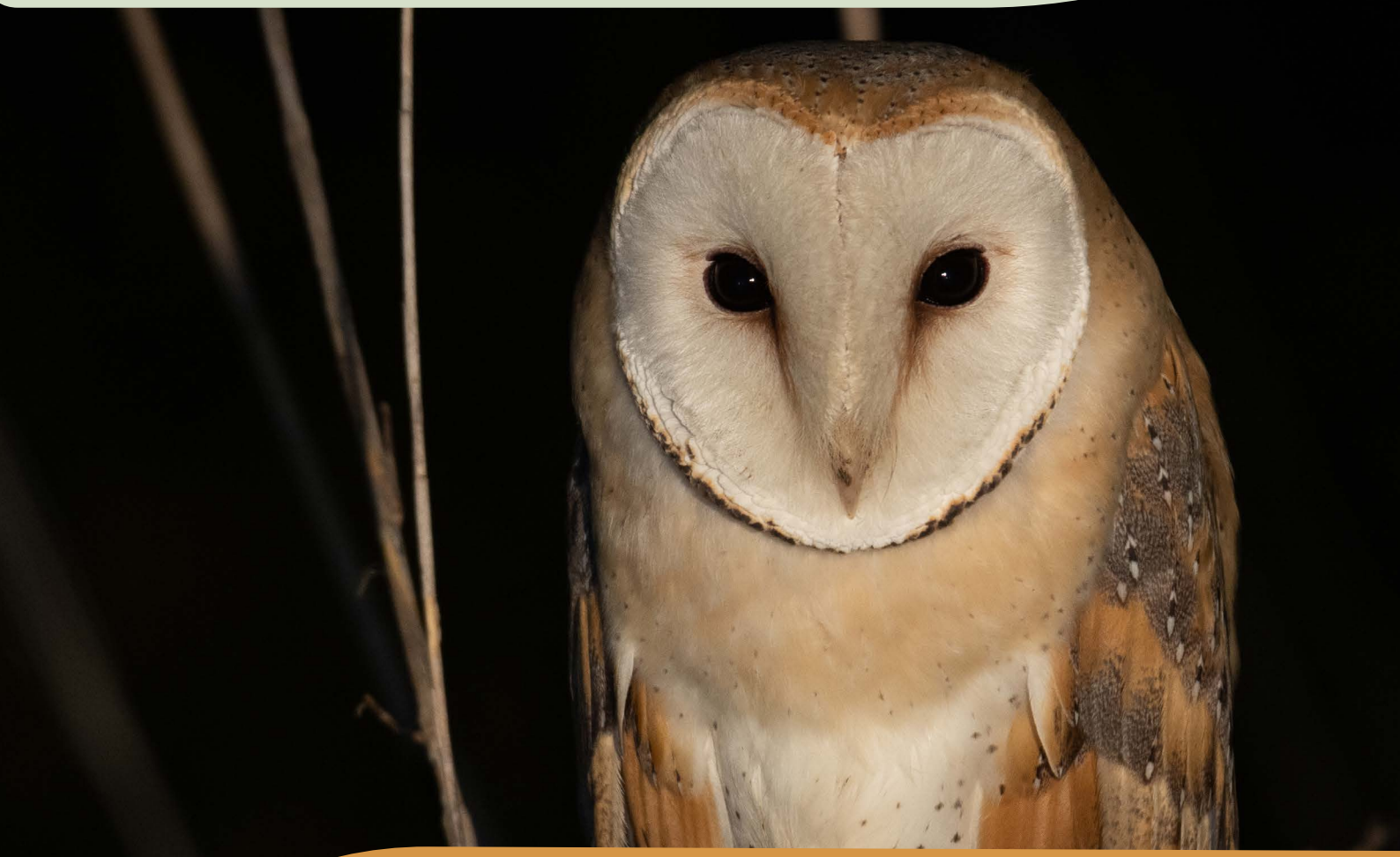
TerraChem



MONITORING ~100,000 ANTHROPOGENIC CHEMICALS IN TERRESTRIAL APEX SPECIES, THEIR FOOD CHAINS AND SOIL, IN EUROPE

The TerraChem Monitoring Approach

Policy brief 02

Introduction

Anthropogenic chemicals are a key driver of biodiversity loss. Terrestrial ecosystems in Europe are exposed to high numbers of anthropogenic chemicals, many classified as hazardous to the environment and/or human health. Yet monitoring of chemicals in soils and terrestrial biota is scarce compared with the aquatic environment, often limited in spatial scale, focussed on single matrices (e.g. soil), and to limited chemical groups (e.g. pesticides). This presents a significant knowledge gap, preventing effective action to deliver the EU zero pollution ambition and towards the restoration of biodiversity.

This policy brief outlines the TerraChem Monitoring Approach as a cost-efficient way to better understand exposure of terrestrial ecosystems to anthropogenic chemicals in Europe. It allows for (semi-) quantitative identification of c.100,000 anthropogenic chemicals, their transformation products and metabolites, in terrestrial apex species and their food chains, including soil.

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THIS BRIEF

This brief presents:

- What the TerraChem Monitoring Approach entails, in terms of sampling of terrestrial apex species and their food chains across Europe, and the chemical analyses involved.
- What supplementary analyses the TerraChem Monitoring Approach applies to better inform understanding of chemical risks and damages to biodiversity.
- Key regulatory applications of the TerraChem Monitoring Approach.
- Cost-efficiency of the TerraChem Monitoring Approach.

WHO SHOULD READ THIS BRIEF

This brief is intended for:

- European policy makers and regulators, notably DG Environment, the European Parliament's Committee on Environment, Climate and Food Safety (ENVI), the European Chemicals Agency (ECHA), European Food Safety Authority (EFSA), European Environment Agency (EEA), Joint Research Centre (JRC), European Medicines Agency (EMA) and member state ministries and competent authorities dealing with chemicals in the environment and with biodiversity.
- Scientists interested in better understanding chemicals exposure in the terrestrial compartment.
- Chemicals industry interested in better understanding exposure of terrestrial biota and soils to the chemicals they produce.

KEY MESSAGES

1. The TerraChem Monitoring Approach entails robust sampling of representative apex species and their food chains at multiple levels, including soil, across multiple EU countries and key habitats. Samples below apex level are pooled to reduce outlier effects.

2. The TerraChem Monitoring Approach entails implementing a powerful platform of chemical analyses, to (semi-) quantitatively identify c. 100,000 anthropogenic chemicals, their transformation products and metabolites, in each and every sample, providing insights into chemical exposure patterns and routes of exposure.

3. Complementary analyses deliver additional information to better understand and address chemical risks and damages to biodiversity: (a) stable isotope analysis of biota samples for calculation of accumulation and magnification of chemical concentrations from soil to biota and across trophic levels; (b) eDNA-based monitoring of species composition in invertebrates and soil, spatially and temporally matched with the chemicals monitoring, to train models of chemicals damages on species diversity.

4 The TerraChem Monitoring Approach delivers evidence on anthropogenic chemicals in the terrestrial compartment, complementary to planned monitoring under the Soil Monitoring Law, with multiple regulatory applications.

5 The likely benefits of the TerraChem Monitoring Approach in terms of reduced costs arising from damages to environmental health far outweigh the modest costs.

6 There are promising options for EU uptake of the TerraChem Monitoring Approach.

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KEY MESSAGE 1

The TerraChem Monitoring Approach entails sampling of representative apex species and their food chains at multiple levels, including soil, across multiple EU countries and key habitats. Samples below apex level are pooled to reduce outlier effects.

Residing at the top of food webs, apex species, such as predatory birds and mammals, are of particular value as sentinels for chemical contaminants in the environment, notably for persistent, bio-accumulative and toxic (PBT) chemicals. Being relatively long-lived, with substantial home ranges, they integrate contaminant exposure over many years and across relatively large areas.

By sampling apex species together with their food chains at the same locations and in the same time period, it is possible to better understand how chemicals are distributed in soils and biota and how they biomagnify (or biodilute) along food chains. Damages to biodiversity may vary considerably at each level. Some chemicals are more frequently found and show higher concentrations at lower trophic levels (e.g. invertebrates), reducing species richness and abundance at these lower levels, with cascading effects up the food web. Other chemicals may be observed more frequently and/or with higher concentrations at higher trophic levels , potentially affecting populations of protected species and humans.

HOW TerraChem HELPS

TerraChem has developed a sampling strategy and demonstrated pragmatic methods for sampling of terrestrial apex species to monitor exposure to anthropogenic chemicals

The TerraChem project identified the barn owl Tyto alba as a species well-suited to pan-European monitoring, given its wide distribution, narrow diet (typically 90-95% rodents) and preference for agricultural habitats. Other widespread raptor species with differing habitat preferences might be selected to complement the barn owl (e.g. tawny owl Strix aluco to represent forest habitats). There are few apex mammal species with Europe-wide distribution but several species lend themselves to single-country monitoring . For TerraChem we selected: stone marten Martes foina in the Netherlands, grey wolf Canis lupus in Germany, European badger Meles meles in Spain, Egyptian mongoose Herpestes ichneumon in Portugal, northern white-breasted hedgehog Erinaceus roumanicus in Greece, and red fox Vulpes vulpes in Romania. These species represent multiple vertebrate families, diets and habitats, providing further insights into patterns of chemicals exposure in Europe. Each apex species + country combination (e.g. barn owl Netherlands, barn owl Germany, European badger Spain) is treated as a separate case study, with six apex animals collected per case study to reduce outlier effects. Apex animals are sampled opportunistically, involving collection of animals found dead (mostly roadkill) or obtained from pre-existing legally sanctioned culling programmes. The chosen apex sample matrix is the liver, the key organ for xenobiotic metabolism and a key repository for lipophilic chemicals. Sampling is done by appropriately qualified and authorised individuals and follows a strict Protocol for collection, transport, processing and storage of samples (developed by TerraChem) to ensure comparability across space and time. Detailed metadata, such a species name, geographical coordinates, date and time of collection, EUNIS habitat type, age, sex and biometrics, are captured in the field.

TerraChem has developed a sampling strategy and demonstrated pragmatic methods for sampling of terrestrial apex species food chains to monitor exposure to anthropogenic chemicals

The sampling strategy for food chain samples involves active co-located sampling (i.e. co-located with the apex animal sample, in both space and time) of biota at several levels in the apex species' food chain, together

with co-located soil sampling. Detailed metadata is collected for all samples. Co-location in space is defined here as a circular area, the radius of which is calculated based on the assumed feeding territory of the apex species in question, and the centre of which is given by the location of find of the apex animal carcass (see figure). Co-location in time is defined as within the same calendar year. Co-location in space and time enables meaningful inferences to be drawn on how chemicals move through food chains.

TerraChem implemented 12 case studies (six barn owl case studies and six apex mammal case studies), each involving sampling at 6 locations. For each location, samples included: one apex species liver sample; one or two pooled rodent/shrew soft body tissue samples (or, for the wolf case study, pooled ungulate muscle samples) (each pool consisting of 2-4 individuals); one pooled mixed-species herbivorous invertebrate sample (each pool consisting of 4 pitfall trap contents); one pooled mixed-species non-herbivorous invertebrates sample (each pool consisting of 4 pitfall trap contents); one pooled mixed-species plant leaves sample (each pool consisting of 4 individual mixed-species leaf samples); and one pooled bulk soil sample (each pool consisting of 4 individual bulk soil samples). This gave a total of six or seven samples per location, thus 36-42 samples per case study and, across the 12 case studies, a total of 432-504 samples. As each sample is analysed for c. 100,000 substances, such a Europe-wide monitoring scheme produces c. 43-50 million data points.

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KEY MESSAGE 2

The TerraChem Monitoring Approach entails implementing a powerful platform of chemical analyses, to (semi-)quantitatively identify c. 100,000 anthropogenic chemicals, their transformation products and metabolites, in each and every sample, providing insights into chemical exposure patterns and routes of exposure.

The panel of analyses includes: wide-scope target analysis for c. 2800 target chemicals; (b) additional, target analyses for legacy persistent organic pollutants (POPs); (c) suspect screening for >93,000 substances; and (d) elemental analysis for metals and other elements. Together, these analyses can detect >95,000 environmentally relevant anthropogenic chemicals, with respective residue concentrations (or estimated concentrations in the case of suspect screening). Supplementary lipid content analysis allows for normalisation for variable lipid content of samples.

The wide coverage of anthropogenic chemicals using these analytical methods contrasts with conventional chemicals monitoring under EU regulations, which tends to focus on a limited list of selected substances, with a high risk that important early warning signals for un-monitored substances are missed (Policy brief 5). There is currently no Europe-wide monitoring involving such wide-ranging chemicals coverage as the TerraChem Monitoring Approach.

HOW TerraChem HELPS

TerraChem demonstrates how the approach delivers insights into patterns and routes of exposure in terrestrial food chains
Data across the 12 TerraChem case studies reveals how many and which chemicals occur above the level of detection, how frequently each chemical occurs and at what concentration. Across all samples, we detected 321 chemicals by target analyses, and an additional 3080 by suspect screening. The data provides insights on the number of chemicals detected within each class of chemicals (e.g. numbers of insecticides, herbicides, fungicides, rodenticides, PCBs, PDBEs, PAHs, PFAS, pharmaceuticals, etc.). The data also provides insights on how exposure differs between soil and each level of the food chain. For example, of the 321 chemicals detected by target analyses, 202 were detected in soil, 126 in plants, 139 in invertebrates, 145 in rodents/shrews, and 150 in apex animals. The data can also provide insights into difference in exposure within countries, and differences in exposure between countries. If monitoring campaigns are repeated periodically, e.g. every 3 or 4 years, it will also be possible to track temporal trends in chemicals exposure.

TerraChem has constructed a database with modules to store the data on samples, target analyses results and non-target screening output
Data generated by the chemicals analyses are stored in the TerraChem Data Management System, with modules including a Sample Catalogue, a database for target data, and a Digital Sample Freezing Platform for non-target results, all connected with the NORMAN database. These data can be made open access to researchers, regulators and industry.

> See TerraChem Policy Brief no. 4 on the TerraChem Data Management System in support of the EU Common Data Platform

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KEY MESSAGE 3

Complementary analyses deliver additional information to better understand and address chemical risks to biodiversity: (a) carbon-13 (^{13}C) and nitrogen-15 (^{15}N) stable isotope analysis of biota samples for calculation of magnification of chemical concentrations from soil to biota and across trophic levels; (b) eDNA-based monitoring of species composition in invertebrates and soil, spatially and temporally matched with the chemicals monitoring, to train models of chemicals damages on species diversity.

Most monitoring of anthropogenic chemicals in the terrestrial environment focuses on a single matrix (e.g. soil, or a specific apex species), which does not provide insight into the extent of chemical bioaccumulation in wildlife food chains. Calculation of biomagnification and trophic magnification. factors requires precise data on trophic levels, which can be obtained using stable isotope analysis.

Most monitoring of anthropogenic chemicals in the terrestrial environment does not involve simultaneous monitoring of species composition and richness in the same samples. This presents a key data gap, as exposure data spatially and temporally matched with species composition and richness data are needed in order to train models of chemical damages on species diversity. Consequently, models of chemical damages on species richness (using species sensitivity distributions – SSDs) are usually based on predicted environmental concentrations of chemicals. By generating real-world data on actual chemicals exposure in soil and invertebrate samples, together with spatially and temporally matched eDNA-based monitoring to derive species lists for the same samples, it is possible to test and train these models to better predict damages on species richness.

HOW TerraChem HELPS

TerraChem has demonstrated how stable isotope analysis can be used alongside chemicals exposure analysis of terrestrial apex food chain samples to explore biomagnification/ biodilution in terrestrial food chains

TerraChem has used ^{13}C and ^{15}N stable isotope analysis to measure the ratios of heavy-to-light isotopes for carbon and nitrogen in a sample, allowing for calculation of the trophic position of each sample (for pooled samples, the mean trophic position of the contributing organisms in the pool). Using trophic position, biota-soil accumulation, biomagnification and trophic transfer factors were calculated, providing insights on routes and extent of trophic transfer of chemicals.

TerraChem has demonstrated metabarcoding of samples to obtain species lists and applied these to train species damage models

TerraChem has demonstrated metabarcoding of soil and invertebrate samples to derive species lists, in collaboration with the Dutch national eDNA infrastructure established at Naturalis Biodiversity Center through the projects ARISE and eDentity. This involved DNA extraction from the samples, purification, PCR amplification with the addition of primers (for soil samples, 16S for bacteria, ITS2 for fungi and 18S for eukaryotes; for invertebrate samples, COI and 18S), library preparation and indexing, and next generation sequencing to generate (millions of) reads of unique DNA sequences. Bioinformatics steps follow, allowing for comparison of reads against reference databases to produce species lists for each sample.

Species composition and richness data per sample, matched spatially and temporally with the chemical exposure data per sample, are being used to train species sensitivity distribution (SSD) models of chemical damages on species diversity.

> See TerraChem Policy Brief no. 3 on Modelling Damage from Chemical Emissions to Terrestrial Biodiversity and Ecosystem Services

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KEY MESSAGE 4

The TerraChem Monitoring Approach delivers evidence on anthropogenic chemicals in the terrestrial compartment, complementary to planned monitoring under the Soil Monitoring Law, with multiple regulatory applications.

Data generated by the TerraChem monitoring approach can:

- feed into the European Early Warning and Action System (EWAS) currently being set up by the European Environment Agency – non-target and suspect screening yields early warning signals for emerging chemicals turning up in apex species with a high frequency of appearance and/or high residue concentrations, indicating ubiquity and/or persistence and/or bioaccumulation.

- support prioritisation of substances for further risk assessment through the application of multiple lines of evidence including the real-world data on exposure, and pre-existing data on hazard and risk.
- inform post-authorisation monitoring and re-assessment of authorised substances (e.g. under the revised Sustainable Use of Pesticides Regulation) using a weight-of-evidence (WoE) approach, including through modelling of damages on species diversity (see Key Message 3 above).
- as data builds up across multiple periodic monitoring campaigns (e.g. every three or four years) allowing for time trends to be determined for each detected chemical, support assessment of effectiveness of risk management measures, assess the general effectiveness of chemicals regulations and other policy measures (e.g. substitution of synthetic pesticides with biopesticides under the Farm to Fork Strategy), and assess progress towards the EU zero pollution ambition in the terrestrial compartment with a view to preventing harm to the environment (and humans).

HOW TerraChem HELPS

TerraChem has generated an Early Warning System and automated prioritisation of chemicals for consideration for further monitoring and risk assessment.
TerraChem has developed the infrastructure for an Early Warning and Action System which brings together the real-world data generated by the TerraChem Monitoring Approach with data on hazard and risk to derive early warning signals, and automates prioritisation of chemicals for consideration for further monitoring and risk assessment. First, early-detection methods flag substances or unknown signals that may warrant attention, using target, suspect and non-target screening. Second, each signal is strengthened by gathering further data on exposure, hazard, risk and potential biodiversity impacts. Third, an automated prioritisation process evaluates the available evidence, assigns signals to categories according to the remaining knowledge gaps, and calculates a prioritisation score using a defined set of indicators. The resulting ranked list within each category helps authorities identify which substances should be investigated further. The prioritization scheme is based on previous work done by the NORMAN network. TerraChem has already applied this approach to submit a prioritised list of substances detected in its samples for consideration under the Soil Monitoring Law.

TerraChem has generated a large dataset on chemicals in soils and terrestrial biota that can be applied in a weight of evidence approach for environmental risk assessment of chemicals

TerraChem has generated c. 50 million data points on chemicals in soils and terrestrial biota, including data on specific substances that occur with high frequency at various trophic levels and/or at concentrations that exceed toxicity thresholds, and on substances that show bioaccumulation in terrestrial food chains. These data can be applied in a WoE approach for further risk assessment of substances on the market.

> See TerraChem Policy Brief no. 5 on Early Warning Systems & Multi-Lines of Evidence Based Chemical Prioritization

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KEY MESSAGE 5

The likely benefits of the TerraChem Monitoring Approach in terms of reduced costs arising from damages to environmental health far outweigh the modest costs.

A one-off pan-European monitoring campaign of similar scale to the TerraChem case studies (six apex bird species food chain case studies (one in each of six countries) and six single-country apex mammal species food chain case studies, with sampling at six locations per case study) costs in the region of €2 million for sample gathering and processing, chemical analyses, matched metabarcoding, data management, and generation of early warning and prioritisation results. A campaign with double the number of samples (e.g. 12 case studies x 12 locations per case study) would cost c. €4 million, and a campaign with 24 case studies x 12 locations per country would cost €8 million. These costs represent a small fraction of the likely total costs of chemicals monitoring under the Soil Monitoring Law, or of chemicals monitoring under the Water Framework Directive (c. €69–105 million per annum).

In practice, periodic monitoring (e.g. every 3 or 4 years, in order to pick up newly emerging signals) employing the TerraChem Monitoring Approach, could be specified under the EU Biodiversity Strategy and or Chemicals Strategy. It could be funded through an allocation of EU funds to the Joint Research Centre (JRC) to subcontract suitably qualified institutions for sampling, analyses, data management and interpretation, through competitive tendering. If performed every 3 or 4 years, the annualised cost would be one third to one quarter of the costs cited above (i.e. from €0.5M to €2M p.a. depending on the chosen number of case studies and locations per case study), just 0.5 to 2% of the annual cost of chemicals monitoring under the WFD.

Benefits of early detection and mitigation of even a single chemical threat to biodiversity might easily be in the tens or hundreds of millions of Euros, and possibly running to billions of Euros. For example, the cost of the impact of diclofenac on vulture populations in the Indian subcontinent has been estimated at $69 billion over the period 1993–2006. Soil degradation (including degradation due to chemical pollution) is estimated to cost the EU €50 billion per annum.

There may be scope for monitoring cost-sharing with the private sector, consistent with the Polluter Pays Principle, similar to the approach instituted under the PPPs Regulation (EC no. 1107/2009).

HOW TerraChem HELPS

TerraChem has demonstrated and documented the costs involved

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KEY MESSAGE 6

There are promising options for EU roll-out of the TerraChem Monitoring Approach.

The most impactful options for EU uptake of the TerraChem Monitoring Approach involve tying roll-out the approach to implementation of the Soil Monitoring Law (SML) (Directive (EU)2025/2360), which provides the new legal framework for chemicals monitoring in the terrestrial environment. The SML provides for both EU-level monitoring (of legacy pollutants and an indicative watch list of emerging contaminants, leveraging the existing LUCAS Soil Monitoring) and complementary Member State level monitoring of 'region-specific pollutants.' For the latter, Member States have considerable freedom to determine which region-specific pollutants they monitor, and how. As development of the EU-level indicative watch list is well-advanced, with limited scope to introduce the TerraChem Monitoring Approach (or elements thereof), the best option may be to seek to implement the Approach, or elements thereof, through region-specific pollutant monitoring in Member States. This would allow for further testing of the approach. Alternately, there may be an option to implement the Approach through a funding mechanism similar to that used for LUCAS soil monitoring, i.e. allocation of EU budget to JRC to contract out periodic application of the TMA across multiple Member States.

A further opportunity, though more limited in scope, might be to apply the Approach in the context of the planned EU-wide PFAS monitoring framework under the European Chemical Industry Action Plan. The EC is expected to propose a framework in late 2026. While the chemical scope is limited to PFAS, this would allow for further testing of apex food chain monitoring.

Looking further ahead, there may be an opportunity to introduce the TerraChem Monitoring Approach (or elements thereof) into EU-level monitoring under the SML when it comes up for revision in 2031-32.

HOW TerraChem HELPS

TerraChem has identified options for EU roll-out of the TerraChem Monitoring Approach

TerraChem has identified the various options outlined above through consultation with its Regulatory Advisory Board, which includes representatives from the European Commission, ECHA, EFSA, EEA and Member State Competent Authorities, as well as through internal consultation within the German Environment Agency (UBA).

Information about TerraChem

TerraChem (From soils to apex species: chemical pathways, effects and impacts on terrestrial biodiversity and ecosystem services and applications for better chemicals management – Project no. 101135483) is a c. €6.5M Horizon Europe collaborative project led by the Environmental Institute (Slovakia), running from November 2023 to October 2026.

The overall aim of TerraChem is to develop, demonstrate and apply a novel systems approach integrating monitoring, environmental modelling, data management, analytical tools and user guidance to better understand exposure of terrestrial biota across trophic levels (from soil and soil water to plants to primary and secondary consumers to apex species) in Europe to the universe of environmentally-relevant anthropogenic chemicals and their damage on terrestrial biodiversity and ecosystem services, with a view to enabling more efficient environmental risk assessment of chemicals in the terrestrial compartment and more effective prevention and mitigation, accelerating achievement of the EU's zero pollution ambition.

TerraChem Partners

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