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Soil thresholds and a decision tool to manage food safety of crops grown in chlordecone polluted soil in the French West Indies[☆]

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A B S T R A C T

Due to the persistent pollution of soils by an organochlorine, chlordecone (CLD also known as Kepone ©) in the French West Indies, some crops may be contaminated beyond the European regulatory threshold, the maximum residue limit (MRL). Farmers need to be able to foresee the risk of not complying with the regulatory threshold in each field and for each crop, if not, farmers whose fields are contaminated would have to stop cultivating certain crops in the fields concerned. To help farmers make the right choices, we studied the relationship between contamination of the soil and contamination of crops. We showed that contamination of a crop by CLD depended on the crop concerned, the soil CLD content and the type of soil. We grouped crop products in three categories: (i) non-uptakers and low-uptakers, (ii) medium-uptakers, and (iii) high-uptakers, according to their level of contamination and the resulting risk of exceeding MRL. Using a simulation model, we computed the soil threshold required to ensure the risk of not complying with MRL was sufficiently low for each crop product and soil type. Threshold values ranged from 0.02 $\mu g kg^{-1}$ for dasheen grown in nitisol to 1.7 $\mu g kg^{-1}$ for yam grown in andosol in the high-uptake category, and from 1 $\mu g kg^{-1}$ for lettuce grown in nitisol to 45 $\mu g kg^{-1}$ for the leaves of spring onions grown in andosol in the medium-uptake category. Contamination of non-uptakers and low-uptakers did not depend on soil contamination. With these results, we built an easy-to-use decision support tool based on two soil thresholds (0.1 and 1 $\mu g kg^{-1}$) to enable growers to adapt their cropping system and hence to be able to continue farming.

1. Introduction

Growers have to comply with regulatory requirements (maximum residue limits, MRL) regarding pesticide content in crop products for sale. Few guidelines exist concerning contamination due to crop uptake of pollutants from historically contaminated soils and environmental pollution. Thresholds of soil contamination by historical organochlorine pollutants are rarely available for agricultural use of the soil. Values have been set for HCH (hexachlorocyclohexane) and/or DDT (dichlorodiphenyltrichloroethane) in Canada (Canadian Council of Ministers of the Environment, 1999), China (regulation GB15618–1995), Poland (regulation Dz.U.02.165.1359), and Romania (regulation O.M. No. 756/03.11.1997). These thresholds apply to all crops regardless of their uptake potential. Moreover, they are not based on the risk of exceeding regulatory thresholds for pesticide content in crop products. To our knowledge, few studies have focused on determining threshold values for soil contamination by pesticides that vary depending on the crop concerned (Donnarumma et al., 2009; Saito et al., 2012).

Chlordecone (CLD) was extensively used in the Caribbean from 1972 to 1978 and from 1982 to 1993 at a yearly dose of 3 kg ha-^{1} to control the black weevil (*Cosmopolites sordidus*) in banana plantations (Cabidoche et al., 2009). It is a highly hydrophobic organochlorine pesticide (K_{ow} between 4.9 and 5.4), strongly sorbed to soil (log $K_{oc} = 4.1–4.2$) and poorly soluble (0.020 mgL^{-1} at 25 °C) (U. S. Environmental Protection Agency, 2012; UNEP, 2007). Degradation of CLD in environmental conditions is considered to be very slow (Epstein, 1978; Orndorff and Colwell, 1980). According to a recent study, despite the possibility of significant mineralization of

Abbreviations: CLD, Chlordecone; DS, Dry soil; FM, Fresh matter; MRL, Maximum residue limits.

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chlordecone after its application, long-term degradation is very low (Fernández-Bayo et al., 2013). Only leaching allows soil decontamination but the process is very slow because of the affinity of CLD for soil organic matter (Cabidoche et al., 2009). CLD continues to contaminate a large proportion of agricultural soils in the French West Indies. According to the Chamber of Agriculture, in Martinique, approximately 45% of utilized agricultural land is contaminated by CLD. Levels of soil contamination can be high enough for some crop products to exceed the MRL (20 μgkg^{-1} of fresh product) that applies to all tropical crops according to European Union regulations No 149/2008 and 839/2008 (Dubuisson et al., 2007; Clostre et al. 2014c, 2015b). To our knowledge, the financial risk involved if the crop has to be destroyed because the MRL is exceeded, is not tolerable for most growers, whose median turnover per hectare is 5000€ (Roux, 2012). In addition, the farmers cannot rely on analysis of their products not only because of the cost (250€) but also the need to wait several weeks for the results of the analysis, which is incompatible with the shelf-life of the products. On the other hand, due to high persistence of CLD, the soil in each plot only needs to be analyzed once to evaluate the potential contamination of the plot. To avoid contaminated fields being abandoned, growers need to be able to foresee the risk of exceeding the MRL when sowing or planting a particular crop.

With the development of sustainable agriculture, several decision tools have already been designed to assist growers mainly in the management of irrigation and the use of pesticides as part of integrated pest management (Thysen and Detlefsen, 2006; Tixier et al., 2008; Gil et al., 2011; Chauhan et al., 2013; Fantke et al., 2011). But no such tool exists for management of the contamination of crop products due to past soil contamination. In the case of CLD, contamination of plants is linked with contamination of the soil, but also depends on the type of soil, the type of crop, and the plant organ concerned (Clostre et al., 2015a, 2015b). The aim of this work was to investigate if it is possible to identify crops that farmers can grow with no risk involved based on the CLD content of the soil. To this end, we first assessed the factors that influence the contamination of a wide range of crops and established categories of crop products based on their contamination potential. We then analyzed and modeled the risk of exceeding MRL for the different crop products, and established thresholds of soil pollution compatible with each crop product to ensure they comply with the MRL. Finally, we built a simple tool the farmers can use to choose the crops they can grow with no, or a very low, risk of exceeding the MRL based on the CLD content in their different fields.

2. Materials and methods

2.1. Data collection

As growing conditions (greenhouse vs. field) influence uptake of CLD by crops (Clostre et al., 2014c) and only 5 ha of greenhouses are used to grow fruit and vegetable crops in Martinique, we used only field data to avoid introducing bias. As part of a series of studies aimed at better understanding and managing the risk of exposure to CLD by local populations through the assessment of CLD uptake by crops, data were collected by CIRAD (French Centre for International Cooperation in Agricultural Research for Development) researchers. Fields contaminated by CLD were sampled in eight municipalities of the Atlantic north and central part of the island of Martinique (Ajoupa-Bouillon, Basse-Pointe, Ducos, Gros Morne, Le Lamentin, Morne Rouge, Trinité and Sainte Marie) that are representative of the contaminated area. Crop products and the corresponding bulk soils (0–30 cm soil layer) were sampled using the procedure described in Clostre et al. (2014a) based on a grid design and 20 pooled subsamples per plot in the majority of cases.

Plots were either cultivated by farmers to produce products for sale or, at our request, for the purpose of scientific research. In this study, the edible parts of 26 different root and tuber vegetables, market garden fruit and vegetables were sampled, see Table 1 SI for details and the number of replications. The crops were representative of local production with five cucurbits (cucumber, chayote, watermelon, pumpkin, melon), tomato, lettuce, guava, banana (plantain banana), and two root and tuber (dasheen and sweet potato), which account for 80–90% of total fruit and vegetable production in Martinique (Roux and Vantard, 2014). In the case of one crop, spring onion (*Allium fistulosum*), two crop compartments, bulb and leaves, were analyzed as both are commonly eaten. Crop products were harvested at marketable size and were rinsed carefully with distilled water to remove soil residues. They were analyzed unpeeled in accordance with the part of the product to which MRL applies (Regulation EC 178/2006).

Five main types of soil are found in Martinique: vertisols (20% of the surface area), andosols (17%), ferralsols (11%), vertic soils and mollisols (9%), and nitisols (6%) (Colmet-Daage et al., 1965). Our study covered three soil types: andosol, ferralsol and nitisol, as these are the main soil types contaminated by chlordecone and used for cultivation in Martinique, French West Indies. CLD was used in banana plantations, a crop cultivated in the northern and central parts of the island where andosols, nitisols and ferralsols are found (Colmet-Daage et al., 1965).

Andosols are found in the vicinity of the Mount Pelée volcano in the north of the island. Ferralsols and nitisols are mainly found in the central lowlands and along part of the northern coast (Colmet-Daage et al., 1965). Andosols have higher organic carbon contents than ferralsols and nitisols (Colmet-Daage et al., 1965; Albrecht et al., 1992; Cabidoche et al., 2009). Andosols also have distinctive physical properties - a large pore volume and a large specific surface area - due the presence of an amorphous clay, allophane, with a fractal and consequently tortuous porous arrangement (Wada, 1985; Woignier et al., 2012). Ferralsols are rich in kaolinite and nitisols are rich in halloysites (Colmet-Daage et al., 1965). These two 1:1 layered phyllosilicate clays are very similar in structure and composition, but differ in a monolayer of water that separates the unit layers in halloysite but not in kaolinite (Schaetzl and Anderson, 2005). Nitisols and ferralsols have similar physical-chemical properties (Colmet-Daage et al., 1965). They both have lower water content and C content than andosols, whereas their bulk density is higher (Table 1).

Organic carbon content could only partially explain the lower uptake observed for plants growing in andosol compared to ferralsol and nitisol (Clostre et al., 2015b). Woignier et al. (2012) hypothesized that trapping of the pollutant in the microstructure of allophanic soils may contribute to the lower availability of CLD for plants. We considered the type of soil as being integrative of the complex relationships between the physical-chemical properties of soil (Table 1). This is why we worked with the soil type as variable in our models.

2.2. Chlordecone analysis

A total of 741 plant samples and their corresponding soils were analyzed. Soil samples were air dried and crushed. Plant samples were shipped frozen to the laboratory.

CLD was extracted with an accelerated solvent extractor at 120 bars and 100 °C, using dichloromethane and acetone (volume 50/50) at two laboratories. In the Martinique analytical laboratory (LDA972), two types of chromatography were used for soil analysis. Concentrations of CLD in samples contaminated with more than 1 mgkg^{-1} were determined using gas chromatography with an electron capture detector (VARIAN GC 3800, Palo Alto, USA). The