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Abstract

For many years, an unprecedented decline in biodiversity is observed. One of the main causes of this decline is 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. The risk posed by persistent pollutants such as chlordecone in these areas is therefore of particular concern. 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, revealing chronic exposure of a wide diversity of terrestrial and aquatic organisms. However, despite 15 years of public policy dedicated to developing knowledge on chlordecone's fate and socio-economic impacts, there is a significant gap regarding its effects on terrestrial and aquatic biodiversity, and on ecosystem functioning. Future research is needed to characterize the effects of legacy pollution by chlordecone and its transformation products on exposed organisms and ecosystems.

Keywords: pesticide, soil ecosystem, aquatic ecosystem, sediment, ecotoxicology, review

Introduction

The scientific community warns of an unprecedented decline in biodiversity due to increasing human pressure on ecosystems (Tilman et al., 2017). Among the main drivers of this decline, chemical pollution has been identified as exceeding planetary boundaries (Persson et al., 2022). This concern is amplified with land and sea use changes, unsustainable direct exploitation of biological resources, climate change, and invasive alien species (IPBES, 2019). Among chemicals, plant protection products (PPPs), used for crop protection together with non-agricultural use such as maintaining gardens, green spaces and infrastructures, are among the substances of concern. In this challenging context, a collective scientific assessment (CSA) 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., 2024). The scope of this CSA covered a wide range of environments excluding groundwater, from the site of PPP application to the ocean, in mainland France and its overseas territories.

The French overseas territories, covering more than 500,000 km², are distributed across all oceans and predominantly in tropical and equatorial areas (Fig. 1). They include more than 11 Mkm^2 of marine exclusive economic zone. These 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, especially by anthropogenic perturbations, 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.

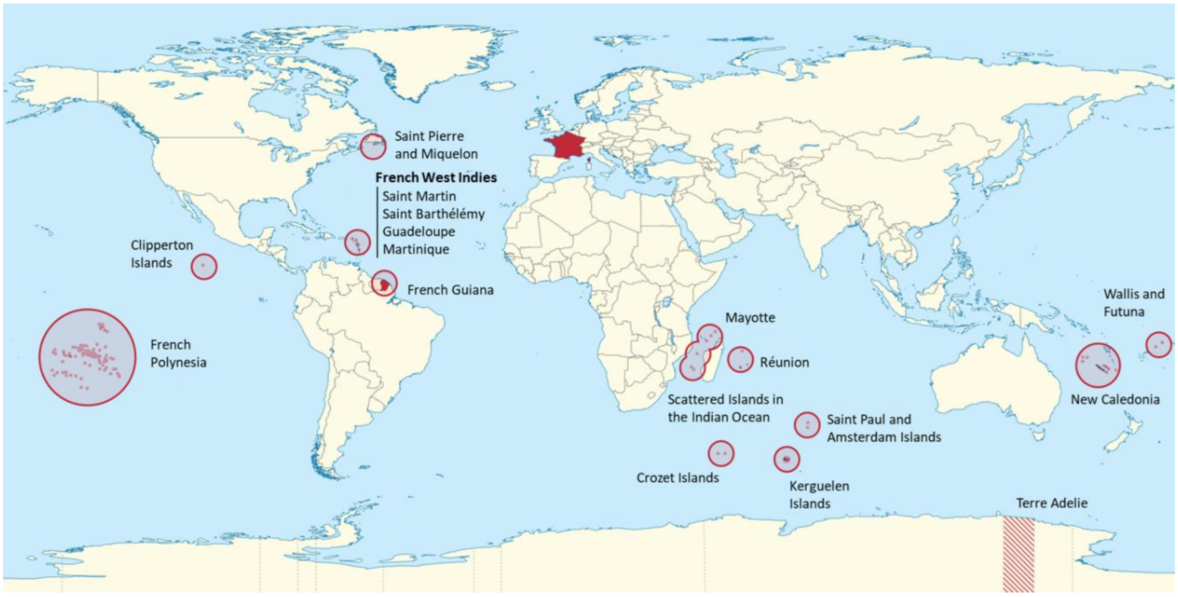

Figure 1 - Location of French overseas territories around the world (© Wikimedia Commons)

The rural development and the role of agriculture overseas, as well as 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 (Fig. 1). As highlighted by the CSA, 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., 2024). This insecticide was also widely applied in Germany, Eastern Europe, the USA, South America and Africa (Cameroon, Ivory Coast) (Cabidoche et al., 2009; Le Déaut & Procaccia, 2009). Toxic to humans and wildlife, highly persistent and bioaccumulative (Comte et al., 2022; 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 (Stockholm Convention on Persistent Organic Pollutants, 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. 2020; Multignier 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 (Plan chlordécone IV, 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 effects 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, 2000 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 2000 - 30 September 2024)
French West Indies (Q2)	TS=(la martinique OR martinique OR “martinique island” OR “petites antilles” OR “petites caraibes” OR “petites caraïbes” OR “iles 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 carribean*” 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 butterfl* OR beetle* OR grasshopper* OR earwig* OR grasshopper* OR carabid* OR andrenidae OR ant$ OR “aphid enem*” OR apidea OR apis OR apoidea OR bombus OR bombyliidae OR bumbleblee 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 (Q7)

TS=((continental 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 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* 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* 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 “agro-ecological 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

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The combination of Q1*Q2*Q3 provided 177 papers; that of Q1*Q2*Q4, 166 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 515 and after removing the numerous duplicates, 186 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, 45 papers were retained for further analysis. They were completed by various additional documents known by the authors and which were not retrieved with the Web of Science™.

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 analyzed 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).

Table 2 - Maximum concentrations of chlordecone measured in soil, freshwater, sediment and seawater 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)
Mangrove water (µg/L)	0.22 ± 0.20	Martinique	Chevallier et al. (2019)
Mangrove sediment (µg/kg)	111	Martinique	Dromard et al. (2022b)
Seawater (µg/L)	0.189	Martinique	De Rock et al. (2020)

Several chlordecone transformation products were detected and identified in soils: chlordecone-5b-hydro, dihydrochlordecone, pentachloroindene, trichloroindene-carboxylic acid (isomers 4 and 7), tetrachloroindene-carboxylic acid (isomers 4 and 7), 10-monohydrochlordecone as well as trihydro-chlordecones, tetra-chloroindenes, 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). However, commercial formulations, which may sometimes contain impurities including transformation products (Devault et al., 2016), can also contribute to the detection of transformation products in soils. 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 chlordecone and the apparition of chlordecone 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).

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; Kemarrec, 1980; Nicoloni et al., 2022) (Table 3). 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 3). 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 (Table 3).

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., 2022b), 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 3).

The various components of coastal and open marine ecosystems are likewise contaminated by chlordecone (Tables 2 and 3). 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, 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 (Table 3). Marine megafauna is not devoid of contamination, as chlordecone was found in dolphins and sperm whale blubbers (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).

Table 3 - Maximum concentrations of chlordecone measured in various terrestrial and aquatic organisms in the French West Indies. nd: Not detected

Ecosystem	Species	Organism	Concentration (µg/kg wet weight except when indicated: * means dry weight)	Location	Reference
Terrestrial	**Trees**	*Artocarpus altilis* (Parkinson) Fosberg	55*	Guadeloupe	Nicolini et al. (2022)
		Cecropia schreberiana Miq.	3595*	Guadeloupe	Nicolini et al. (2022)
		Chimarrhis cymosa Jacq.	855*	Guadeloupe	Nicolini et al. (2022)
		Cordia cf. sulcata DC.	5290*	Guadeloupe	Nicolini et al. (2022)
		Inga ingoïdes (Rich.) Willd.	5243*	Guadeloupe	Nicolini et al. (2022)
		Melastomataceae sp1	289*	Guadeloupe	Nicolini et al. (2022)
		Melastomataceae sp2	112*	Guadeloupe	Nicolini et al. (2022)
		Ocotea cf. *krugii* (Mez) R.A.	2406*	Guadeloupe	Nicolini et al. (2022)
		Rubiaceae sp.	452*	Guadeloupe	Nicolini et al. (2022)
		Sapium caribaeum Urb.	0*	Guadeloupe	Nicolini et al. (2022)
		Simarouba amara Aubl.	2106*	Guadeloupe	Nicolini et al. (2022)
		Sterculia caribea R. Br.	91*	Guadeloupe	Nicolini et al. (2022)
		Swietenia mahagony (L.) Jacq.	3*	Guadeloupe	Nicolini et al. (2022)
	Root vegetables	*Colocasia esculenta*	1105.3. ± 225.93	Martinique	Clostre et al. (2015)
		Dioscorea spp.	272.82 ± 55.76	Martinique	Clostre et al. (2015)
		Ipomea batatas	376.49 ± 76.95	Martinique	Clostre et al. (2015)
	Invertebrates	*Amynthas rodericensis*	1.26*	Martinique	Coulis et al. (2024)
		Camponotus sexguttatus	0.118*	Martinique	Coulis et al. (2024)
		Cosmopolites sordidus	1.43*	Martinique	Coulis et al. (2024)
		Dactyloa roquet	3.49*	Martinique	Coulis et al. (2024)
		Eudrilus eugeniae	1.89*	Martinique	Coulis et al. (2024)
		Geoplanidae spp.	8.36*	Martinique	Coulis et al. (2024)
		Hirudinea sp.	8.72*	Martinique	Coulis et al. (2024)
		Lissachatina fulica	0.049*	Martinique	Coulis et al. (2024)
		Otostigmus salticus	9.28*	Martinique	Coulis et al. (2024)
		Pontoscolex corethrurus	8.82*	Martinique	Coulis et al. (2024)
		Perionyx excavatus	0.392*	Martinique	Coulis et al. (2024)
		Scolopendra subspinipes	1.5*	Martinique	Coulis et al. (2024)
		Scolopocryptops ferrugineus	11.5*	Martinique	Coulis et al. (2024)
		Trigoniulus corallinus	0.152*	Martinique	Coulis et al. (2024)
	Birds	*Falco sparverius*	13800	Guadeloupe	Kermarrec (1980)
		Saltator albicollis	8000	Guadeloupe	Kermarrec (1980)
		Melanospiza bicolor	43800	Guadeloupe	Kermarrec (1980)
		Butorides virescens	nd	Guadeloupe	Kermarrec (1980)
	Duck (livestock)	*Cairina moschata* (liver)	1215	Martinique	Jondreville et al. (2014)
		Cairina moschata (abdominal fat)	278	Martinique	Jondreville et al. (2014)
		Cairina moschata (leg with skin)	169	Martinique	Jondreville et al. (2014)
		Cairina moschata (leg without skin)	145	Martinique	Jondreville et al. (2014)
		Cairina moschata (eggs)	1001	Martinique	Jondreville et al. (2014)
	Mammals	Rodent	105600	Guadeloupe	Kermarrec (1980)
		Bos taurus (livestock)	54 (estimate)	Guadeloupe	Collas et al. (2019)
Freshwater	**Plankton**	River mouth plankton	5100	Guadeloupe	Coat et al. (2011)

		Zooplankton	272	Martinique	Dromard et al. (2022a)
		Zooplankton	306	Guadeloupe	Dromard et al. (2022a)
	Algae	Filamentous green algae	2406	Guadeloupe	Coat et al. (2011)
	Invertebrates	*Atya innocous*	2727	Guadeloupe	Monti (2007)
		Atya scabra	1604	Guadeloupe	Coat et al. (2011)
		Cherax quadricarinatus	74.9 ± 51.0	Martinique	Baudry et al. (2022)
		Macrobrachium acanthurus	4486	Guadeloupe	Coat et al. (2011)
		Macrobrachium carcinus	4739	Guadeloupe	Monti (2007)
		Macrobrachium crenulatum	5124	Guadeloupe	Coat et al. (2011)
		Macrobrachium faustinum	5338	Guadeloupe	Coat et al. (2011)
		Macrobrachium heterochirus	4810	Guadeloupe	Coat et al. (2011)
		Macrobrachium spp. (juveniles)	14624	Guadeloupe	Coat et al. (2011)
		Melanoides tuberculata	3570	Guadeloupe	Coat et al. (2011)
		Neritina punctulata	3271	Guadeloupe	Coat et al. (2011)
		Pomacea glauca	2014	Guadeloupe	Coat et al. (2011)
		Xiphocaris elongata (juveniles)	3987	Guadeloupe	Coat et al. (2011)
		Xiphocaris elongata	4002	Guadeloupe	Monti (2007)
	Fish	*Agonostomus monticola*	209	Guadeloupe	Monti (2007)
		Anguilla rostrata	9026	Guadeloupe	Monti (2007)
		Awaous banana	12366	Guadeloupe	Coat et al. (2011)
		Eleotris perniger (juveniles)	6700	Guadeloupe	Coat et al. (2011)
		Eleotris perniger	11733	Guadeloupe	Monti (2007)
		Gobiomorus dormitor	13	Guadeloupe	Monti (2007)
		Oreochromis sp.	386	Martinique	Coat et al. (2006)
		Oreochromis mossambicus	12971	Guadeloupe	Monti (2007)
		Sicydium antillarum	2922	Guadeloupe	Monti (2007)
		Sicydium punctatum	2122	Guadeloupe	Coat et al. (2011)
Mangrove	**Plankton**	Phytoplankton	191.3 ± 38.5	Guadeloupe	Dromard et al. (2018a)
	Invertebrates	*Callinectes* sp.	1547.3 ± 1387.8	Guadeloupe	Dromard et al. (2018b)
		Callinectes sp.	4250	Martinique	De Rock et al. (2020)
		Crassostrea rhizophorae	122.3 ± 3.8	Guadeloupe	Dromard et al. (2018b)
		Crassostrea rhizophorae	969	Martinique	Dromard et al. (2022b)
		Isognomon alatus	12.4	Martinique	Bertrand et al. (2009)
		Shrimp	1332	Martinique	Dromard et al. (2022b)
		Mix of species	300.3 ± 96.4	Guadeloupe	Dromard et al. (2018a)
	Fish	*Anchoa lyolepis*	323.7 ± 47.5	Guadeloupe	Dromard et al. (2018b)
		Anchoa lyolepis	7	Martinique	Coat et al. (2006)
		Atherinella brasiliensis	1800	Martinique	Dromard et al. (2022b)
		Bairdiella ronchus	1800	Martinique	Dromard et al. (2022b)
		Eucinostomus gula	202.3 ± 12.9	Guadeloupe	Dromard et al. (2018b)
		Gerres cinereus	1861	Martinique	Dromard et al. (2022b)
		Harengula clupeola	265.0 ± 137.2	Guadeloupe	Dromard et al. (2018b)
		Mugil curema	1019	Martinique	Dromard et al. (2022b)
		Sparisoma radians	42.0 ± 20.3	Guadeloupe	Dromard et al. (2018a)
		Sphoeroides spp.	2620	Martinique	Dromard et al. (2022b)
		Mix of species	337.5 ± 201.5	Guadeloupe	Dromard et al. (2018a)
Coral reef	**Plankton**	Phytoplankton	30.3 ± 2.1	Guadeloupe	Dromard et al. (2018a)

	Plankton	20.7 ± 2.1	Guadeloupe	Dromard et al. (2018b)
Algae	*Acanthophora spicifera*	11.3 ± 0.6	Guadeloupe	Dromard et al. (2018b)
	Caulerpa racemosa	11	Martinique	Contarini & Dromard (2021)
	Caulerpa sertularoides	31	Guadeloupe	Contarini & Dromard (2021)
	Dictyota spp.	588	Guadeloupe	Contarini & Dromard (2021)
	Dictyota spp.	1458	Martinique	Contarini & Dromard (2021)
	Galaxaura rugosa	2.7	Guadeloupe	Contarini & Dromard (2021)
	Halimeda incrassata	3.8	Guadeloupe	Contarini & Dromard (2021)
	Laurencia sp.	112	Martinique	Contarini & Dromard (2021)
	Lobophora variegata	54	Martinique	Contarini & Dromard (2021)
	Mix of species	2.3 ± 1.1	Guadeloupe	Dromard et al. (2018a)
Invertebrates	*Lithopoma tectum*	21.3 ± 1.5	Guadeloupe	Dromard et al. (2018b)
	Panulirus argus	86.7 ± 18.5	Guadeloupe	Dromard et al. (2018b)
	Panulirus sp.	590	Martinique	De Rock et al. (2020)
	Panulirus spp.	605	Martinique	Dromard et al. (2022b)
	Porites astreoides	2.4 ± 0.5	Guadeloupe	Dromard et al. (2018b)
	Porites furcata	2.6 ± 0.4	Guadeloupe	Dromard et al. (2018b)
	Stichodactyla helianthus	41.7 ± 6.0	Guadeloupe	Dromard et al. (2018b)
	Tripneustes ventricosus	424	Martinique	Dromard et al. (2022b)
Fish	*Acanthurus* spp.	170	Martinique	Dromard et al. (2022b)
	Acanthurus bahianus	nd	Guadeloupe	Bertrand et al. (2009)
	Acanthurus bahianus	4.1	Martinique	Coat et al. (2006)
	Acanthurus chirurgus	12.57 ± 15.42	Martinique	Bodiguel et al. (2011)
	Aulostomus maculatus	413	Martinique	Dromard et al. (2022b)
	Caranx crysos	504	Martinique	Dromard et al. (2022b)
	Cephalopholis fulva	37	Guadeloupe	Bertrand et al. (2009)
	Cephalopholis fulva	nd	Martinique	Bertrand et al. (2009)
	Epinephelus guttatus	41	Guadeloupe	Bertrand et al. (2009)
	Haemulon flavolineatum	29.00 ± 1.73	Martinique	Bodiguel et al. (2011)
	Holocentrus spp.	400	Martinique	Dromard et al. (2022b)
	Holocentrus rufus	92	Guadeloupe	Bertrand et al. (2009)
	Holocentrus rufus	113	Martinique	Bertrand et al. (2009)
	Lutjanus analis	57.83 ± 9.68	Martinique	Bodiguel et al. (2011)
	Lutjanus apodus	160.3 ± 114.9	Guadeloupe	Dromard et al. (2018a)
	Lutjanus apodus	52.61 ± 47.63	Martinique	Bodiguel et al. (2011)
	Lutjanus synagris	133	Martinique	Bertrand et al. (2009)
	Lutjanus synagris	133	Guadeloupe	Dromard et al. (2018a)
	Mulloidicthys martinicus	13	Guadeloupe	Bertrand et al. (2009)
	Ocyurus chrysurus (juveniles)	34.5	Martinique	Bodiguel et al. (2011)
	Ocyurus chrysurus	40	Guadeloupe	Bertrand et al. (2009)
	Ocyurus chrysurus	132	Martinique	Bertrand et al. (2009)
	Pseudupeneus maculatus	18.67 ± 12.34	Martinique	Bodiguel et al. (2011)
	Pterois volitans	87.7 ± 26.1	Guadeloupe	Dromard et al. (2018b)
	Scarus taeniopterus	11.2 ± 1.7	Guadeloupe	Dromard et al. (2018b)
	Scomberomorus sp.	614	Martinique	Bertrand et al. (2009)
	Scomberomorus regalis	12	Guadeloupe	Bertrand et al. (2009)
	Scorpaena plumieri	311	Martinique	Dromard et al. (2022b)
	Sparisoma chrysopterum	17	Guadeloupe	Bertrand et al. (2009)
	Sparisoma chrysopterum	50.5	Martinique	Bertrand et al. (2009)

		Sparisoma viride	nd	Guadeloupe	Bertrand et al. (2009)
		Sparisoma viride	144	Martinique	Dromard et al. (2022b)
		Mix of species	133.6 ± 87.1	Guadeloupe	Dromard et al. (2018a)
Seagrass bed	**Plankton**	Phytoplankton	31.7 ± 2.9	Guadeloupe	Dromard et al. (2018a)
		Padina sp.	4.8	Guadeloupe	Contarini & Dromard (2021)
		Padina sp.	90	Martinique	Contarini & Dromard (2021)
	Seagrass	*Halophila stipulacea*	4.6 ± 0.9	Guadeloupe	Dromard et al. (2018b)
		Syringodium filiforme	6.9 ± 0.3	Guadeloupe	Dromard et al. (2018)
		Thalassia testudinum	3.0 ± 0.6	Guadeloupe	Dromard et al. (2018)
		Thalassia testudinum	47	Martinique	Dromard et al. (2022b)
		Mix of species	10.6 ± 7.6	Guadeloupe	Dromard et al. (2018a)
	Invertebrates	*Amphimedon compressa*	367	Martinique	Dromard et al. (2022b)
		Cerithium vulgatum	27.0 ± 1.0	Guadeloupe	Dromard et al. (2018b)
		Holothuria Mexicana	4.1 ± 2.1	Guadeloupe	Dromard et al. (2018b)
		Holothuria Mexicana	29	Martinique	Dromard et al. (2022b)
		Neopetrosia carbonaria	14.7 ± 1.5	Guadeloupe	Dromard et al. (2018b)
		Panulirus spp.	571	Martinique	Dromard et al. (2022b)
		Panulirus argus	102 ± 29.7	Guadeloupe	Dromard et al. (2018a)
		Tripneustes ventricosus	nd	Guadeloupe	Bertrand et al. (2009)
		Tripneustes ventricosus	<5	Martinique	Bertrand et al. (2009)
	Fish	*Acanthurus* spp.	813	Martinique	Dromard et al. (2022b)
		Archosargus rhomboidalis	24.4 ± 35.4	Martinique	Bodiguel et al. (2011)
		Holocentrus spp.	1454	Martinique	Dromard et al. (2022b)
		Lutjanus griseus	284	Guadeloupe	Dromard et al. (2018a)
		Sparisoma radians	63.3 ± 37.2	Guadeloupe	Dromard et al. (2018b)
		Sphyraena barracuda	169	Guadeloupe	Dromard et al. (2018a)
		Mix of species	154.7 ± 44.6	Guadeloupe	Dromard et al. (2018a)
Marine (overall)	**Plankton**	Plankton	3500	Guadeloupe	Coat et al. (2011)
	Algae	*Sargassum*	2697	Guadeloupe	Devault et al. (2022b)
		Sargassum	798.9	Martinique	Devault et al. (2022b)
		Sargassum sp.	1714	Martinique	Devault et al. (2022a)
		Sargassum sp.	16	Martinique	Contarini & Dromard (2021)
	Invertebrates	*Callinectes danae*	178.35 ± 166.82	Martinique	Bodiguel et al. (2011)
		Callinectes larvatus	1056	Martinique	Bertrand et al. (2009)
		Farfantepenaeus subtilis	445	Martinique	Bertrand et al. (2009)
		Panulirus argus	61	Guadeloupe	Bertrand et al. (2009)
		Panulirus argus	326	Martinique	Bertrand et al. (2009)
		Panulirus guttatus	55	Martinique	Bertrand et al. (2009)
		Strombus gigas	nd	Guadeloupe	Bertrand et al. (2009)
		Strombus gigas	nd	Martinique	Bertrand et al. (2009)
		Mix of species	388	Guadeloupe	Dromard et al. (2016a)
		Mix of species	15200	Martinique	Dromard et al. (2016a)
	Fish	*Bairdiella ronchus*	18.33 ± 7.57	Martinique	Bodiguel et al. (2011)
		Caranx latus	365	?	Dromard et al. (2016a)
		Centropomus undecimalis	158.6 ± 119.7	Martinique	Bodiguel et al. (2011)

	Centropomus undecimalis	628	?	Dromard et al. (2016a)
	Chloroscombrus chrysurus	109.1 ± 85.1	Martinique	Bodiguel et al. (2011)
	Chloroscombrus chrysurus	185	?	Dromard et al. (2016a)
	Coryphaena hippurus	44	Guadeloupe	Bertrand et al. (2009)
	Decapterus sp.	4	Martinique	Coat et al. (2006)
	Diapterus auratus	9.0 ± 2.0	Martinique	Bodiguel et al. (2011)
	Eleotris perniger (juveniles)	6700	Guadeloupe	Coat et al. (2011)
	Eleotris perniger	11733	Guadeloupe	Monti (2007)
	Haemulon bonariense	22.56 ± 5.27	Martinique	Bodiguel et al. (2011)
	Haemulon carbonarium	126	Martinique	Bertrand et al. (2009)
	Haemulon plumieri	32	Martinique	Bertrand et al. (2009)
	Harengula humeralis	194	?	Dromard et al. (2016a)
	Larimus breviceps	129.33 ± 75.57	Martinique	Bodiguel et al. (2011)
	Megalops atlanticus	1760	?	Dromard et al. (2016a)
	Mugil cephalus	705	?	Dromard et al. (2016a)
	Polydactylus virginicus	40.33 ± 15.37	Martinique	Bodiguel et al. (2011)
	Pterois volitans	144	Guadeloupe	Dromard et al. (2016b)
	Scomberomorus cavalla	696	?	Dromard et al. (2016a)
	Selar crumenophthalmus	59.25 ± 22.94	Martinique	Bodiguel et al. (2011)
	Selene vomer	95.67 ± 45.06	Martinique	Bodiguel et al. (2011)
	Thunnus atlanticus	nd	Martinique	Bertrand et al. (2009)
	Umbrina coroides	47	Martinique	Bertrand et al. (2009)
	Mix of species	1760	Guadeloupe	Dromard et al. (2016a)
	Mix of species	705	Martinique	Dromard et al. (2016a)
Cetaceans	*Lagenodelphis hosei*	6.73	Guadeloupe	Méndez-Fernandez et al. (2018)
	Physeter macrocephalus	34.9	Guadeloupe	Méndez-Fernandez et al. (2018)
	Pseudorca crassidens	3.92	Guadeloupe	Méndez-Fernandez et al. (2018)
	Stenella attenuata	12.3	Guadeloupe	Méndez-Fernandez et al. (2018)
Chelonian	*Chelonia mydas* (dermis)	378	Guadeloupe	Dyc et al. (2015)
	Chelonia mydas (egg content)	2.83	Guadeloupe	Dyc et al. (2015)
	Eretmochelys imbricata (dermis)	26.7	Guadeloupe	Dyc et al. (2015)
	Eretmochelys imbricata (egg content)	14.24	Guadeloupe	Dyc et al. (2015)

Chlordecone transfer through ecosystems

Because of its intrinsic properties, chlordecone is strongly adsorbed in soils, particularly the ones in the FWI, which are rich in organic matter and clay (Cabidoche et al., 2009; Fernández-Bayo et al., 2013a; Lewis et al., 2016). 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, dechlorinated derivatives are more mobile in soil than chlordecone (Ollivier et al., 2020). Using TyPol (Typology of Pollutants), a clustering tool based on molecular, environmental and ecotoxicological properties of organic compounds, Benoit et al. (2017) suggested that mono- and di-hydrochlordecone transformation products have similar physicochemical properties to chlordecone, including environmental persistence, and thus might potentially cause similar risks in ecosystems.

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., 2016a; 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., 2016a). More specifically, detritivorous-omnivorous species (*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 carnivorous fish feeding invertebrates, and small fish. The trophic group with the lowest levels of contamination are herbivorous fish (i.e., *Acanthurus bahianus*) (Dromard et al., 2016a). The trophic transfer of chlordecone in coastal marine habitats (mangroves, seagrass beds and coral reefs) was also reported by Dromard et al. (2018a). 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 fresh waters of this island.

For 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).

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 aquatic invertebrates, proteome analysis of the decapod crustacean *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 *Macrobrachium 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., 2017). In fish, various ecotoxicological studies conducted on model species exposed to chlordecone document its capacity to bind to oestrogen (ERα and ERβ) and androgen (AR) receptors, to increase the level of expression of numerous genes involved in the oestrogen synthesis pathway (erβ, erβ, vtg, cyp19a1, cyp17a1, cyp11a1), or to disrupt the histological structure of the female gonad, including decreases in the gonadal-somatic index (Yang et al., 2016). These studies highlighted the impacts of chlordecone on key biological functions such as reproduction and development. 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.

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 with or without chlordecone, shows a change in the abundance of Gram-negative bacterial groups and a decrease in sodium acetate mineralisation in contaminated soils, the nature of 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 prolongated exposure to this organochlorine in the environment (Merlin et al., 2014).

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. (2016a) indicated that the contamination of the marine biota resulted in strong impacts on local fisheries due to fishing activities 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. 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. In particular, 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 beneficiate 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 in the FWI (Pesce et al., 2024). Accordingly, research should also focus on the ecological effects of mixtures containing chlordecone and other PPPs that are reported 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.

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Conflict of interest disclosure

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

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