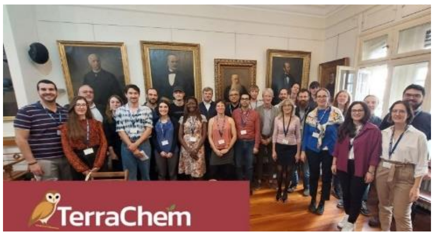

TerraChem: A Systems Approach for Understanding and Managing Chemical Risks to Terrestrial Biodiversity

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Abstract
TerraChem (2023–2026) is an ambitious research collaboration that strives to better understand how anthropogenic chemicals affect different levels of terrestrial biodiversity. The project's central aim is to develop, demonstrate, and apply a novel systems approach that integrates monitoring, environmental modelling, data management, and chemical analysis tools to assess exposure to and effects of anthropogenic chemicals in terrestrial ecosystems and strengthen environmental risk assessment and risk management to reduce harm to biodiversity. This short article introduces the structure of the project and provides insights into preliminary results.

Introduction

TerraChem (2023–2026), co-funded by the European Union under the Horizon Europe programme and the Swiss Government, is an ambitious research collaboration that strives to better understand how anthropogenic chemicals affect different levels of terrestrial biodiversity. The project's central aim is to develop, demonstrate, and apply a novel systems approach that integrates monitoring, environmental modelling, data management, and chemical analysis tools to assess the exposure and effects of anthropogenic chemicals on terrestrial ecosystems. TerraChem addresses the full range of environmentally-relevant chemicals and is building a comprehensive, data-rich, predictive framework that assesses chemical risks to biodiversity – at the level of genes, organisms, species population and ecosystems - based on multiple lines of evidence. TerraChem is generating data and tools that will enable more ecologically realistic environmental risk assessment (ERA) and support chemical risk management in the terrestrial compartment, aligned with the European Union's Zero Pollution Action Plan, the Biodiversity Strategy to 2030 and the One Health approach.

Biodiversity crises and current problems of environmental risk assessments and risk management

Global biodiversity loss, together with climate change and environmental pollution, is one of the most serious environmental crises of our time (see triple planetary crisis). Climate change and the destruction of habitats are seen as the main causes of biodiversity loss, for instance, decline in insects (Sánchez-Bayo and Wyckhuys 2019), amphibians (Luedtke et al. 2023), plants (Daru et al. 2021; Jandt et al. 2022), mammals (Brodie et al. 2021) and birds (Burns et al. 2021; Ogada et al. 2022).

However, there is also ample evidence that the release of chemicals plays a major role as a driver of biodiversity loss (Henn et al. 2024; Sylvester et al. 2023; Groh et al. 2022). In contrast to research on the interlinkages between climate and biodiversity, research on the interlinkages between chemical pollution and biodiversity are rare, in particular in the terrestrial compartment. Furthermore, ecosystems are highly complex and subject to a multitude of interactions. This makes it difficult to establish cause and effect (e.g. the reasons for the loss of a species in a specific location) and to draw conclusions on the extent to which chemicals are responsible for the decline in biodiversity (Keck et al. 2025). However, it is undisputed that anthropogenic chemicals are omnipresent in nature and have the potential to have both direct and indirect negative effects on biodiversity. This includes pollution from pesticides, industrial chemicals, pharmaceuticals and personal care products. Thus, it is essential to better understand how chemical pollution specifically contributes to biodiversity loss in the terrestrial compartment, particularly when striving towards improving chemical-related global policy frameworks, sustainable investment, and chemical risk assessment (Sigmund et al. 2023; Sylvester et al. 2023).

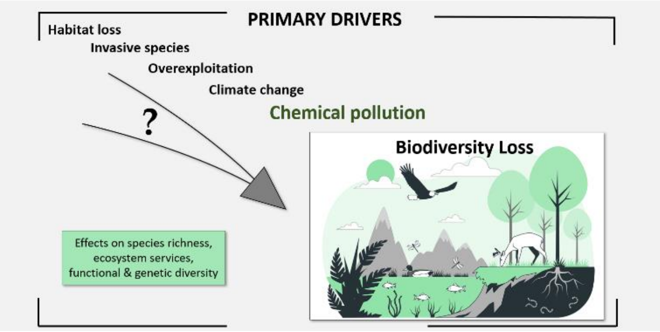

Figure 1. Drivers of biodiversity loss (Gabriele Treu, 2024)

Despite increasing awareness of the damage-level impacts of chemical pollutants on biodiversity, current European chemicals regulations relating to industrial chemicals (REACH), plant protection products (PPPs), biocides, and human and veterinary pharmaceuticals remain limited in the extent to which they address and consider biodiversity, especially terrestrial biodiversity, in ERA and chemical risk management. Current ERA of chemicals is based on laboratory studies in a few focus species, from which conclusions are then drawn about entire populations or even ecosystems. These laboratory studies only depict short-term effects and typically use proxy species, and only from aquatic compartments (aquatic triad - algae, daphnia and fish). The terrestrial compartment remains under-represented in the current approach, except under the regulation on PPPs, where higher-tier and mesocosm studies can be part of the ERA. Additionally, ERA:

- Does not address chemical mixture effects, even though wild organisms are exposed to complex chemical cocktails;
- Does not adequately account for effects in complex ecosystems, trophic transfer, or spatial distribution.

The consequences are substantial knowledge gaps and inability to derive targeted and adequate risk management measures to prevent further biodiversity loss.

TerraChem's Systems Approach and Pillars

To overcome these limitations, TerraChem is structured around four reinforcing pillars (Figure 2).

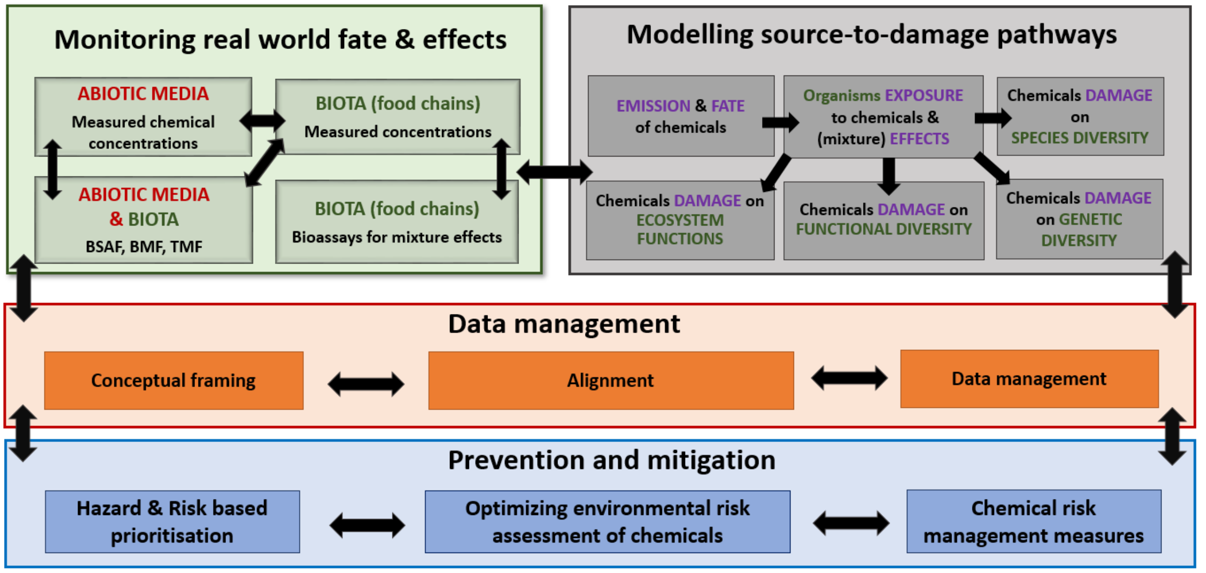

Figure 2. Conceptual approach of TerraChem

A cornerstone of the project is a portfolio of 12 empirical apex species food chain case studies examining exposure and effects in representative biomes across Europe. Each case study involves sampling of the apex species, its immediate mammalian prey (in most cases, rodents), invertebrates, plants and soil, with sampling of each trophic level and soil co-located in space and in time. The case studies are as follows:

- Six case studies on the barn owl *Tyto alba* food chain, in The Netherlands, Germany, Spain, Portugal, Greece and Romania, together making up a pan-European case study.
- Six single-country case studies on apex mammal species food chains – that of the beech 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 europaeus in Greece*, and red fox *Vulpes vulpes* in Romania.

Each case study involves the collection of six replicate sample sets, each sample set consisting of one apex individual, together with the following samples collected from within the individual's feeding territory: up to eight immediate mammal prey individuals; four mixed-species invertebrate samples (pitfall trap contents); four mixed species plants leaf samples; and four bulk soil samples. Samples below the level of the apex species are pooled to reduce the influence of outliers.

Each sample (or pooled sample) is analysed by target, suspect and non-target screening of environmentally relevant chemicals using state-of-the-art analytical methodologies and chemometric tools to reveal the chemical fingerprint of terrestrial food chains. Additional analyses include:

- Stable isotope analyses on all biotic samples to inform analysis of trophic transfer and biomagnification of chemicals
- A battery of bioassays on a subset of samples to determine chemical mixture effects on vertebrates
- Metabarcoding of soil and invertebrate samples to determine species composition to provide TerraChem modelers with matched data on species composition/ richness and chemical occurrence.
- Analysis of soil physical characteristics to support modelling of the fate of chemicals in the terrestrial compartment

To our knowledge, this is the first such pan-European terrestrial apex species food chain monitoring in which more-or-less the full universe of environmentally relevant anthropogenic chemicals has been analysed for frequency of appearance and residue concentrations, trophic transfer and mixture effects.

TerraChem is also collating large volumes of data from literature on chemicals in terrestrial apex species and their food chains. This will inform interpretation of the results of the empirical case studies, TerraChem modelling of source-to-damage pathways, and TerraChem work to prioritise substances for further risk assessment and management.

Environmental Modelling Tools

Under this pillar TerraChem is refining existing environmental fate and damage models to understand how chemicals impact biodiversity at different levels — including genes, species, biological functions, and ecosystem services. We model chemicals' distribution and environmental fate across multiple environmental compartments — including air, water, and soil — by applying multimedia environmental fate model (Wannaz et al. 2018).

For species diversity, we establish a linkage between ecotoxicity, quantified as the multi-substance Potentially Affected Fraction (msPAF) for chemical mixtures, and observed changes in species richness. By calibrating this relationship with biomonitoring data, we can estimate the Potentially Disappeared Fraction of species (PDF), a key indicator of species loss along ecotoxicity gradients.

Using public datasets, we assess how chemical pollution affects genetic diversity by linking chemical data and genetic variability in wild populations. These computational methods help filling gaps that lab and field studies cannot address, identifying where more research is needed.

Functional diversity is evaluated by quantifying loss in functional richness by integrating species-specific toxicity and abundance of species data with corresponding functional traits, acknowledging that different traits underpin distinct ecological functions.

Furthermore, we investigate how chemical stressors affect essential ecosystem services by assessing how chemical disruptions of ecological roles influence the provision of ecosystem services.

Data Management

Under this pillar, TerraChem is developing: 1) a TerraChem Data Management System building on The NORMAN Database System, providing open access to target and non-target data on chemicals in terrestrial biodiversity in Europe, deriving from TerraChem and related studies; 2) an Early Warning System for chemicals in the terrestrial environment in Europe, integrated with the Early Warning System under development by the European Partnership on Risk Assessment of Chemicals (PARC); 3) developing a front-end dashboard providing tools for visualization of the data.

Prevention and Mitigation

Based on results from monitoring, modelling and data management this pillar aims at developing and revising current ERA practices and developing recommendations and guidance on how to improve environmental risk assessment and risk management. TerraChem is developing a new prioritization scheme based on multiple lines of evidence for substances that pose environmental risks and need to be further managed by regulations. In addition, the reliability of registration data will be analysed for 20 selected compounds by comparing registration data with data of those chemicals derived from TerraChem monitoring and modelling work. Moreover, current ERA methods as well as risk management structures and processes will be analysed and assessed with a view to better protection of biodiversity. Policy options on how to better integrate biodiversity in risk assessment and risk management will be assessed.

First Results and Insights

In the real-world monitoring arena, a chemical exposure dataset for the barn owl Tyto alba food chain is complete and undergoing analysis, promising insights into spatial contamination patterns. Preliminary findings of this empirical monitoring show spatial variation in contaminant loads, with elevated levels in western Europe and a significant influence of historical pesticide usage.

A meta-analysis and literature review of organic pesticides and biocides in European terrestrial organisms is nearly finalized. This has compiled data from over 300 studies, encompassing a wide range of taxa and habitats. It reveals key patterns in data availability and highlights critical research gaps. First results of the meta-analysis show a research bias towards legacy chemicals (e.g. DDT, lindane) and western Europe, a dominant focus on bird species and a lack of data on chemical mixtures. This database provides a foundation for exposure modelling, trophic transfer assessments, and identification of key data gaps for future monitoring. Similar work is ongoing on extraction of secondary data on other (non-PPP) organic compounds and on metals and metalloids in apex species and their food chains.

In the modelling arena, a framework has been established to model the fate of chemicals in terrestrial ecosystems using Pangea and USEtox and has been applied to map the spatial distribution of ten pesticides (e.g. Cypermethrin, Deltamethrin) across Europe. In parallel, a quantitative method has been developed to link invertebrate biomonitoring data with ecotoxicity thresholds, enabling estimation of species loss in freshwater ecosystems and revealing a near 1:1 relationship between affected and potentially disappearing species (Oginah et al. 2025); this approach is currently being adapted for terrestrial ecosystems.

TerraChem researchers are also exploring the genetic and evolutionary consequences of chemical exposure. Two main approaches are being pursued:

- Linking existing toxicogenomics data to chemical structures, exposure pathways, and phenotypic traits using public datasets (e.g. on wild mice);
- Applying landscape genetics to assess associations between pesticide concentrations and wild genetic variation in species such as wild boar *Sus scrofa*.

The results provide a mechanistic link between pollution and evolutionary adaptation, enabling the integration of genetic diversity endpoints into environmental risk assessment. Initial associations between pesticide exposure and wild boar genetic variants have been identified, demonstrating proof of concept for evolutionary toxicology within ERA.

Additionally, a novel method has been developed to assess functional biodiversity loss by integrating species traits, abundances, and ecotoxicity data, allowing for the construction of functional sensitivity distributions and establishing proof-of-concept for grasses (Poales) exposed to atrazine and fish (Cypriniformes) exposed to malathion, with ongoing efforts to expand its applicability in the terrestrial compartment.

In the regulatory arena, TerraChem researchers have developed a first version of an ERA chemicals prioritization scheme. This scheme incorporates various lines of evidence of effects and damage of chemicals at molecular, organism, population and ecosystem level. Such a scheme will help authorities to more efficiently identify and prioritize the chemicals that most urgently need to be regulated due to their damage to biodiversity.

A review of EU legislative text and technical guidance documents of different substance related chemical regulations has been conducted. This reveals that current EU regulatory frameworks do not allow quantification of outcomes for biodiversity (as a subject of protection). This is because ecotoxicological studies report effects of chemicals at different levels of biological organization, mostly at individual and sub-organism levels, while biodiversity is typically measured by taxonomic richness and abundance (JRC et al. 2025). This misalignment of metrics, lack of clear definition of specific protection goals and assessment methodologies hamper the assessment of causal links between chemical pollution and its effects on biodiversity (JRC et al. 2025). We will further investigate refinements and uptake of the TerraChem methodologies in ERA and run several in depth analyses on policy options to improve chemical risk management. Specifically upcoming analyses will investigate; a) the feasibility of integrating ecosystem services into weighing procedures (socio-economic analysis, cost-benefit analysis) of the various chemicals regulations; and b) how to overcome existing barriers and problems to linking ecological/ biodiversity monitoring with chemical pollution monitoring to train more accurate models for impact prediction and to identify more precise risk management measures.

Outlook

By October 2026, TerraChem aims to deliver:

- Insights into patterns of chemicals in terrestrial apex species food chains across Europe, trophic transfer of chemicals and effects of chemical mixtures on wild vertebrates;
- A fully integrated damage-level model linking monitoring data, exposure modelling with genetic, species and functional endpoints, and ecosystem-level impacts;
- A validated prioritization framework for identifying high-risk chemicals in terrestrial environments that show a need for better regulation;
- Recommendations for adjustment of technical guidance documents to better reflect chemical risks to terrestrial biodiversity and ecosystem services, and for enhanced risk management measures;
- A data management system and early warning system for chemicals in terrestrial biota and soils in Europe, providing open-access datasets and models to support future research and policy design;
- Recommendations for an ongoing, periodic pan-European monitoring scheme for terrestrial apex species food chains to underpin efficient ERA, risk management of chemicals and to the effectiveness of chemicals regulations in protecting biodiversity in the terrestrial compartment.

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