	EPA ECOTOX
		Lumbricus terrestris	270	EPA ECOTOX
		Aporrectodea longa	486	EPA ECOTOX
		Aporrectodea caliginosa	486	EPA ECOTOX
		Eisenia foetida	486	EPA ECOTOX
Chlorpyrifos-methyl	5598130	Eisenia foetida	12.5	PPDB
Clothianidin	210880925	Eisenia foetida	2.5	PPDB
		Eisenia foetida	0.256	EPA ECOTOX
		Eisenia foetida	0.52	EPA ECOTOX
		Eisenia foetida	0.98	EPA ECOTOX
Cymoxanil*	57966957	Eisenia foetida	6.6	EFSA OpenFoodTox

Cyproconazole*	94361065	Folsomia candida	55.8	EFSA OpenFoodTox
		Eisenia foetida	0.75	PPDB
Cyprodinil*	121552612			
DDD*	72548			
DDE*	72559			
DDT*	50293	Eisenia foetida	280	RIVM 2015
		Folsomia candida	176	RIVM 2015
Deltamethrin	52918635	Eisenia foetida	0.165	PPDB
		Folsomia candida	16	PPDB
Diazinon*	333415	Aporrectodea caliginosa	12	EPA ECOTOX
Dieldrin*	60571	Eisenia foetida	100	EPA ECOTOX
Difenoconazole*	119446683	Folsomia candida	500	EFSA OpenFoodTox
		Eisenia foetida	0.2	EFSA OpenFoodTox
Diflufenican	83164334	Eisenia foetida	1000	EFSA OpenFoodTox
		Folsomia candida	5000	PPDB
Dimethenamid	163515148	Eisenia foetida	10.56	EFSA OpenFoodTox
		Eisenia foetida	8.32	EFSA OpenFoodTox
		Folsomia candida	12.5	EFSA OpenFoodTox
		Eisenia foetida	25.4	EFSA OpenFoodTox
		Eisenia foetida	100	EFSA OpenFoodTox
Dimethomorph*	110488705	Eisenia foetida	60	PPDB
Dimoxystrobin	149961524	Eisenia foetida	0.089	PPDB
Diuron*	330541	Eisenia foetida	14.4	EFSA OpenFoodTox
		Eisenia foetida	15.78	PPDB
		Folsomia candida	22.35	PPDB
Endosulfan*	115297	Folsomia candida	10	EPA ECOTOX
		Heteromurus nitidus	0.1	EPA ECOTOX
		Heteromurus nitidus	0.1	EPA ECOTOX
		Heteromurus nitidus	0.1	EPA ECOTOX
Endrin*	72208			
Epoxiconazole*	133855988	Eisenia foetida	0.167	EFSA OpenFoodTox
		Eisenia foetida	0.084	PPDB
Ethion*	563122			
Fenbuconazole	114369436	Eisenia foetida	39	PPDB
		Folsomia candida	46.5	EFSA OpenFoodTox
Fenpropidin	67306007	Eisenia foetida	10	PPDB
		Folsomia candida	93	PPDB
Fenpropimorph*	67564914	Eisenia foetida	9.92	EFSA OpenFoodTox
		Folsomia candida	1.57	EFSA OpenFoodTox
Fluazinam	79622596	Eisenia andrei	0.35	EFSA OpenFoodTox
		Eisenia andrei	0.175	PPDB
		Folsomia candida	0.615	PPDB
Fludioxonil	131341861	Eisenia foetida	20	EFSA OpenFoodTox
		Folsomia candida	57.6	EFSA OpenFoodTox
		Folsomia candida	14.4	PPDB

Flufenacet	142459583	Folsomia candida	98.43	PPDB
Fluometuron*	2164172	Eisenia foetida	15	PPDB
		Folsomia candida	6.7	PPDB
Fluopicolide	239110157	Eisenia foetida	250	EFSA OpenFoodTox
		Folsomia candida	31.25	EFSA OpenFoodTox
Fluopyram	658066354	Eisenia foetida	62.5	EFSA OpenFoodTox
		Folsomia candida	103.8	EFSA OpenFoodTox
Fluoxastrobin	361377299	Eisenia foetida	11.42	EFSA OpenFoodTox
		Folsomia candida	5	EFSA OpenFoodTox
Fluquinconazole	136426545	Eisenia foetida	89	PPDB
		Eisenia foetida	0.5	EFSA OpenFoodTox
Fluroxypyr*	69377817	Folsomia candida	47	PPDB
Folpet*	133073	Eisenia foetida	3.05	EFSA OpenFoodTox
Glyphosate*	1071836	Eisenia foetida	5.18	EFSA OpenFoodTox
Heptachlor	76448	Folsomia candida	587	PPDB
Heptachlor endo epoxide (iso A)	28044839			
Heptachlor epoxide (iso B)	1024573			
Hexachlorobenzene*	118741			
hexachlorocyclohexane alpha-*	319846			
hexachlorocyclohexane beta-*	319857			
hexachlorocyclohexane gamma- (lindane)*	58899	Enchytraeus albidus	5.6	EPA ECOTOX
		Enchytraeus albidus	18	EPA ECOTOX
Imazalil*	35554440	Hypoaspis aculeifer	106.6	PPDB
Imazamox	114311329	Folsomia candida	500	EFSA OpenFoodTox
		Eisenia foetida	3.04	EFSA OpenFoodTox
Imidacloprid*	138261413	Eisenia foetida	5.85	PPDB
		Folsomia candida	4.74	PPDB
		Folsomia candida	0.06	EPA ECOTOX
		Folsomia candida	0.1	EPA ECOTOX
		Aporrectodea caliginosa	0.1	EPA ECOTOX
		Allolobophora icterica	0.1	EPA ECOTOX
		Eisenia andrei	0.12	EPA ECOTOX
		Eisenia andrei	0.125	EPA ECOTOX
		Eisenia foetida	0.15	EPA ECOTOX
		Eisenia foetida	0.25	EPA ECOTOX
		Eisenia andrei	0.37	EPA ECOTOX
		Eisenia foetida	0.745	EPA ECOTOX
		Eisenia andrei	0.75	EPA ECOTOX
		Heteromurus nitidus	1	EPA ECOTOX
		Eisenia andrei	5	EPA ECOTOX
		Folsomia candida	10	EPA ECOTOX

		Eisenia andrei	12.5	EPA ECOTOX
Indoxacarb	173584446	Folsomia candida	1	EFSA OpenFoodTox
Isoproturon*	34123596	Folsomia candida	24.3	EFSA OpenFoodTox
		Eisenia foetida	14	EFSA OpenFoodTox
Isoxaben	82558507	Eisenia foetida	1000	EFSA OpenFoodTox
		Eisenia foetida	3.34	PPDB
Lenacil	2164081	Eisenia foetida	1000	PPDB
Linuron*	330552	Hypoaspis aculeifer	3.388	EFSA OpenFoodTox
		Eisenia foetida	6.775	EFSA OpenFoodTox
		Eisenia foetida	6.78	PPDB
		Folsomia fcandida	57.06	PPDB
Malathion*	121755			
MCPA	94746			
Metalaxyl*	57837191	Eisenia foetida	40	PPDB
Metamitron*	41394052	Eisenia foetida	28	PPDB
		Folsomia candida	100	PPDB
Metconazole	125116236	Eisenia foetida	1.8	EFSA OpenFoodTox
		Folsomia candida	160	PPDB
Metolachlor	51218452			
Metrafenone	220899036	Eisenia foetida	3	EFSA OpenFoodTox
		Eisenia foetida	10.44	EFSA OpenFoodTox
		Eisenia foetida	50.89	PPDB
Myclobutanil*	88671890	Folsomia candida	37.5	PPDB
		Folsomia candida	20.5	EFSA OpenFoodTox
		Eisenia foetida	10.3	EFSA OpenFoodTox
Parathion*	56382	Eisenia andrei	10	EPA ECOTOX
		Eisenia andrei	18	EPA ECOTOX
		Eisenia andrei	32	EPA ECOTOX
		Eisenia andrei	56	EPA ECOTOX
Parathion-methyl*	298000			
Penconazole*	66246886	Folsomia candida	98.8	EFSA OpenFoodTox
Pendimethalin	40487421	Folsomia candida	193	EFSA OpenFoodTox
		Eisenia foetida	33.45	EFSA OpenFoodTox
		Folsomia candida	30	EPA ECOTOX
Penflufen	494793678	Folsomia candida	231	EFSA OpenFoodTox
		Eisenia foetida	33	EFSA OpenFoodTox
		Folsomia candida	493	PPDB
Pentachlorbenzene*	608935			
Penthiopyrad	183675823			
Phthalimide*	85416			
Pinoxaden*	243973208			
Pirimicarb	23103982	Eisenia foetida	5.46	PPDB
		Folsomia candida	33	PPDB
Pirimiphos-methyl*	29232937			
Prochloraz*	67747095	Folsomia candida	100	EFSA OpenFoodTox

		Eisenia foetida	8.4	EFSA OpenFoodTox
		Eisenia foetida	4.2	PPDB
Procymidone*	32809168			
Promethryn	7287196			
		Hypoaspis aculeifer	22.4	EFSA OpenFoodTox
Propiconazole*	60207901	Folsomia candida	25.4	PPDB
		Eisenia foetida	6.47	PPDB
Prosulfocarb	52888809			
Prothioconazole desthio*	120983644			
Pyraclostrobin*	175013180	Eisenia foetida	23.1	PPDB
Pyriofenone	688046619	Eisenia foetida	32	PPDB
Quinoxyfen*	124495187	Eisenia foetida	2.67	PPDB
Simazine*	122349			
		Hypoaspis aculeifer	50	EFSA OpenFoodTox
Tebuconazole*	107534963	Eisenia foetida	10	EFSA OpenFoodTox
		Folsomia candida	250	PPDB
		Folsomia candida	50	EPA ECOTOX
Terbuthylazine*	5915413	Folsomia candida	42.24	EFSA OpenFoodTox
Terbuthylazine-desethyl*	30125634			
Terbutryn	886500			
		Folsomia candida	25	EFSA OpenFoodTox
Thiabendazole	148798	Eisenia foetida	2.1	EFSA OpenFoodTox
		Eisenia foetida	4.2	PPDB
		Eisenia foetida	5.34	PPDB
		Folsomia candida	1	EPA ECOTOX
		Eisenia andrei	2.5	EPA ECOTOX
Thiamethoxam	153719234	Eisenia andrei	3.3	EPA ECOTOX
		Eisenia andrei	250	EPA ECOTOX
		Folsomia candida	500	EPA ECOTOX
		Eisenia andrei	1000	EPA ECOTOX
Thiophanate-methyl	23564058	Folsomia candida	100	EFSA OpenFoodTox
		Eisenia foetida	1.6	PPDB
Triadimenol*	55219653	Eisenia foetida	100	PPDB
		Eisenia foetida	27.24	EFSA OpenFoodTox
		Hypoaspis aculeifer	100	EFSA OpenFoodTox
Tri-allate	2303175	Folsomia candida	100	EFSA OpenFoodTox
		Eisenia foetida	50.75	EFSA OpenFoodTox
		Eisenia foetida	13.62	PPDB
Triclopyr	55335063	Eisenia foetida	9.6	EFSA OpenFoodTox
		Folsomia candida	249	EFSA OpenFoodTox
		Hypoaspis aculeifer	249	EFSA OpenFoodTox
Trifloxystrobin*	141517217	Eisenia foetida	3.5	EFSA OpenFoodTox
		Folsomia candida	50	EFSA OpenFoodTox
		Hypoaspis aculeifer	50	EFSA OpenFoodTox

Eisenia foetida	50	EFSA OpenFoodTox
Folsomia candida	10	EFSA OpenFoodTox
Hypoaspis aculeifer	100	EFSA OpenFoodTox
Eisenia foetida	100	EFSA OpenFoodTox
Folsomia candida	100	EFSA OpenFoodTox

* Substances analysed in LUCAS 2015 soil module

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