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EDITORIAL

Aquatic and terrestrial ecotoxicology considering the soil:water continuum in the Anthropocene context

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In 2020 two main French research institutes, INRA and IRSTEA, merged to form INRAE the French National Research Institute for Agriculture, Food and Environment. This was a timely opportunity to update the ecotoxicology delineations and to identify new key issues to be developed at INRAE, notably by including aquatic ecosystems biodiversity and public policies as new research priorities, and for the French ECOTOX Network of terrestrial and aquatic ecotoxicology supported by INRAE (https://www6.inrae.fr/ecotox/) to address new research and development topics. Within this context, the ecotoxicology of the soil:water continuum (SWC) was chosen as the theme of the 7th seminar of the ECOTOX Network held as a 2-day webinar in November 2020. This special issue proposes a selection of some of the presented studies, covering subjects from terrestrial to aquatic ecotoxicology, including experimental and modelling approaches, to finally tentatively describe what could stand for SWC ecotoxicology in the Anthropocene context.

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Can the "soil:water continuum" be a research object?

The different physical compartments that structure ecosystems are linked to each other on a basis of environmental continuum. Not surprisingly, the soil-plant-atmosphere continuum is well recognized as the pathway for water to move from the soil through the plant and then to the atmosphere. However, the SWC is rarely considered as a research object, whereas water quality clearly depends on that of soils (Issaka and Ashraf 2017). The challenge of defining this environmental continuum as keystone for the One Health concept (Destoumieux-Garzón et al. 2018) is to recognize that such special areas can be defined in a system where both particulate, chemical but also biological transfers can take place, leading to specific changes in various processes. Chemical or particulate transfers are already taken into account in many studies involving watersheds or the outlets of rivers in estuaries. Studies aim at modelling the particulate or solution transfers from soil to rivers and from rivers to oceans. When chemicals are applied on soil, intentionally or unintentionally, to protect cultures or to bring organic matter to soil via sewage sludge spreading, for example, they can run off from soil, be transferred and released into hydrosystems and alter water resources. This transfer from soil to water involves different mechanisms, leading to contamination and affecting the quality of aquatic ecosystems. Agroecosystems, as highly anthropized systems, are exposed to strong anthropogenic pressures that can combine with climate change. They are also at the heart of major socio-economic challenges where the SWC plays a pivotal role. Indeed, the close links between ecosystems with watersheds and adjacent aquatic environments is crucial for their own sustainability.

In the last 10 years, many authors argued for studies taking into account "the ecosystem perspective in ecotoxicology" (De Laender and Janssen 2013) advocating holistic approaches (van Gestel 2012). The need to better describe and understand the processes that govern the fate of contaminants in ecosystems was highlighted, including transfers along the SWC and, depending on the type of substance involved, dissipation (e.g. through biodegradation) and persistence (e.g. through retention due to sorptive processes). Although microbiota is recognized as a keystone player in the regulation of the persistence of contaminants in soil, until now its influence on the dispersal and persistence of various contaminants in ecosystems along the SWC remains poorly documented.

What does the "soil:water continuum ecotoxicology" refer to?

The presence of contaminants is detected worldwide in both terrestrial and aquatic compartments of all ecosystems. However, in ecotoxicological studies, these two compartments are mostly considered separately and seldom as connected and interdependent. Terrestrial and aquatic compartments interact at their interface, namely the SWC, a hotspot where many ecological processes occur including those of agroenvironmental interest. Watershed studies have best showed the links between terrestrial and aquatic compartments concerning the particulate transfers (through erosion) or chemical substances transfers (like nitrates, phosphates, pesticide—or pharmaceutical—residues). Very few studies concern the transfer of biological components between these two compartments and the subsequent impacts on ecological functions supporting ecosystem services.

However, recently, the application of the concept of ecological coalescence to the SWC suggests that soil input loaded with its own microbiota in the water compartment will lead to the creation of a third environment occupied by its own microbiota and having its own chemical and biological properties. Ecological coalescence is expected to occur in various ecosystemic context, such as downstream of watersheds between freshwater and marine environments at estuary level or at the outlet of sewage treatment plants along a river (Mansour et al. 2018). Due to erosion, soil particles and microbiota are transported to the river where they mix and interact with the sediment particles. However, this transfer is not a one-way direction, as the reversal occurs during floods, which in turn bring sediments and associated microbiota to riparian soils.

The concept of coalescence is a subject of recent and growing interest in microbial ecology, which is also just starting to be considered in microbial ecotoxicology. Pioneering works carried out nearly 15 years ago (collaboration between Irstea and INRA teams) on a vineyard survey site[1] demonstrated the importance of transfers of microbial populations responsible for herbicide mineralization from soil to aquatic microbiota (Pesce et al. 2010). Authors showed that the transfer of microorganisms from the catchment area to the receiving water environment had a major influence on the ability of the microbiota to adapt to the biodegradation of the herbicide diuron (Pesce et al. 2010).

As well as plant protection products, pharmaceuticals, including antibiotics used in livestock and poultry productions or in human medicine, are often found as contaminants in both aquatic and terrestrial environments. Their presence in the environment exerts a selection pressure favourable to the emergence and/or the maintenance of antibiotic-resistant bacteria. Very recently, the importance of coalescence was assessed for the transfer of sulfonamide, sulfonamide resistance and sulfonamide biodegradation capacities along the SWC in the agroecosystems (Martin-Laurent et al. 2019).

Finally, at the spatial scale of a territory, ponds are also water ecosystems of functional importance. A recent study showed the influence of the landscape shape on their contamination and associated risks to organisms living thanks to these media. The landscape shape was seen through the pond's location in urban, peri-urban or agricultural areas. It was found to be of prime importance to predict the contamination of the ponds with various contaminants such as pesticides, PAHs, pharmaceuticals or inorganic as nitrates, phosphates or trace elements (Nélieu et al. 2020). Such works showing the importance of landscape shape pave the way for spatial ecotoxicology for which the SWC is crucial to explain the transfer, fate and processes governing the persistence and the effects of a range of contaminants in the agroecosystems.

What are the needs to go further?

While the ecotoxicology of the SWC is still a new topic remaining largely unexplored, it is clear that the scientific questions specific to this interface feed those addressed to terrestrial and aquatic environments and vice versa. The ECOTOX Network seminar of November 2020 provided an overview of the topics currently investigated in terrestrial and aquatic ecotoxicology. While the purposes of the presented studies overlap, i.e. establishing a causal link between exposure to contaminants and observed effects on organisms or ecosystem functioning, methodological differences persist, e.g. in terms of technical means and model organisms, as well as confounding effects to be considered.

Two of the papers of this special issue concern both terrestrial and aquatic ecotoxicology and the issue of raw data interpretation in terms of impact of biological importance that remains a challenge to be tackled. Many studies are conducted under controlled conditions and compare samples

[1] https://www.recotox.eu/Dispositifs-et-sites/ZABR-Zone-Atelier-Bassin-du-Rhone-Ardieres-Morcille

exposed to contaminants to non-exposed ones (as the reference), but this is not easily doable in situ where often the reference is lacking, in particular when it comes to the study of SWC ecotoxicology. Metabolomics, which are still under development, appear as promising tools for understanding the mechanisms involved at the scale of communities along the SWC.

Seven presented papers are related to the determinism of contaminant availability and bioavailability, a theme shared by terrestrial and aquatic ecotoxicology. The ecotoxicology of the SWC can feed on such works, especially those focusing on the role of organic matter. This is a strong anchor on the cross-dynamics of both organic carbon and contaminants, linking ecodynamics of contaminants to the major element cycles. The effects of contaminants applied alone or in combination as cocktails are studied on model organisms in both terrestrial and aquatic ecotoxicology. While relevant to improve the ecotoxicological description of various contaminants along the SWC, these approaches still need better taking into account confounding factors such as environmental conditions, life stage or route of exposure, which deeply influence the values of recorded endpoints.

One paper of this special issue introduces modelling the transfers and ecotoxicological impacts of contaminants (pesticides, microplastics…) to soil organisms, terrestrial animals or plants, a topic that remains major in terrestrial ecotoxicology. It is also a challenge in aquatic ecotoxicology, but with other assumptions concerning exposure to contaminants in water. The organisms colonizing and occupying the two environments, be it continuously (interstitial organisms) or sequentially (e.g. emerging insects), are probably the ones that will best represent biological models for advancing knowledge on SWC ecotoxicology. In the same way, as predictive models used in terrestrial ecotoxicology are based on those developed for the aquatic environment, the modelling of contaminants effects in the SWC will benefit from recent developments in each of the two compartments.

Finally, two papers concern processes involved in the remediation of contaminated soils, as assessed by the restoration of soil ecological functions during the reclamation. However, most of these studies stayed focused on soil properties and did not consider consequences on the aquatic environment, although soil reclamation can obviously contribute to the rehabilitation of adjacent aquifers. Similarly, there is no evidence that threshold values derived from soil protection goals can equally protect aquatic ecosystems. These open issues explicitly appeal the ecotoxicology research community better considering the SWC to describe, understand and propose innovative technologies in order to monitor the fate and impacts of contaminants and to rehabilitate the soil and water resources to improve the sustainability of the agroecosystems.

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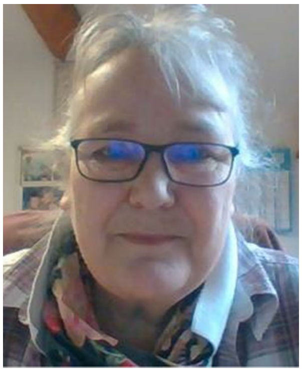

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Juliette Faburé, PhD, is a lecturer at AgroParisTech, the Paris Institute of Technology for Life, Food and Environmental Sciences. For several years, she has been co-leading the ecotoxicology team of the joint research unit (Université Paris/Saclay, INRAE, AgroParisTech) ECOSYS (Functional Ecology and Ecotoxicology of Agro-Ecosystems). Her research concerns assessing the exposure and effects of contaminants for soil invertebrates using methods and early tools. She is interested in improving the ecological relevance of environmental diagnoses studying changes in biological scale and taking into account the soil:water continuum. Actually, she leads as president the SEFA association (Société d'Ecotoxicologie Fondamentale et Appliquée, https://asso-sefa.fr/), and she co-leads the ECOTOX terrestrial and aquatic ecotoxicology network (https://www6.inrae.fr/ecotox/).

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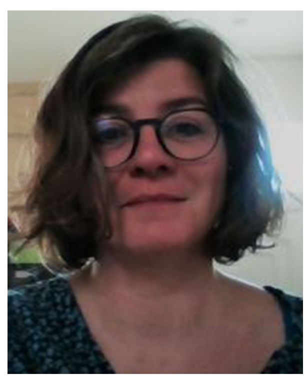

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