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Impact of chlordecone pollution on biodiversity: The blind spot of 15 years of public policy in the French West Indies

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Abstract

For many years, there has been an unprecedented decline in biodiversity on a global scale, triggered largely by the use of plant protection products. In this context, a collective scientific assessment was conducted to identify current consensus knowledge and further needs regarding the impacts of plant protection products on biodiversity and ecosystem services in France, including its overseas territories. A particular focus was placed on chlordecone, a highly persistent organochlorine insecticide used extensively in the French West Indies (FWI) for more than 20 years (1972-1993) to control the banana root borer, but also in Eastern Europe, the USA, South America and Africa for various uses. The FWI support biodiversity hotspots, with many endemic and endangered species, and include marine and terrestrial protected areas. Such an environmental context is therefore highly relevant for studying the links between chlordecone contamination and potential effects on biodiversity. Thus, the objective of this work was to review the contamination of the FWI environment by chlordecone, its transfer through ecosystems, and its effects on biodiversity and ecosystem services. Literature analysis emphasized valuable knowledge of chlordecone ecodynamics in terrestrial, freshwater, and marine ecosystems. A wide diversity of terrestrial and aquatic organisms is chronically exposed to chlordecone. However, despite 15 years of public policy dedicated to developing knowledge on chlordecone's fate and impacts, the knowledge gap remains critical regarding its effects on biodiversity and on ecosystem services. As the local environment is often contaminated for tens or even hundreds of years, future research is needed to characterize the effects of legacy pollution by chlordecone and its transformation products on organisms and ecosystems.

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Introduction

The scientific community warns of an unprecedented decline in biodiversity due to increasing human pressure on ecosystems (Tilman et al., 2017). The main causes of this decline are land and sea use changes, unsustainable direct exploitation of biological resources, climate change, chemical pollution, and invasive alien species (IPBES, 2019). Chemical pollution has been identified as exceeding planetary boundaries (Persson et al., 2022) and among the chemicals of concern, there are plant protection products (PPPs) (IPBES, 2019). PPPs consist of or contain active substances, safeners or synergists, and are intended for several uses such as to protect plants or plant products against all harmful organisms or to prevent the action of such organisms, to influence the life processes of plants, to preserve plant products, and to destroy undesired plants or parts of plants (Regulation (EC) No 1107/2009, The European Parliament and EU Council, 2009). In this challenging context, a collective scientific assessment of current scientific knowledge relating to the impacts of PPPs on biodiversity and ecosystem services was conducted in France, at the request of several ministries (Pesce et al., 2021; Pesce et al., 2025). The scope of this collective scientific assessment covered a wide range of environments, from the site of PPP application to the ocean, in mainland France and its overseas territories.

The French overseas territories host a wide terrestrial, freshwater and marine biodiversity, accounting for 80% of the overall French biodiversity (Gargominy & Boquet, 2011), and for a significant amount of the world's biodiversity (Russell & Kueffer, 2019). However, this biodiversity is endangered as indicated by the red list of threatened species established by the International Union for Conservation of Nature (IUCN, 2024). For example, in Guadeloupe and French Guiana, 15% and 10% of terrestrial, marine and freshwater animal species are threatened with extinction, respectively (IUCN, 2024).

The use of PPPs differ according to the territory. Thus, PPPs are more commonly used in territories that export agricultural products, such as the French West Indies (FWI), than in small territories with dominant subsistence agriculture such as Pacific territories. As highlighted by the collective scientific assessment, the most studied PPP in French overseas territories is chlordecone ($C_{10}Cl_{10}O$), an organochlorine insecticide used extensively from 1972 to 1993 in the FWI to control the banana root borer (*Cosmopolites sordidus*) (Pesce et al., 2025). A few non-agricultural uses have been identified in French Polynesia where it has been used to protect homes against termites and to combat fire ants (Salvat et al., 2012). This insecticide was also applied in Germany, Eastern Europe, the USA, South America, and Africa (Cameroon, Ivory Coast) in banana and potato crops (Cabidoche et al., 2009; Le Déaut & Procaccia, 2009). The FWI support biodiversity hotspots, with many endemic and endangered species, and include marine and terrestrial protected areas (Ministère de la Transition Ecologique, 2025; Office français de la biodiversité, 2025). Consequently, they are a key workshop area for studying the effects of contamination by a well-known pesticide on biodiversity.

Toxic to humans and wildlife, highly persistent and bioaccumulative (Fernández-Bayo et al., 2013b; Lewis et al., 2016; Saaidi et al., 2023), chlordecone is listed as a persistent organic pollutant (POP) in the Stockholm Convention (United Nations, 2023). Its legacy remains a health, environmental, agricultural, economic and social current concern of unprecedented magnitude (Andrés-Domenech et al., 2023; Ayhan et al., 2021; Boum Make, 2022; Dubuisson et al., 2007; Multigner et al., 2010; Resiere et al., 2023).

Since 2008, the French government has successively set up four dedicated action plans to develop knowledge on chlordecone, to implement measures to reduce environmental contamination and human exposure, and to improve communication to stakeholders and local communities aiming at strengthening population protection, still ongoing (Gouvernement Français, 2021; Resiere et al., 2023). Regarding the environmental impact, this public policy has improved and expanded our knowledge about the contamination levels and the fate of chlordecone in the different compartments of terrestrial and aquatic environments, including vegetal and animal biota. In this context, the objective of this work is, for the first time, to review the contamination of the

FWI environment by chlordecone, its transfer through ecosystems, and its impact on biodiversity and ecosystem services.

Bibliographic corpus

To perform the literature review on the contamination of the environment by chlordecone and its effects on biodiversity and ecosystem services, nine queries (Q1: chlordecone, Q2: French West Indies, Q3: Contamination, Q4: Ecotoxicology, Q5: Biodiversity, Q6: Terrestrial ecosystems, Q7: Freshwater ecosystems, Q8: Marine ecosystems, Q9: Ecosystem services) and related keywords were formulated (Table 1). The literature search was then conducted on the Web of Science database from January 1st, 1955 to September 30th, 2024.

Table 1 - List of bibliographic queries and keywords

Query	Keywords
Chlordecone (Q1)	TS = (chlordecone OR mirex OR kepone OR curlone) AND PY = (1 January 1955 - 30 September 2024)
French West Indies (Q2)	TS = ("la martinique" OR martinique OR "martinique island" OR "petites antilles" OR "petites caraïbes" OR "petites caraïbes" OR "îles du vent" OR "îles du vent" OR antilles OR guadeloupe OR "la guadeloupe" OR "guadeloupe island" OR "la desirade" OR "desirade island" OR "la desirade island" OR "french west indies" OR "french antilles" OR "french caribbean" OR "petite terre" OR "grande terre" OR "marie galante" OR "marie galante island" OR "archipel des saintes" OR "les saintes" OR "les saintes island" OR "saint barthelemy" OR "st barts" OR "st barths" OR "saint martin" OR "saint martin island" OR "st martin island" OR "basse terre island" OR "grande terre island" OR "antilles francaises" OR "antilles françaises")
Contamination (Q3)	TS = (contamin* OR concentrat* OR bioaccumul* OR monitor* OR pollut* OR fate OR residu* OR dissipat* OR occur* OR behavi*) NOT TS = ("crop residu*")
Ecotoxicology (Q4)	TS = (biomarker* OR "mode of action" OR "pesticide adaptation" OR bioaccumulat* OR biodisponibility OR biomonitoring OR ecotoxic* OR effect* OR epigenetics OR epigenome OR exposome OR exposure* OR genotoxicity OR immunotoxicity OR impact* OR resistance OR neurotoxicity OR recovery OR reprotoxicity OR resilience OR respons* OR toxicit* OR toxicology OR transgenerational OR risk* OR endpoint)
Biodiversity (Q5)	TS = ("bio diversity" OR biodiversity OR "biological diversity" OR "plant diversity" OR "vegetation* diversity" OR "weed diversity" OR "animal diversity" OR "faunal diversity" OR "invertebrate diversity" OR "arthropod diversity" OR "insect diversity" OR "microbial diversity" OR "bacterial diversity" OR "species diversity" OR "species richness" OR "species abundance" OR "functional diversity" OR "genetic diversity" OR biomarker* OR bioindicator* OR "bio indicator*" OR "population dynamic*" OR "food web" OR "structural response")
Terrestrial ecosystems (Q6)	TS = ("soil fauna*" OR "soil biota*" OR "soil organism*" OR "soil animal*" OR microorganism* OR "micro organism*" OR bacteria* OR bee* OR pollinator* OR pollinating insect* OR wasp OR earthworm* OR nematod* OR protozoa* OR collembol* OR mesofauna* OR macrofauna* OR microfauna* OR "meso fauna*" OR "macro fauna*" OR "micro fauna*" OR "soil decomposer*" OR microbiota* OR "micro biota*" OR mite\$ OR enchytraeid* OR microarthropod* OR "micro arthropod*" OR lumbricid* OR acarina* OR animal* OR mammal* OR isopod* OR diplopod* OR invertebrate* OR arthropod* OR insect* OR arachnid* OR crustacean* OR odonata* OR dictyoptera* OR orthoptera* OR hemiptera* OR hymenoptera* OR coleoptera* OR diptera* OR butterfly* OR beetle* OR grasshopper* OR earwig* OR carabid* OR andrenidae OR ant\$ OR "aphid enem*" OR apidea OR apis OR apoidea OR bombus OR bombyliidae OR bumblebee OR coccinellid* OR colletidae OR eristalinae OR "generalist predator*" OR "ground beetle\$" OR halictidae OR honey bee OR honeybee OR hoverfl* OR lacewing\$ OR "lady beetle\$" OR "lady bird\$" OR ladybeetle\$ OR ladybird\$ OR lepidoptera OR megachilidae OR melittidae OR "natural enem*" OR papilionidae OR parasitoid* OR "rove beetle\$" OR sarcophagidae OR "solitary bee\$" OR spider* OR staphylin* OR "stink bug\$" OR syrphid* OR syrphinae OR tachinidae OR "wild bee\$" OR vertebrate* OR rodent* OR bat\$ OR chiropteran\$ OR amphibian* OR herpetofauna* OR reptile* OR lizard\$ OR bird\$ OR partridge\$ OR songbird\$ OR raptor\$ OR eagle\$ OR owl\$ OR "food web" OR "trophic web" OR "food cycle" OR carabid* OR "microbial communit*" OR phytotoxicit* OR "non-target plant" OR "non target plant") AND TS = (landscape* OR field* OR grassland* OR "terrestrial ecosystem*" OR soil* OR meadow* OR agroecosystem* OR "agro ecosystem*" OR orchard* OR vineyard* OR "field margin*" OR "field boundar*" OR hedgerow* OR pasture* OR fallow* OR "arable crop*" OR "buffer strip*" OR "buffer zone*" OR Ditch OR "grass\$ cover" OR "grass\$ strip*" OR hedge* OR "vegetated filter strip*" OR "vegetative buffer\$" OR air OR atmosphere)
Freshwater ecosystems	TS = ((continental NEAR aquatic NEAR ecosystem*) OR fish OR fishes OR insect* OR invertebrate* OR macroinvertebrate* OR "macro invertebrate*" OR crustacean* OR mayfly* OR

(Q7)	ephemeroptera* OR stonefly* OR plecoptera* OR caddisfl* OR trichoptera* OR coleoptera* OR diptera* OR chironomid* OR mollusca* OR snail* OR mussel* OR annelid* OR protozoa* OR microorganism* OR "micro organism*" OR bacteria* OR plankton* OR zooplankton* OR phytoplankton* OR benthos* OR benthic* OR amphibian* OR alga* OR microalga* OR "micro alga*" OR macrophyt* OR rotifera* OR cladocera* OR copepod* OR mammal* OR bird\$ OR "food web" OR "trophic web" OR "food cycle" OR periphyt* OR biofilm OR fung* NOT (fish fluor* in situ hybrid*)) AND TS = (floodplain* OR "flood plain*" OR fluvial* OR impoundment* OR "inland water" OR lagoon* OR lake* OR lentic* OR lotic* OR marsh* OR pond* OR reservoir* OR riparian* OR river* OR springs OR stream\$ OR swamp* OR "water body" OR wetland* OR watershed OR mesocosm* OR sediment OR microcosm OR channel OR freshwater)
Marine ecosystems (Q8)	TS = ((marine NEAR aquatic NEAR ecosystem*) OR fish OR fishes OR insect* OR invertebrate* OR macroinvertebrate* OR "macro invertebrate*" OR crustacean* OR mayfly* OR ephemeroptera* OR stonefly* OR plecoptera* OR caddisfl* OR trichoptera* OR coleoptera* OR diptera* OR chironomid* OR mollusca* OR snail* OR mussel* OR annelid* OR protozoa* OR microorganism* OR "micro organism*" OR bacteria* OR plankton* OR zooplankton* OR phytoplankton* OR benthos* OR benthic* OR amphibian* OR alga* OR microalga* OR "micro alga*" OR macrophyt* OR rotifera* OR cladocera* OR copepod* OR mammal* OR bird* OR "food web" OR "trophic web" OR "food cycle" OR biofilm NOT (fish fluor* in situ hybrid*)) AND TS = (coastal* OR estuar* OR wetland* OR brackish* OR shore* OR swamp* OR lagoon* OR "coral reef*" OR saltmarsh* OR "salt marsh*" OR bay OR delta OR ocean OR sediment OR microcosm)
Ecosystem services (Q9)	TS = ("eco-system* service" OR "eco*system* service" OR "eco-system* services" OR "eco*system* services" OR "agro*system* service" OR "agro*-system* service" OR "agro*system* services" OR "agro*-system* services" OR "agro*system* services" OR "agro*-system* services" OR "environmental service" OR "environmental services" OR "agro*environmental service" OR "agro-environmental service" OR "agri*environmental service" OR "agri-environmental service" OR "agro*environmental services" OR "agroenvironmental services" OR "agri*environmental services" OR "agri-environmental services" OR "ecological service" OR "ecological services" OR "agro*ecological service" OR "agro-ecological service" OR "agro*ecological services" OR "agroecological services" OR "landscape service" OR "landscape services" OR "land service" OR "land services" OR "land-use service" OR "landuse services" OR "eco-system* function" OR "eco*system* function" OR "eco-system* functions" OR "eco*system* functions" OR "agro*system* function" OR "agro*-system* function" OR "agro*system* functions" OR "agro*-system* functions" OR "agro*system* functions" OR "agro*-system* functions" OR "environmental function" OR "environmental functions" OR "agro*environmental function" OR "agroenvironmental function" OR "agri*environmental function" OR "agri-environmental function" OR "agro*environmental functions" OR "agro-environmental functions" OR "agri*environmental functions" OR "agri-environmental functions" OR "ecological function" OR "ecological functions" OR "agro*ecological function" OR "agro-ecological function" OR "agro*ecological functions" OR "agroecological functions" OR "landscape function" OR "landscape functions" OR "land function" OR "land functions" OR "land-use function" OR "land-use functions" OR "eco-system* good" OR "eco*system* good" OR "eco-system* goods" OR "eco*system* goods" OR "agro*system* good" OR "agro*-system* good" OR "agro-system good" OR "agro*-system* good" OR "agro*system* goods" OR "agro*-system* goods" OR "agro*system* goods" OR "agro*-system* goods" OR "environmental good" OR "environmental goods" OR "agro*environmental good" OR "agro-environmental good" OR "agri*environmental good" OR "agri-environmental good" OR "agro*environmental goods" OR "agroenvironmental goods" OR "agri*environmental goods" OR "agri-environmental goods" OR "agro*ecological good" OR "agro-ecological good" OR "agro*ecological goods" OR "agroecological goods" OR "landscape good" OR "landscape goods" OR "land good" OR "land goods" OR "land-use good" OR "land-use goods" OR "eco-system* amenity" OR "eco*system* amenity" OR "eco-system* amenities" OR "eco*system* amenities" OR "agro*system* amenity" OR "agro*-system* amenity" OR "agro*system* amenities" OR "agro*-system* amenities" OR "agro*system* amenities" OR "agro*-system* amenities" OR "environmental amenity" OR "environmental amenities" OR "agro*environmental amenity" OR "agroenvironmental amenity" OR "agri*environmental amenity" OR "agri-environmental amenity" OR "agro*environmental amenities" OR "agroenvironmental amenities" OR "agri*environmental amenities" OR "agri-environmental amenities" OR "ecological amenity" OR "ecological amenities" OR "agro*ecological amenity" OR "agro-ecological amenity" OR "agro*ecological amenities" OR "agroecological amenities" OR "landscape amenity" OR "landscape amenities" OR "land amenity" OR "land amenities" OR "land-use amenity" OR "land-use amenities" OR biodegradation OR denitrif*)

The combination of Q1*Q2*Q3 provided 177 papers; that of Q1*Q2*Q4, 167 papers; Q1*Q2*Q5, 14 papers; Q1*Q2*Q6, 91 papers; Q1*Q2*Q7, 34 papers; Q1*Q2*Q8, 23 papers; Q1*Q2*Q9, 10 papers. The total number of papers was 516 and after removing the numerous duplicates, 187 papers remained. These papers were read in details and several of them were discarded because they were out of the scope of this review, for instance when dealing exclusively about toxicological studies or human epidemiology. In addition, we focused on the most integrative

and ecologically realistic studies as possible. The results of single-species exposure tests were only used if they provided explanatory elements for processes observed under environmental conditions.

Therefore, at the end of selection process, 58 papers were retained for further analysis. They were completed by various additional documents (28 French and international papers, 13 study reports, 1 PhD thesis, 1 book chapter) found by the authors and which were not retrieved with the Web of Science.

Regarding the contamination of the environment and biota, the maximum measured concentrations of chlordecone and its transformation products were reviewed and retained from each reference as they correspond to the worst-case exposure.

Environmental contamination by chlordecone

In the FWI, chlordecone content in topsoil was extensively mapped in Martinique and at a lesser extent in Guadeloupe, highlighting a significant contamination in particular in actual and former banana farming plots and their neighbouring (DAAF, 2024; Desprats, 2021; Devault et al., 2016; Martin-Laurent et al., 2014). For example, in Martinique, among the 11,349 hectares analysed out of 112,800 hectares of total territory surface, 52% had a detectable chlordecone concentration, *i.e.* above 2 µg/kg, and concentrations varied up to exceed 1 mg/kg in 16.1% of the analysed soils (Desprats, 2021). In Guadeloupe, available data produced on 7,236 hectares out of 162,800 hectares of total territory surface showed similar results with 46% of the surface having a detectable chlordecone concentration, including 20% with soil concentrations exceeding 1 mg/kg (DAAF, 2024). The highest observed concentrations in soils reached 35.4 mg/kg in Guadeloupe (Martin-Laurent et al., 2014) and 17.4 mg/kg in Martinique (Devault et al., 2016) (Table 2). Analysis of the temporal variation in chlordecone concentrations in FWI soils from 2001 to 2020 does not reveal any downward trend in these concentrations (Saaidi et al., 2023).

Table 2 - Maximum (worst-case) concentrations of chlordecone measured in soil, freshwater, freshwater sediment, groundwater, mangrove water, mangrove sediment, and open sea water in the French West Indies

Matrix	Concentration	Location	Reference
Soil (µg/kg)	35400	Guadeloupe	Martin-Laurent et al. (2014)
	17400	Martinique	Devault et al. (2016)
Freshwater (µg/L)	44	Guadeloupe	Voltz et al. (2023)
	22.98	Martinique	Della Rossa et al. (2017)
Freshwater sediment (µg/kg)	401	Guadeloupe	Coat et al. (2011)
	552	Martinique	Bertrand et al. (2009)
Groundwater (µg/L)	28.91 ± 1.77	Guadeloupe	Martin et al. (2024)
	25.96	Martinique	ARS Martinique (2018)
Mangrove water (µg/L)	0.22 ± 0.20	Martinique	Chevallier et al. (2019)
Mangrove sediment (µg/kg)	111	Martinique	Dromard et al. (2022)
Open sea water (µg/L)	0.189	Martinique	De Rock et al. (2020)

Several chlordecone transformation products were detected and identified in soils: 5b-hydrochlordecone, dihydrochlordecone, pentachloroindene, trichloroindene-carboxylic acid (isomers 4 and 7), tetrachloroindene-carboxylic acid (isomers 4 and 7), 10-monohydrochlordecone as well as trihydrochlordecone, tetrachloroindene, a monohydrochlordecol derivative, and two dichloroindene-carboxylic acids (Chevallier et al., 2019). Most of these transformation products come from abiotic and/or biotic (mostly microbial) degradation. Their reported concentrations vary from a few µg/kg to 5 mg/kg depending on the soil type (Chevallier et al., 2019) (Table 3). Though it is sometimes stated that the occurrence in soils of transformation product such as 5b-

hydrochlordecone is due to its presence as impurity in the commercial PPP, Devault et al. (2016) demonstrated that the amounts observed in the fields cannot be justified by its sole input as an impurity but rather by natural transformation of chlordecone. The maximum concentrations of transformation products were mostly observed in the soil where the concentration of chlordecone was the highest, *i.e.* andosol, but there were some exceptions, for example for 2,5,7-trichloro-1H-indene-4-carboxylic acid and 2,4,6-trichloro-1H-indene-7-carboxylic acid which were mainly detected in nitisol (Martin-Laurent et al., 2014; Devault et al., 2016; Chevallier et al., 2019; Comte et al., 2022). Microbial degradation of chlordecone leading to several transformation products was observed under anaerobic conditions in microbial enrichment cultures, carried out from wastewater sludges collected in treatment plant exposed to chlordecone (Chaussonnerie et al., 2016). In addition, anaerobic digestion of plant and animal waste contaminated with chlordecone led to the dissipation of the insecticide and the appearance of transformation products, thereby offering the possibility of treating organic wastes produced by farming in methanogenic conditions and stopping further recirculation of chlordecone in the environment (Martin et al., 2023).

Table 3 - Maximum (worst-case) concentrations of chlordecone transformation products measured in soil, freshwater, groundwater, mangrove water, and marine sediment in the French West Indies

Matrix	Transformation product	Concentration	Location	Reference
Soil (µg/kg)	β-monohydrochlordecone	649	Guadeloupe	Martin-Laurent et al. (2014)
	5b-hydrochlordecone	181	Guadeloupe	Comte et al. (2022)
	Chlordecol	784	Guadeloupe	Comte et al. (2022)
	Chlordecol	70 ± 10	Martinique	Chevallier et al. (2019)
	Monohydrochlordecone	280 ± 220	Martinique	Chevallier et al. (2019)
	Pentachloroindene	5080 ± 2200	Martinique	Chevallier et al. (2019)
	Tetrachloroindene-4-carboxylic acid	450 ± 180	Martinique	Chevallier et al. (2019)
	& Tetrachloroindene-7-carboxylic acid			
	2,5,7-trichloro-1H-indene-4-carboxylic acid	1200 ± 1180	Martinique	Chevallier et al. (2019)
	& 2,4,6-trichloro-1H-indene-7-carboxylic acid			
Freshwater (µg/L)	Pentachloroindene	1.81 ± 0.32	Martinique	Chevallier et al. (2019)
	Tetrachloroindene-4-carboxylic acid	0.04 ± 0.01	Martinique	Chevallier et al. (2019)
	& Tetrachloroindene-7-carboxylic acid			
Groundwater (µg/L)	5b-hydrochlordecone	1	Martinique	Arnaud et al. (2013)
Mangrove water (µg/L)	Pentachloroindene	0.14 ± 0.03	Martinique	Chevallier et al. (2019)
Marine sediment (µg/kg)	Pentachloroindene	20 ± 10	Martinique	Chevallier et al. (2019)

In terrestrial biota, chlordecone accumulation has been documented in livestock (Collas et al., 2019; Collas et al., 2023; Jondreville et al., 2014; Lastel, 2015) and more occasionally in wildlife (Coulis et al., 2024; Kermarrec, 1980; Nicolini et al., 2022) (Figure 1, Table S1). In Guadeloupe and Martinique, concentrations ranging from 0.1 to 43.8 mg/kg wet weight (ww) were measured in livers of four wild bird species (Kermarrec, 1980) while concentrations up to 105.6 mg/kg ww were reported in rats sampled in Guadeloupe (Kermarrec, 1980) (Table S1). Terrestrial phytophagous organisms are more likely to be exposed to chlordecone if they consume underground parts of plants, and to its 5b-hydro derivative if they consume aerial parts (Clostre et al., 2015). This observation was further confirmed by Coulis et al. (2024) reporting the important contamination of endogeous earthworms, and suggesting that geophagy was the main route of soil macrofauna contamination by chlordecone and its transformation products.

In rivers, chlordecone was found in surface waters (*e.g.* Della Rossa et al., 2017; Mottes et al., 2017; Mottes et al., 2020; Rochette et al., 2020), sediments (*e.g.* Bertrand et al., 2009; Bocquené & Franco, 2005; Bouchon et al., 2016; Coat et al., 2011; Dromard et al., 2022), and biota (*e.g.* Baudry et al., 2022; Coat et al., 2011). The concentrations reached 44 µg/L in water, 552 µg/kg

dry weight (dw) in sediments (Table 2), and more than 10 mg/kg ww in fish and crustaceans sampled in Guadeloupe (Coat et al., 2011; Monti, 2007) (Table S1). Some transformation products (pentachloroindene, and tetrachloroindene-4-carboxylic acid and tetrachloroindene-7-carboxylic acid) were found in river water in Martinique up to 1.81 µg/L (Chevallier et al., 2019) (Table 3).

Chlordecone was measured in groundwater in Guadeloupe and in Martinique at very high maximum concentrations, *i.e.* 28.91 µg/L (Martin et al., 2024) and 25.96 µg/L (ARS Martinique, 2018), respectively (Table 2), while its transformation product 5b-hydrochlordecone was observed at concentration reaching 1 µg/L in Martinique (Arnaud et al., 2013) (Table 3).

The various components of coastal and open sea ecosystems are likewise contaminated by chlordecone and its transformation products (Figures 1 and 2, Tables 2, 3, S1 and S2). As a consequence, this insecticide is responsible for downgrading the quality level of almost all of Martinique's coastal water bodies according to the Water Framework Directive (Directive 2000/60/EC, The European Parliament and EU Council, 2000). Biota is the marine compartment where the chlordecone is the most frequently detected and quantified, with reported concentrations of up to mg or even tenths of mg/kg ww (Figure 1, Table S1). Marine megafauna is not devoid of contamination, as chlordecone was found in dolphins and sperm whale blubbers (Figure 1, Table S1) (Méndez-Fernandez et al., 2018).

Chlordecone has not been detected in air quality monitoring in the FWI despite methodological efforts to increase the sensitivity of the assay method used (ANSES, 2020).

Overall, the terrestrial environments are the most contaminated ones by chlordecone and its transformation products, followed by freshwater, mangrove, marine, seagrass bed and coral reef environments (Figure 1, Tables 2, 3, S1 and S2).

Comparing environmental contamination data for the FWI and the organisms living there with existing data for other regions of the world (the USA, French overseas territories other than the FWI) shows that the level of contamination is much higher in the FWI (Table S3). This result can be explained by the massive use of chlordecone in the FWI compared with other regions of the world and by the very late ban on chlordecone in the FWI (1993) compared for example with the USA (1975) (Huggett & Bender, 1980; Cabidoche et al., 2009).

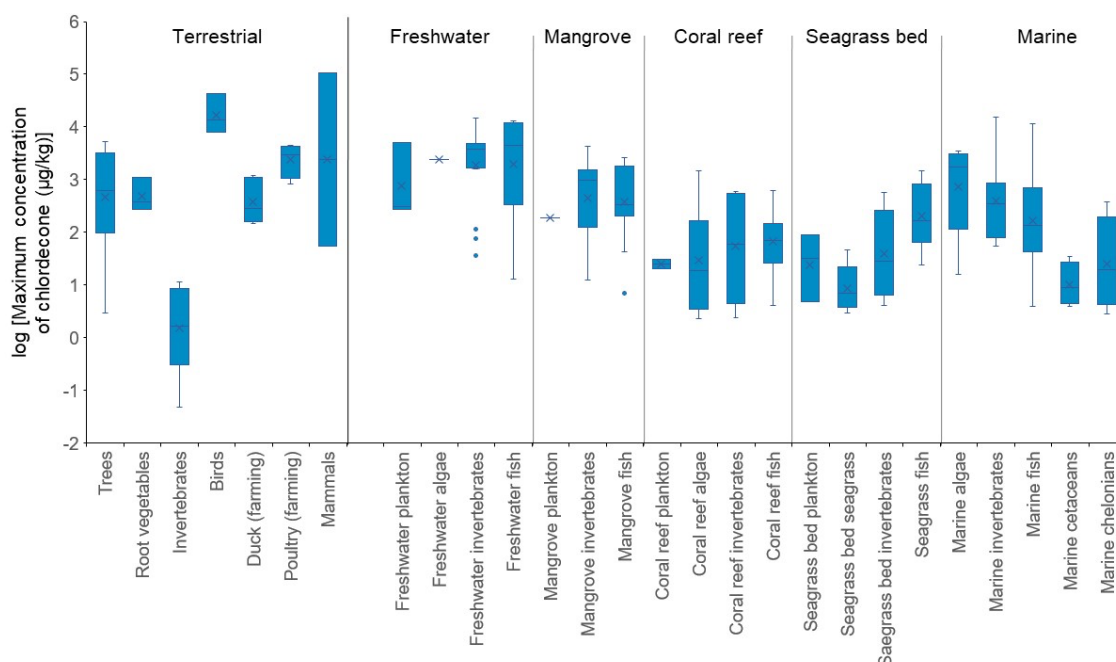


Figure 1 - Range of variation (box-and-whisker plots) of the maximum (worst-case) concentrations of chlordecone measured in various terrestrial and aquatic organisms in the French West Indies (FWI)

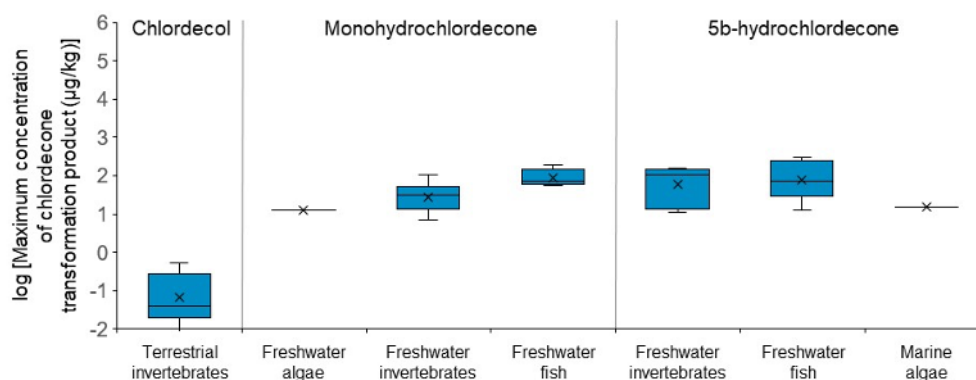


Figure 2 - Range of variation (box-and-whisker plots) of the maximum (worst-case) concentrations of chlordecone transformation products measured in various terrestrial and aquatic organisms in the French West Indies (FWI)

Chlordecone transfer through ecosystems

Because of its intrinsic properties, chlordecone is strongly adsorbed in soils, particularly the ones in the FWI (andosol > ferralsol = nitisol), which are rich in organic matter and clay (Cabidoche et al., 2009; Fernández-Bayo et al., 2013a; Lewis et al., 2016; Woignier et al., 2012). The retention of chlordecone, and thus the soil contamination, increases with the allophane content (typical of andosols) but also with the mesopore volume, the tortuosity, and the size of the allophane fractal aggregate (Woignier et al., 2012; Woignier et al., 2018). The main source of chlordecone input to aquatic environments is soil leaching and erosion (Crabit et al., 2016; Della Rossa et al., 2017; Mottes et al., 2016). Chlordecone inputs are therefore highly dependent on rainfall (De Rock et al., 2020) but also on soil type and cover (Sabatier et al., 2021). Once in the coastal environment, a decreasing gradient is observed from the coast to the open sea (Bodiguel et al., 2011; Bodiguel & Doussan, 2021; De Rock et al., 2020; Dromard et al., 2018a).

Considering the transformation products, Benoit et al. (2017) suggested, using TyPol (Typology of Pollutants), a clustering tool based on molecular, environmental and ecotoxicological properties of organic compounds, that mono- and di-hydrochlordecone have similar physicochemical properties to chlordecone, including environmental persistence, and thus might potentially cause similar risks in ecosystems. Regarding dechlorinated derivatives, Ollivier et al. (2020) showed they are more mobile in soil than chlordecone.

In terrestrial ecosystems, contaminated soils could be a possible source of contamination for terrestrial invertebrates and vertebrates. A recent study carried out on domestic pigs whose diet includes soil ingestion gives details on chlordecone contamination by this way (Collas et al., 2023). Some results also highlighted the transfer of chlordecone to trees (Nicolini et al., 2022), to root vegetables such as yam (*Dioscorea* spp.), sweet potato (*Ipomea batatas*) (Clostre et al., 2015) and radish (*Raphanus sativus*) (Clostre et al., 2014b; Létondor et al., 2015), and to various cucurbitaceae species (*Cucumis sativus*, *Cucurbita moschata*, *Sechium edule*) (Clostre et al., 2014a; Clostre et al., 2014b) (Table 3). The amount of chlordecone absorbed by plants was found to be correlated to the agricultural intensification of land use (Liber et al., 2020).

The contamination of aquatic food webs by chlordecone is to date the best described due to the large number of species that have been analysed. Two modes of contamination appear: contamination by bathing on the one hand, which depends on the concentration in the water, and contamination by trophic route on the other hand, with bioaccumulation or even biomagnification in certain cases along freshwater or marine food webs (Bodiguel et al., 2011; Coat et al., 2006; Coat et al., 2011; De Rock et al., 2020; Dromard et al., 2016; Dromard et al., 2018a; Méndez-Fernandez et al., 2018). The bioaccumulation (and/or depuration) of chlordecone depends on the feeding mode and on the location of the species, and therefore varies among species. In fish living

in the FWI coastal environments, chlordecone accumulation depends both on the geographical location of populations in relation to discharge points and on the trophic behavior of the species. Thus, the highest chlordecone levels were observed in fish populations living in coastal mangroves, where terrestrial sediments and organic matter accumulation is favored by the strong presence of roots in these ecosystems, and because mangroves are calm and semi-enclosed areas which receive direct discharges of chemical from the terrestrial ecosystem (Dromard et al., 2016). More specifically, detritivorous fish (*Oreochromis mossambicus*: maximum concentration of 1036 µg/kg; *Mugil cephalus*: 705 µg/kg; *Mugil curema*: 690 µg/kg) are the most contaminated trophic group, followed by invertebrate and fish feeders (67.4 ± 14.9 µg/kg), planktivores (57.5 ± 4.2 µg/kg) and piscivores (55.9 ± 3.7 µg/kg), then invertebrate feeders (33.2 ± 11.2 µg/kg) and herbivores (10.4 ± 4.6 µg/kg). The trophic group with the lowest levels of contamination are herbivorous fish (*i.e.* *Acanthurus bahianus*) (Dromard et al., 2016). The trophic transfer of chlordecone in coastal marine habitats (mangroves, seagrass beds, and coral reefs) was also reported by Dromard et al. (2018b). In this study, all Trophic Magnification Factors (TMF) values exceeded 1, indicating that chlordecone levels are biomagnified along food webs. Interestingly, the study indicates that the level of contamination varied considerably between wet and dry seasons in seagrass beds with higher contamination during the rainy season. Reef organisms were more moderately affected by this pollution, while mangrove organisms showed a high level of chlordecone whatever the season. Low concentrations of chlordecone were likewise detected in marine mammal fat tissues in Guadeloupe's coastal environments (Méndez-Fernandez et al., 2018). The authors indicate that these concentrations are much lower than those provided by the literature in organisms living in brackish or freshwater of this island.

Chlordecone effects on biodiversity and ecosystem services

Despite more than 15 years of public policy to increase knowledge on chlordecone fate and impacts, little is known on the effect of this insecticide on biodiversity. The main studies about the ecotoxicological effects of chlordecone were mostly performed on mono-specific experiments, mainly carried out under controlled conditions with experimental exposure concentrations generally higher than those detected in contaminated ecosystems (*e.g.* Moreau et al., 2022).

In terrestrial wildlife, although experimental studies have shown that chlordecone is carcinogenic, reprotoxic and neurotoxic for mammals and birds (Multigner et al., 2016), and despite exposure was demonstrated (see above), the absence of data on the effects of chlordecone contamination on individuals and populations is noted. Only a study conducted on the red-bellied kingfisher (*Megaceryle torquata stictipennis*) in Guadeloupe suggests a link between population decline of this species and the contamination of their habitat by chlordecone but no additional monitoring has been made, for instance on exposure or life-traits, to support this assumption (Villard et al., 2021). To our knowledge, only one study, performed under experimental conditions, investigated the effects of chlordecone at the community level, by considering soil microorganisms. This work, carried out on different soils (not previously exposed to chlordecone) with or without chlordecone, shows a change in the abundance of Gram-negative bacterial groups and a decrease in sodium acetate mineralisation in soils exposed to chlordecone, with a stronger effect in a sandy soil which allows greater availability of chlordecone (Merlin et al., 2016). Another work showed that a total of 103 fungal strains isolated from different FWI soils contaminated with chlordecone were able to grow on chlordecone-mineral salt media, among which the *Fusarium oxysporum* MIAE01197 isolate was found to be tolerant to chlordecone because of its prolonged and repeated exposure to this organochlorine in the environment (Merlin et al., 2014).

In aquatic invertebrates, proteome analysis of the Giant freshwater prawn *Macrobrachium rosenbergii* exposed to three environmental relevant concentrations of chlordecone (*i.e.* 0.2, 2 and 20 µg/L) revealed that 62 proteins were significantly up- or down-regulated in exposed organisms, compared to control animals. Impacted proteins are involved in various physiological processes such as ion transport, immune system, or protein synthesis and degradation. Moreover, 6% of the deregulated proteins are involved in the endocrine system and in the hormonal control of

reproduction or development processes of *M. rosenbergii*, such as vitellogenin or farnesoic acid o-methyltransferase. These results indicate that chlordecone is a potent endocrine disruptor compound for decapod crustaceans (Lafontaine et al., 2017a). An ecotoxicological study also conducted on *M. rosenbergii* is interesting as it corresponds to a long-term experiment carried out *in situ* (Lafontaine et al., 2017b). Giant freshwater prawn from the same contamination-free production farm were allocated to two sites with different levels of chlordecone in water (below the limit of detection, *i.e.* 0.01 µg/L, and 0.19 µg/L) for an exposure duration of 8 months. The authors observed a dose- and time-dependent accumulation of chlordecone in shrimp tissues, especially in cuticle. Moreover, female shrimp had lower chlordecone levels than males, probably due to passive detoxification during egg-laying. Gaume et al. (2015) observed an induction of genes involved in the defense mechanism against oxidative stress (catalase and selenium-dependent glutathione peroxidase) in *M. rosenbergii* exposed to low environmental concentrations of chlordecone (0.02, 0.2, 2 and 20 µg/L for 96h).

In aquatic vertebrates, ecotoxicological studies conducted on the model fish species rare minnow (*Gobiocypris rarus*) exposed to chlordecone document its capacity to bind to oestrogen (ER α and ER β) and androgen (AR) receptors, to increase the level of expression of numerous genes involved in the oestrogen synthesis pathway (er β , er β , vtg, cyp19a1, cyp17a1, cyp11a1), or to disrupt the histological structure of the female gonad, including decreases in the gonado-somatic index (Yang et al., 2016). More recently, a thyroid hormone disruption was observed in adult *G. rarus* after *in vivo* chronic exposure to environmental concentrations in chlordecone (freshwater fish embryos exposed to 0, 0.01, 0.1, 1, and 10 µg/L chlordecone from 2 h post-fertilisation until 5 months corresponding to individual sexual maturity) (Yang et al., 2020). But, in the same study, *in vitro* and *in silico* observations indicated that thyroidic effects may be related to chlordecone interactions with ERs (Yang et al., 2020). The direct or indirect modulating effects on thyroid function observed in fish raise the question of possible consequences of chlordecone exposure on metamorphosis occurring during ontogeny in various aquatic vertebrates (Roux et al., 2019; Thambirajah et al., 2019). Chlordecone has a direct *in vitro* inhibitory effect on sperm motility in the Atlantic croaker fish *Micropogonias undulatus*, a Sciaenidae indigenous fish of the Gulf of Mexico and Caribbean Sea (Thomas et al., 1998). In other aquatic vertebrates such as the Florida alligator (*Alligator mississippiensis*), chlordecone is believed to exert its toxic action by binding to progesterone receptors (Vonier et al., 1996). These studies highlighted the impacts of chlordecone on key biological functions such as reproduction and development in relation to endocrine disrupting activities (Lafontaine et al., 2016; Yang et al., 2020) even if the reality of these ecotoxic effects has not yet been demonstrated in natural environments. Moreover, it should be noted that these observations were done in non-native species of FWI and only few studies concerned local aquatic vertebrates. In this context, the consequences of chlordecone contamination of these island ecosystems should be observed, particularly on endemic fauna (Bony et al., 2023). While ecotoxicological analysis remain delicate for protected species, such as the endangered frog *Eleutherodactylus martinicensis*, ecotoxicological observations should be made on populations of the exotic cane toads *Rhinella marina* or tree frogs *Scinax x-signatus* populations (Burac et al., 2018) even if the extrapolation of results between endemic and exotic species are always difficult to do. For these amphibian species, their past and current interactions with banana production activity would be worth studying (Burac et al., 2018).

While these disturbances at individual level could have an impact on the animal populations concerned, no study provides information on the effects at higher levels of organisation, namely populations, communities, or ecosystems. For aquatic fauna, only one study was carried out on populations of the endemic freshwater shrimp *Macrobrachium faustinum*, living in the downstream section of the river Pérou (Guadeloupe) which have significantly slower individual growth compared to populations in the upstream section of the same river (Lagadic et al., 2012). These demographic effects may be related to higher levels of chlordecone in both water and shrimp tissue in the river downstream zone (Lagadic et al., 2012). Under controlled conditions, Huang et al. (2013) demonstrated that chlordecone affected the asexual and sexual reproductions of the freshwater rotifer *Brachionus calyciflorus*, and changed the population structure. The future of

research into the aquatic ecotoxicological effects of chlordecone lies in the refinement of observation protocols towards greater environmental realism. If the pollution-induced community tolerance (PICT) method could be done for microorganisms and microfauna in the FWI context (Tiili et al., 2016; Pesce et al., 2020), other strategies must be developed for macrofauna observations. Fish population monitoring programs have been conducted for many years in FWI rivers. In other French regions, examination of such databases has revealed negative growth rates for the populations of at least 5 common freshwater fish species (Santos et al., 2020; Santos et al., 2022). The evolution of animal populations and their life traits could be examined in FWI, especially in the caribbean coast human-environment observatory context, and linked to the levels of anthropogenic pressures they are exposed to, particularly by examining PPP use in banana production, before and after the ban of chlordecone (Hervé et al., 2023). Innovative molecular approaches based on sedimentary ancient DNA research could provide data on the temporal evolution of biodiversity over the past 50 years (Hervé et al., 2023). It could help understand the way of disappearance of some emblematic animal species such as the West Indian manatee (*Trichechus manatus*). Research should also focus on the ecological effects of chlordecone interactions with notorious xenobiotics such as glyphosate or fipronil which were reported in FWI (Legrand et al., 2017; Lee et al., 2018). Finally, the effects of the interaction of chlordecone contamination with emerging contaminations such as microplastics deserve to be studied (Sandre et al., 2019). This is all the more important since chlordecone is mainly associated with the particulate matters in waters (Bocquené & Franco, 2005).

While the works presented above show that chlordecone can have an impact on several organisms, including microbial communities and on the functions they perform in ecosystems, to the best of our knowledge there is no data on the effects of chlordecone on ecosystem services. If Dromard et al. (2016) indicated that the contamination of the marine biota resulted in strong impacts on local fisheries due to fishing activity restrictions, the closure of several coastal areas and the distancing of fishing area, no economic and social assessment is available to date valuing the impact on the fisheries ecosystem service.

Conclusion and research needs

The review of the literature shows that both the environment and biota are significantly impregnated by chlordecone and its transformation products in the FWI. However, the processes involved in the abiotic and biotic transformation of chlordecone in the environment remain poorly described and understood. In addition, little is known about the effects of this insecticide and its transformation products on the biodiversity and the related ecosystem services in the contaminated terrestrial and aquatic environments.

Observations of the possible effects of xenobiotics such as chlordecone on animal populations and communities are confronted with major methodological difficulties explaining the lack of reliable data in this area. Ecotoxicological data obtained from observations at the sub-individual level in laboratory, where the effects observed are far from ecosystem reality, are numerous but they often raise more questions than they resolve. Indeed, the molecular and cellular variables studied are modulated by many intrinsic and extrinsic factors to the organisms, making it difficult to extrapolate the results to the higher levels of organisation (populations and communities). Data observed at population and biological community level are scarce and often concern species with short life cycles. In this case, population effects are easily observed. This is not the case for living forms with long life cycles and often positioned at the top of trophic chains, such as vertebrate organisms. For these species, the effects are all the more difficult to observe, as individuals are difficult to sample in natural environments. In this context, improving the ecotoxicological risk assessment of chlordecone must involve integrating the methodologies used in population bioecology into ecotoxicological issues (Relyea & Hoverman 2006; Gessner & Tiili, 2016; Thompson et al., 2016) and for instance those related to stoichiometric ecotoxicology and modelling (Peace et al., 2021).

Moreover, there are almost no studies documenting the effects of chlordecone on groups that ensure key functions within ecosystems, such as pollinators, earthworms or microbial communities, and also on the functions and ecosystem services provided by such engineer species.

To bridge this gap, field studies monitoring in the land-sea continuum addressing both chlordecone exposure and individual and population responses in different species should be initiated, to ascertain whether legacy chlordecone remains among the main threats to biodiversity. Recent works related to observation of local fish species (*Sicydium* sp.) and the development of high-throughput analysis methods for marine biodiversity assessment (e-DNA) may open up interesting prospects (Bony et al., 2023; Haderlé et al., 2024). This is particularly critical considering that islands, such as the FWI where protected areas cover more than 60% of the territory, host a significant amount of the world's biodiversity and have experienced a disproportionate loss of it (Russell & Kueffer, 2019). Field studies have also to assess the effects of chlordecone contamination on ecosystem functions and services. To do so, they need to rely on skills in biological sciences but also in human and social sciences including economy and sociology. These works will also benefit to other countries still facing the chlordecone issue.

Finally, this knowledge must not be limited to chlordecone alone as this organochlorine is far from being the sole PPP that contaminates ecosystems and that impacts the biodiversity in the FWI (Pesce et al., 2025). Accordingly, research should also focus on the ecological effects of mixtures containing chlordecone and other PPPs that are present in these territories.

The public policies implemented around chlordecone over the past 15 years should take into account the effects of this molecule on biodiversity.

Appendices

Table S1 - Maximum (worst-case) concentrations of chlordecone measured in various terrestrial and aquatic organisms in the French West Indies. nd: not detected

Table S2 - Maximum (worst-case) concentrations of chlordecone transformation products measured in various terrestrial and aquatic organisms in the French West Indies

Table S3 - Maximum (worst-case) concentrations of chlordecone measured in water and sediments, and in various terrestrial and aquatic organisms in parts of the world other than the French West Indies

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Conflict of interest disclosure

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Data, scripts, code, and supplementary information availability

Supplementary information is available online: <https://hal.inrae.fr/hal-05090822> (Sanchez et al., 2025).

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