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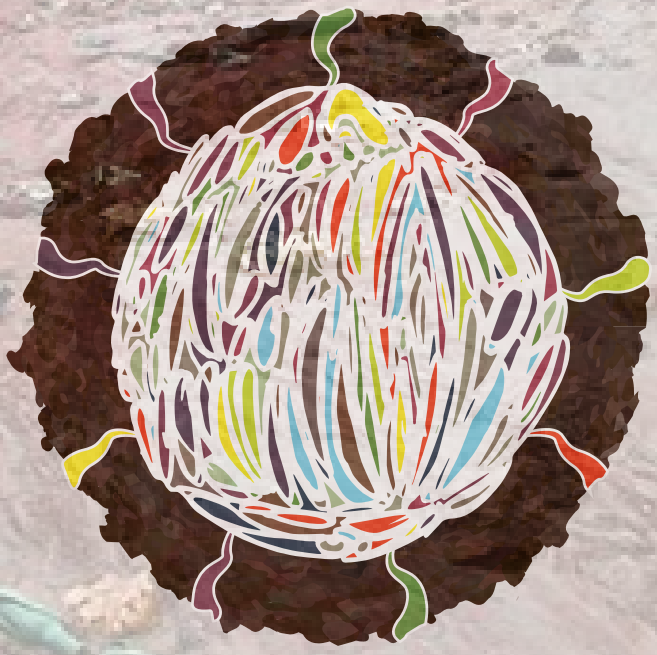

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1.1.14. Assessing agricultural soil pollution risks from organic waste recycling: informing regional participatory waste management

Tom Wassenaar[1,3], Frédéric Feder[2,3], Emmanuel Doelsch[1,3]

[1]CIRAD, UPR Recyclage et risque, 34398 Montpellier Cedex 5, France. E-mail: tom.wassenaar@cirad.fr
[2]CIRAD, UPR Recyclage et risque, LMI IE SOL, DP Divecosys, BP 1386, 18524 Dakar, Sénégal
[3]Recyclage et Risque, Univ Montpellier, CIRAD, Montpellier, France

Abstract

The well-informed recycling of organic waste to agricultural land becomes increasingly desirable in dynamic, developing regions worldwide. Pursuing locally optimal benefit-risk ratios, agro-environmental research in support of OW recycling does not focus on avoiding contamination *per se*, but on the control of dynamics, in soil and other environmental compartments, in order not to exceed risk thresholds. We present a series of empirical research efforts that inform decision-making in regions under OW pressure on OW-contained trace contaminant fate under local conditions. Their results illustrate that the present understanding of trace elements fate allows for the ex-ante assessment of fate under specific use scenarios and local conditions, with a limited set of simplifications. A well-established set of analytical tools provides the information required by such assessments. Understanding of OW-borne organic contaminants is less advanced, but the present capacity to project fate under local conditions does allow for the approximate appreciation of risk levels, the major benefit of which is to focus subsequent research on substances of concern. Ongoing long-term field trials may critically advance our understanding of OW-borne contaminant fate in soil. Developing a reasonable capacity to assess biological contaminant fate is one of its priorities.

Keywords: organic waste, recycling, industrial symbiosis, trace elements, organic contaminants, fate modelling, decision support

Introduction: costs and benefits of recycling organic waste in agriculture

Recycling organic waste (OW) to agricultural land is as old as agriculture itself. However, industrialization, agriculture's subsequent green revolution (particularly synthetic fertilizer use) and globalization largely disrupted this habit and therefore local nutrient cycling and soil preservation. While allowing for major increases in agricultural production and expansion of the producing area, the environmental boomerang effect of these profound changes has put the recycling of organic residues progressively back on the political agenda. The current interest in OW recycling relates to its potential contribution to the improvement of eco-efficiency and resilience, i.e. two high priority goals on agricultural research agendas (Deane *et al.* 2010; http://resilience2011.org). OW recycling is particularly desirable in strongly developing regions where, on the one side, organic residue concentration induces critical environmental and human health risk levels while, on the other, long-term intensive conventional agriculture provides a significant potential for ecological intensification (Doré *et al.* 2011). Two main types are: (1) isolated territories (e.g. islands) with very limited natural resources, especially arable land, and increasing demographic pressure, and (2) peri-urban areas of fast growing large cities in emerging countries. The latter type of situation is rapidly becoming more frequent. In such strongly developing regions, OW recycling carries the promise (i) to avoid pollution and health risks due to their accumulation and uncontrolled discharge; (ii) to reduce the environmental footprint of cropping; (iii) to reduce

the level of dependence on external inputs of the region's agricultural sector. As such, OW recycling would contribute to SDGs 3, 6, 9 and 11.

However, like all waste flows and in line with the second law of thermodynamics, OW has a high entropy. Besides elements and compounds of potential value to agriculture, depending on the amount applied to soil, others constitute notorious contaminants, even though they mostly originate from marketed products, their use in the manufacturing of which was duly authorized (e.g. pharmaceutical and health care products, hormones, feed additives, but also plasticizers, flame retardants, etc.). Through a range of pathways, many such contaminants have become ubiquitous, while most are mobile to various extents. Molecular compounds can degrade and living pathogens may not survive. Science indeed should monitor and evaluate the consequences of "life in a contaminated world" (Guillette and Iguchi 2012). The focus of agro-environmental research in support of OW recycling though is not on avoiding contamination *per se*, but on the control of dynamics, in soil and other environmental compartments, in order not to exceed pollution thresholds, be they set by regulation, risk assessment or stakeholder concerns. In the following, we provide an outline of our view on the characteristics of such agro-environmental research in support of OW recycling, as well as examples of achievements by our research group.

Methodology: hard science in a constructivist framework

We argue that general guidelines and uniform national policies are imperfect and often insufficient tools for achieving an effective control of soil pollution. First, regulation lags behind the state-of-the-art, even in most stringently regulated countries: due to the sheer number of substances produced by industry, as well as the increasing technical capacity of science to determine their presence in the environment. Some 50,000-100,000 chemicals are currently produced commercially in a range of quantities, with approximately 1000 (mostly organic) chemicals being added each year (Mackay *et al.* 2006). The fact is that we know very little about the vast majority of the chemicals we use. Consequently, many organic compounds of recent concern are not (yet) covered by regulations and norms, while standards for elements tend to correspond to worst-case scenarios and may preclude efficient solutions. Lastly, with contaminant *fate* being the focus, and fate being highly dependent on local condition, science should aim to inform stakeholders directly, through ex ante, modelling based fate assessment.

In regions where the accumulation of organic waste induces critical environmental and human health risk levels, industrial symbiosis may provide a systemic solution to a problem induced by the sectoral partitioning of the economy. We developed a facilitated, participatory approach for co-designing agricultural OW recycling solutions, starting from a science-based plausible promise (Wassenaar *et al.* 2014; Wassenaar and Queste 2015). Empirical science informs such initiatives to best of its abilities, both on risks and services of envisaged agricultural recycling solutions, in order to generate information for society in such situations where "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz 1991).

Results and discussion: examples of research for the ex-ante assessment of contaminant fate

Informing agricultural OW recycling in a specific context: the case of trace elements in Réunion

Réunion is an increasingly densely populated island. It is a large nutrient sink due to net imports, both for agriculture and inhabitants. Soils have developed on mafic lava rock and heavy metal contents are naturally high. National regulations, without considering the origin of metals, prohibit the recycling of certain organic residues on soils with such concentrations. The impact of recycling

organic residues on trace metal mobility (in soil and risks of transfer to groundwater or crops) in Réunion was studied through field experiments over several years with sewage sludge (Doelsch *et al.* 2006b) and pig slurry (Legros *et al.* 2012) applied on crop fields. Laboratory-scale basic research results have shown that the mobility and phytoavailability of trace metals in Réunion soils are very limited. This has been confirmed by field level observations (Collin and Doelsch 2010; Legros *et al.* 2012) and contrasts with our findings in other settings, like the mobility of OW-borne trace metals in the arenosol and fluvisol of the market gardening agrosystem near Dakar, Senegal (Hodomihou *et al.*, 2016). In collaboration with institutional stakeholders, researchers have convinced competent authorities to issue a waiver authorizing the use of sewage sludge in agriculture in Réunion (Collin and Doelsch 2010), as well as the use of green waste, exceeding the regulatory threshold for chrome and nickel, but which proved to originate from soil particles attached to roots.

At the same time though, these results underscore a long-term accumulation risk, hence the relevance of modelling the fate of heavy metals in tropical soils. Available accumulation models are usually parameterised through generic multiples regression equations taken from the dominantly temperate climate based literature. This proves to substantially over-predicted trace metals concentration in the edible organs of plants and in the soil solution and thus overestimated trace metals output from the upper soil layer by plant uptake and leaching. Once adjusted to local data, the model correctly predicted trace metals accumulation in the upper soil layer amended with organic wastes (Oustrière *et al.* 2013). This constitutes a precious decision support tool since it allows relating application frequency and dose to a time lag before reaching e.g. regulatory or eco-toxicity soil concentration thresholds. Its major limitation is that the OW induced evolution of basic soil physical, chemical and biological parameters (pH, CEC, hydraulic conductivity, microbial biomass, etc.) is not taken into account.

Developing knowledge and tools for ex-ante risk assessment in a wide range of settings

Our research also revealed that predicting OW trace metal fate in a wide range of soils requires considering trace metal speciation, in OW (Legros *et al.* 2010), in soils (Doelsch *et al.* 2006a; Levard *et al.* 2007), in soils after residue application (Doelsch *et al.* 2006b) and speciation changes due to mineralization (Doelsch *et al.* 2010). This is a worthwhile aim to pursue. Livestock manure contained zinc and copper for example account for the highest metalloid elements inputs in agricultural soils (Belon *et al.* 2012; Jensen *et al.* 2016). We deploy the full range of analysis techniques available: size fractionation, X-ray diffraction, scanning electron microscopy, coupled with energy dispersive spectrometer, and extended X-ray absorption fine structure, which is one of the most widely known structural techniques for direct determination of speciation of trace elements present in complex solid samples even at very low concentration. Applied to pig slurry-contained zinc, these techniques revealed that 75% of total Zn was bound to particles in the 0.45 to 20 µm size range, thus drawing attention to colloidal transport in soil. They also revealed that 49% Zn was bound to organic matter, 37% amorphous Zn hydroxide, and 14% sphalerite. These three Zn forms seemed to be soluble in neutral or weakly acid soil systems, meaning that the long-term impact of pig slurry spreading could lead to Zn leaching (Legros *et al.* 2010).

A technique for experimentally assessing contaminant phyto-availability completes this set of approaches deployable, at a low cost, to inform stakeholders on risks in their local context. The RHIZOtest (ISO 16198) is a plant-based biotest to account for rhizosphere processes (Bravin *et al.* 2010). Beyond trace elements, the test is currently also used to assess plant transfer risks of OW contained organic contaminants – persistent pollutants as well as pharmaceutical and personal care products – and even the possible transfer of biological contaminants: pathogens as well as antimicrobial resistant genes.

The scope for the ex-ante assessment of OW-borne organic contaminant induced risk

Concerning organic and biological contaminants, the sketchy understanding of OW-borne biological contaminants' fate so far precludes any meaningful ex-ante risk assessment. The uncertainty surrounding the fate of organic contaminants in a particular setting and soil also remain very high. Nevertheless, combining currently available models with general and easily obtainable information on OW and soils allows producing useful fuzzy fate estimates. For particular recycling scenarios of wastewater sludge and pig slurry onto Réunion soils, a soil balance calculation based on first order removal constants allowed to approximate the possibility range for the remaining soil concentration at user-defined time horizons (Wassenaar *et al.* 2015; figure 1). Local soil pH allowed to assess each particular organic contaminant detected in OW as being present in soil either in a dominantly neutral or dominantly ionized form. Removal through volatilization, biodegradation and leaching could then be approached thanks to information on local conditions and their variation like soil mixing depth, bulk density, temperature, carbon content, rainfall and crop yield. The main limitation of such an approach is the impossibility to estimate plant uptake of ionic substances: no model has yet been adapted to them. We anticipate that continued empirical research efforts soon will allow addressing various such limitations. While not restricted to organic contaminants, the by now extensive documentation of the structural presence of trace levels of organic contaminants in many OW sources makes it a pressing issue. Among other initiatives, an increasing collection of long-term field trials like those of the French network of SOERE-PRO observatories (https://www6.inra.fr/valor-pro/) exemplifies such efforts.

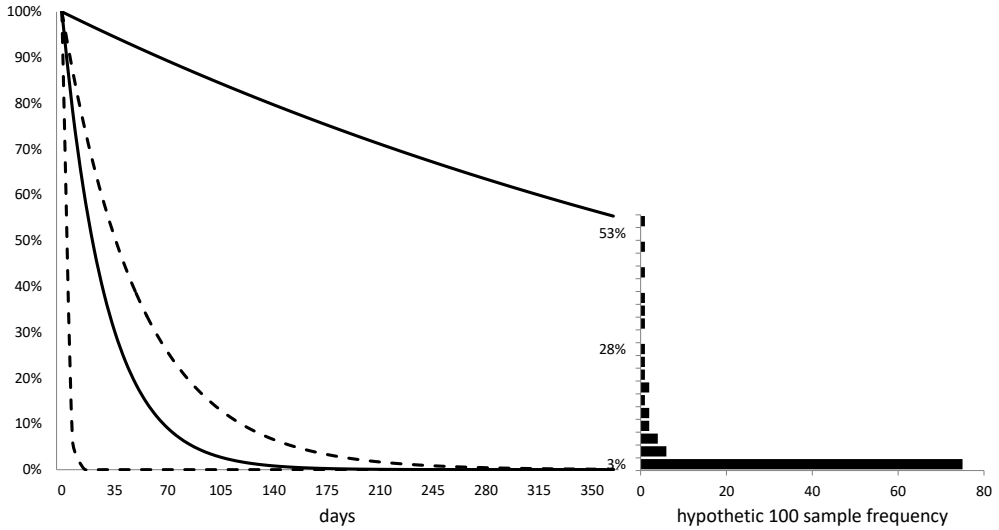

Figure 1. Interpretation of upper and lower bounds based removal dynamics. Solid lines indicate high and low soil removal dynamics of Tris(chloropropyl)phosphate, a sludge-borne flame retardant, recalcitrant when compared, for instance, to nonylphenol (dashed lines). The histogram on the right indicates the frequency distribution that would be obtained between these high and low removal limits from a hundred samples after 1 year if the removal rate distribution would be uniform. From Wassenaar *et al.*, 2015

Conclusions

The above research examples testify of a rapidly increasing understanding of, as well as an increasing capacity to model the fate of contaminants in soil other than the classically considered nutrient loading risks. Clearly, while biophysical research continues to progress, the present state-of-the-art allows to inform local development efforts in order to avoid adverse effects of initiatives. Directly informing stakeholders, through ex-ante, modelling based contaminant fate assessment within the frame of participatory OW management centred industrial symbioses carries the promise to contribute to SDG targets 6.3, 9.4 and 11.3.

Beyond the present capacity to inform, there is an increasingly realistic prospect for a near future capacity to account in a satisfactory manner for the fate of all contaminants in all situations. One example of current developments pointing in that direction is a new clustering methodology called TyPol, which allows classification of organic contaminants and their degradation products, according to both their environmental behavior and molecular properties (Servien *et al.* 2014). Another essential direction we presently explore is the integration of fate models into dynamic system models. Such models allow simulating the functioning of modifications envisaged in complex systems. Dynamically representing contaminant fate in complex human-environment systems will allow to go beyond characterizing selective individual situations, to increase the probability of simulated situations to be realistic, and to assess environmental fate and impact at larger scales.

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