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Chlordecone pollution and its effects on biodiversity: Knowledge gaps despite 15 years of public policy in the French West Indies

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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,

46 freshwater, and marine ecosystems, revealing chronic exposure of a wide diversity of
47 terrestrial and aquatic organisms. However, despite 15 years of public policy
48 dedicated to developing knowledge on chlordane's fate and socio-economic
49 impacts, there is a significant gap regarding its effects on terrestrial and aquatic
50 biodiversity, and on ecosystem functioning. Future research is needed to characterize
51 the effects of legacy pollution by chlordane and its transformation products on
52 exposed organisms and ecosystems.

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

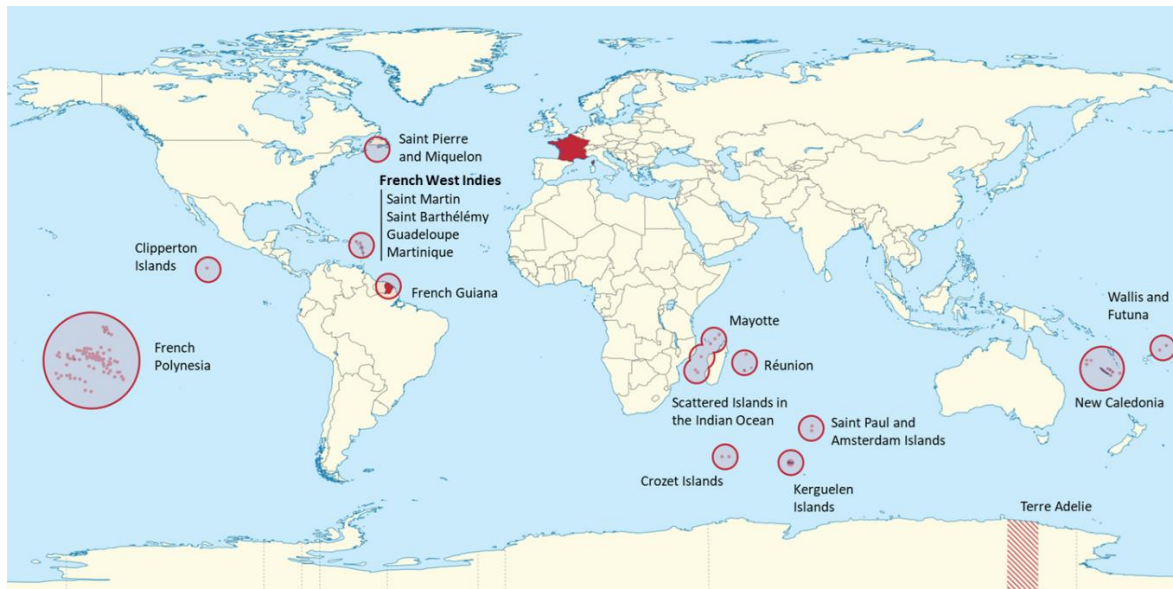
Introduction

58 The scientific community warns of an unprecedented decline in biodiversity due to increasing
 59 human pressure on ecosystems (Tilman et al., 2017). Among the main drivers of this decline,
 60 chemical pollution has been identified as exceeding planetary boundaries (Persson et al., 2022).
 61 This concern is amplified with land and sea use changes, unsustainable direct exploitation of
 62 biological resources, climate change, and invasive alien species (IPBES, 2019). Among chemicals,
 63 plant protection products (PPPs), used for crop protection together with non-agricultural use such
 64 as maintaining gardens, green spaces and infrastructures, are among the substances of concern.
 65 In this challenging context, a collective scientific assessment (CSA) of current scientific knowledge
 66 relating to the impacts of PPPs on biodiversity and ecosystem services was conducted in France,
 67 at the request of several ministries (Pesce et al., 2021; Pesce et al., 2024). The scope of this CSA
 68 covered a wide range of environments excluding groundwater, from the site of PPP application to
 69 the ocean, in mainland France and its overseas territories.

70 The French overseas territories, covering more than 500,000 km², are distributed across all
 71 oceans and predominantly in tropical and equatorial areas (Fig. 1). They include more than 11
 72 Mkm² of marine exclusive economic zone. These territories host a wide terrestrial, freshwater and
 73 marine biodiversity, accounting for 80% of the overall French biodiversity (Gargominy & Boquet,
 74 2011), and for a significant amount of the world's biodiversity (Russell & Kueffer, 2019). However,
 75 this biodiversity is endangered, especially by anthropogenic perturbations, as indicated by the red
 76 list of threatened species established by the International Union for Conservation of Nature (IUCN,
 77 2024). For example, in Guadeloupe and French Guiana, 15% and 10% of terrestrial, marine and
 78 freshwater animal species are threatened with extinction, respectively.

79

80



81

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

84

85 The rural development and the role of agriculture overseas, as well as the use of PPPs, differ
 86 according to the territory. Thus, PPPs are more commonly used in territories that export agricultural
 87 products, such as the French West Indies (FWI), than in small territories with dominant subsistence
 88 agriculture such as Pacific territories (Fig. 1). As highlighted by the CSA, the most studied PPP in
 89 French overseas territories is chlordecone (C₁₀Cl₁₀O), an organochlorine insecticide used
 90 extensively from 1972 to 1993 in the FWI to control the banana root borer (*Cosmopolites sordidus*)

91 (Pesce et al., 2024). This insecticide was also widely applied in Germany, Eastern Europe, the
 92 USA, South America and Africa (Cameroon, Ivory Coast) (Cabidoche et al., 2009; Le Déaut &
 93 Procaccia, 2009). Toxic to humans and wildlife, highly persistent and bioaccumulative (Comte et
 94 al., 2022; Fernández-Bayo et al., 2013b; Lewis et al., 2016; Saaidi et al., 2023), chlordecone is
 95 listed as a persistent organic pollutant (POP) in the Stockholm Convention (Stockholm Convention
 96 on Persistent Organic Pollutants, 2023). Its legacy remains a health, environmental, agricultural,
 97 economic and social current concern of unprecedented magnitude (Andrés-Domenech et al.,
 98 2023; Ayhan et al. 2021; Boum Make, 2022; Dubuisson et al. 2020; Multignier et al., 2010; Resiere
 99 et al., 2023).

100 Since 2008, the French government has successively set up four dedicated action plans to
 101 develop knowledge on chlordecone, to implement measures to reduce environmental
 102 contamination and human exposure, and to improve communication to stakeholders and local
 103 communities aiming at strengthening population protection, still ongoing (Plan chlordécone IV,
 104 2021; Resiere et al., 2023). Regarding the environmental impact, this public policy has improved
 105 and expanded our knowledge about the contamination levels and the fate of chlordecone in the
 106 different compartments of terrestrial and aquatic environments, including vegetal and animal biota.
 107 In this context, the objective of this work is, for the first time, to review the contamination of the
 108 FWI environment by chlordecone, its transfer through ecosystems, and its effects on biodiversity
 109 and ecosystem services.
 110

111 Bibliographic corpus

112 To perform the literature review on the contamination of the environment by chlordecone and
 113 its effects on biodiversity and ecosystem services, nine queries (Q1: chlordecone, Q2: French
 114 West Indies, Q3: Contamination, Q4: Ecotoxicology, Q5: Biodiversity, Q6: Terrestrial ecosystems,
 115 Q7: Freshwater ecosystems, Q8: Marine ecosystems, Q9: Ecosystem services) and related
 116 keywords were formulated (Table 1). The literature search was then conducted on the Web of
 117 Science™ database from January 1st, 2000 to September 30th, 2024.
 118

119 **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 caraïbes" 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 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")

"agroenvironmental goods" OR "agri*environmental goods" OR "agri-environmental goods" OR "ecological good" OR "ecological 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* 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 "agro-environmental 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 "agro-ecological amenities" OR "landscape amenity" OR "landscape amenities" OR "land amenity" OR "land amenities" OR "land-use amenity" OR "land-use amenities" or biodegradation or bio-degradation or denitrif*)

120

121 The combination of Q1*Q2*Q3 provided 177 papers; that of Q1*Q2*Q4, 166 papers;
122 Q1*Q2*Q5, 14 papers; Q1*Q2*Q6, 91 papers; Q1*Q2*Q7, 34 papers; Q1*Q2*Q8, 23 papers;
123 Q1*Q2*Q9, 10 papers. The total number of papers was 515 and after removing the numerous
124 duplicates, 186 papers remained. These papers were read in details and several of them were
125 discarded because they were out of the scope of this review, for instance when dealing exclusively
126 about toxicological studies or human epidemiology. In addition, we focused on the most integrative
127 and ecologically realistic studies as possible. The results of single-species exposure tests were
128 only used if they provided explanatory elements for processes observed under environmental
129 conditions.

130 Therefore, at the end of selection process, 45 papers were retained for further analysis. They
131 were completed by various additional documents known by the authors and which were not
132 retrieved with the Web of Science™.

Environmental contamination by chlordecone

134 In the FWI, chlordecone content in topsoil was extensively mapped in Martinique and at a lesser
 135 extent in Guadeloupe, highlighting a significant contamination in particular in actual and former
 136 banana farming plots and their neighbouring (DAAF, 2024; Desprats, 2021; Devault et al., 2016;
 137 Martin-Laurent et al., 2014). For example, in Martinique, among the 11,349 hectares analysed out
 138 of 112,800 hectares of total territory surface, 52% had a detectable chlordecone concentration,
 139 i.e., above 2 µg/kg, and concentrations varied up to exceed 1 mg/kg in 16.1% of the analyzed soils
 140 (Desprats, 2021). In Guadeloupe, available data produced on 7,236 hectares out of 162,800
 141 hectares of total territory surface showed similar results with 46% of the surface having a
 142 detectable chlordecone concentration, including 20% with soil concentrations exceeding 1 mg/kg
 143 (DAAF, 2024). The highest observed concentrations in soils reached 35.4 mg/kg in Guadeloupe
 144 (Martin-Laurent et al., 2014) and 17.4 mg/kg in Martinique (Devault et al., 2016) (Table 2).
 145

146 **Table 2** - Maximum concentrations of chlordecone measured in soil, freshwater,
 147 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)

148

149

150 Several chlordecone transformation products were detected and identified in soils:
 151 chlordecone-5b-hydro, dihydrochlordecone, pentachloroindene, trichloroindene-carboxylic acid
 152 (isomers 4 and 7), tetrachloroindene-carboxylic acid (isomers 4 and 7), 10-monohydrochlordecone
 153 as well as trihydro-chlordecones, tetra-chloroindenes, a monohydrochlordecol derivative, and two
 154 dichloroindene-carboxylic acids (Chevallier et al., 2019). Most of these transformation products
 155 come from abiotic and/or biotic (mostly microbial) degradation. Their reported concentrations vary
 156 from a few µg/kg to 5 mg/kg depending on the soil type (Chevallier et al., 2019). However,
 157 commercial formulations, which may sometimes contain impurities including transformation
 158 products (Devault et al., 2016), can also contribute to the detection of transformation products in
 159 soils. Microbial degradation of chlordecone leading to several transformation products was
 160 observed under anaerobic conditions in microbial enrichment cultures, carried out from wastewater
 161 sludges collected in treatment plant exposed to chlordecone (Chaussonnerie et al., 2016). In
 162 addition, anaerobic digestion of plant and animal waste contaminated with chlordecone led to the
 163 dissipation of chlordecone and the apparition of chlordecone transformation products, thereby
 164 offering the possibility of treating organic wastes produced by farming in methanogenic conditions
 165 and stopping further recirculation of chlordecone in the environment (Martin et al., 2023).

166 In terrestrial biota, chlordecone accumulation has been documented in livestock (Collas et al.,
 167 2019; Collas et al., 2023; Jondreville et al., 2014; Lastel, 2015) and more occasionally in wildlife
 168 (Coulis et al., 2024; Kermarrec, 1980; Nicoloni et al., 2022) (Table 3). In Guadeloupe and
 169 Martinique, concentrations ranging from 0.1 to 43.8 mg/kg wet weight (ww) were measured in livers
 170 of four wild bird species (Kermarrec, 1980) while concentrations up to 105.6 mg/kg ww were
 171 reported in rats sampled in Guadeloupe (Kermarrec, 1980) (Table 3). Terrestrial phytophagous
 172 organisms are more likely to be exposed to chlordecone if they consume underground parts of

173 plants, and to its 5b-hydro derivative if they consume aerial parts (Clostre et al., 2015). This
174 observation was further confirmed by Coulis et al. (2024) reporting the important contamination of
175 endogenous earthworms, and suggesting that geophagy was the main route of soil macrofauna
176 contamination by chlordecone and its transformation products (Table 3).

177 In rivers, chlordecone was found in surface waters (e.g. Della Rossa et al., 2017; Mottes et al.,
178 2017 ; Mottes et al., 2020 ; Rochette et al., 2020), sediments (e.g. Bertrand et al., 2009; Bocquené
179 & Franco, 2005; Bouchon et al., 2016; Coat et al., 2011; Dromard et al., 2022b), and biota (e.g.
180 Baudry et al., 2022 ; Coat et al., 2011). The concentrations reached 44 µg/L in water, 552 µg/kg
181 dry weight (dw) in sediments (Table 2), and more than 10 mg/kg ww in fish and crustaceans
182 sampled in Guadeloupe (Coat et al., 2011; Monti, 2007) (Table 3).

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

190 Chlordecone has not been detected in air quality monitoring in the FWI despite methodological
191 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 ($\mu\text{g}/\text{kg}$ wet weight except when indicated: * means dry weight)	Location	Reference
Terrestrial	Trees	<i>Artocarpus altilis</i> (Parkinson) Fosberg	55*	Guadeloupe	Nicolini et al. (2022)
		<i>Cecropia schreberiana</i> Miq.	3595*	Guadeloupe	Nicolini et al. (2022)
		<i>Chimarrhis cymosa</i> Jacq.	855*	Guadeloupe	Nicolini et al. (2022)
		<i>Cordia cf. sulcata</i> DC.	5290*	Guadeloupe	Nicolini et al. (2022)
		<i>Inga ingoides</i> (Rich.) Willd.	5243*	Guadeloupe	Nicolini et al. (2022)
		<i>Melastomataceae</i> sp1	289*	Guadeloupe	Nicolini et al. (2022)
		<i>Melastomataceae</i> sp2	112*	Guadeloupe	Nicolini et al. (2022)
		<i>Ocotea cf. krugii</i> (Mez) R.A.	2406*	Guadeloupe	Nicolini et al. (2022)
		<i>Rubiaceae</i> sp.	452*	Guadeloupe	Nicolini et al. (2022)
		<i>Sapium caribaeum</i> Urb.	0*	Guadeloupe	Nicolini et al. (2022)
		<i>Simarouba amara</i> Aubl.	2106*	Guadeloupe	Nicolini et al. (2022)
		<i>Sterculia caribea</i> R. Br.	91*	Guadeloupe	Nicolini et al. (2022)
		<i>Swietenia mahagony</i> (L.) Jacq.	3*	Guadeloupe	Nicolini et al. (2022)
		Root vegetables	<i>Colocasia esculenta</i>	1105.3. \pm 225.93	Martinique
	<i>Dioscorea</i> spp.		272.82 \pm 55.76	Martinique	Clostre et al. (2015)
	<i>Ipomea batatas</i>		376.49 \pm 76.95	Martinique	Clostre et al. (2015)
	Invertebrates	<i>Amyntas rodericensis</i>	1.26*	Martinique	Coulis et al. (2024)
		<i>Camponotus sexguttatus</i>	0.118*	Martinique	Coulis et al. (2024)
		<i>Cosmopolites sordidus</i>	1.43*	Martinique	Coulis et al. (2024)
		<i>Dactyloa roquet</i>	3.49*	Martinique	Coulis et al. (2024)
		<i>Eudrilus eugeniae</i>	1.89*	Martinique	Coulis et al. (2024)
		<i>Geoplanidae</i> spp.	8.36*	Martinique	Coulis et al. (2024)
		<i>Hirudinea</i> sp.	8.72*	Martinique	Coulis et al. (2024)
		<i>Lissachatina fulica</i>	0.049*	Martinique	Coulis et al. (2024)
		<i>Otostigmus salticus</i>	9.28*	Martinique	Coulis et al. (2024)
		<i>Pontoscolex corethrurus</i>	8.82*	Martinique	Coulis et al. (2024)
		<i>Perionyx excavatus</i>	0.392*	Martinique	Coulis et al. (2024)
		<i>Scolopendra subspinipes</i>	1.5*	Martinique	Coulis et al. (2024)
		<i>Scolopocryptops ferrugineus</i>	11.5*	Martinique	Coulis et al. (2024)
		<i>Trigoniulus corallinus</i>	0.152*	Martinique	Coulis et al. (2024)
		Birds	<i>Falco sparverius</i>	13800	Guadeloupe
	<i>Saltator albicollis</i>		8000	Guadeloupe	Kermarrec (1980)
	<i>Melanospiza bicolor</i>		43800	Guadeloupe	Kermarrec (1980)
	<i>Butorides virescens</i>		nd	Guadeloupe	Kermarrec (1980)
	Duck (livestock)	<i>Cairina moschata</i> (liver)	1215	Martinique	Jondreville et al. (2014)
		<i>Cairina moschata</i> (abdominal fat)	278	Martinique	Jondreville et al. (2014)
		<i>Cairina moschata</i> (leg with skin)	169	Martinique	Jondreville et al. (2014)
		<i>Cairina moschata</i> (leg without skin)	145	Martinique	Jondreville et al. (2014)
		<i>Cairina moschata</i> (eggs)	1001	Martinique	Jondreville et al. (2014)
	Mammals	Rodent	105600	Guadeloupe	Kermarrec (1980)
		<i>Bos taurus</i> (livestock)	54 (estimate)	Guadeloupe	Collas et al. (2019)
	Freshwater	Plankton	River mouth plankton	5100	Guadeloupe

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

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

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

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

Chlordecone transfer through ecosystems

196 Because of its intrinsic properties, chlordecone is strongly adsorbed in soils, particularly the
197 ones in the FWI, which are rich in organic matter and clay (Cabidoche et al., 2009; Fernández-
198 Bayo et al., 2013a; Lewis et al., 2016). The main source of chlordecone input to aquatic
199 environments is soil leaching and erosion (Crabit et al., 2016; Della Rossa et al., 2017; Mottes et
200 al., 2016). Chlordecone inputs are therefore highly dependent on rainfall (De Rock et al., 2020) but
201 also on soil type and cover (Sabatier et al., 2021). Once in the coastal environment, a decreasing
202 gradient is observed from the coast to the open sea (Bodiguel et al., 2011; Bodiguel & Doussan,
203 2021; De Rock et al., 2020; Dromard et al., 2018a).

204 Considering the transformation products, dechlorinated derivatives are more mobile in soil than
205 chlordecone (Ollivier et al., 2020). Using TyPol (Typology of Pollutants), a clustering tool based on
206 molecular, environmental and ecotoxicological properties of organic compounds, Benoit et al.
207 (2017) suggested that mono- and di-hydrochlordecone transformation products have similar
208 physicochemical properties to chlordecone, including environmental persistence, and thus might
209 potentially cause similar risks in ecosystems.

210 The contamination of aquatic food webs by chlordecone is to date the best described due to
211 the large number of species that have been analysed. Two modes of contamination appear:
212 contamination by bathing on the one hand, which depends on the concentration in the water, and
213 contamination by trophic route on the other hand, with bioaccumulation or even biomagnification
214 in certain cases along freshwater or marine food webs (Bodiguel et al., 2011; Coat et al., 2006;
215 Coat et al., 2011; De Rock et al., 2020; Dromard et al., 2016a; Dromard et al., 2018a; Méndez-
216 Fernandez et al., 2018). The bioaccumulation (and/or depuration) of chlordecone depends on the
217 feeding mode and on the location of the species, and therefore varies among species. In fish living
218 in the FWI coastal environments, chlordecone accumulation depends both on the geographical
219 location of populations in relation to discharge points and on the trophic behavior of the species.
220 Thus, the highest chlordecone levels were observed in fish populations living in coastal
221 mangroves, where terrestrial sediments and organic matter accumulation is favored by the strong
222 presence of roots in these ecosystems, and because mangroves are calm and semi-enclosed
223 areas which receive direct discharges of chemical from the terrestrial ecosystem (Dromard et al.,
224 2016a). More specifically, detritivorous-omnivorous species (*Oreochromis mossambicus*:
225 maximum concentration of 1036 µg/kg; *Mugil cephalus*: 705 µg/kg; *Mugil curema*: 690 µg/kg) are
226 the most contaminated trophic group, followed by carnivorous fish feeding invertebrates, and small
227 fish. The trophic group with the lowest levels of contamination are herbivorous fish (i.e., *Acanthurus*
228 *bahianus*) (Dromard et al., 2016a). The trophic transfer of chlordecone in coastal marine habitats
229 (mangroves, seagrass beds and coral reefs) was also reported by Dromard et al. (2018a). In this
230 study, all Trophic Magnification Factors (TMF) values exceeded 1, indicating that chlordecone
231 levels are biomagnified along food webs. Interestingly, the study indicates that the level of
232 contamination varied considerably between wet and dry seasons in seagrass beds with higher
233 contamination during the rainy season. Reef organisms were more moderately affected by this
234 pollution, while mangrove organisms showed a high level of chlordecone whatever the season.
235 Low concentrations of chlordecone were likewise detected in marine mammal fat tissues in
236 Guadeloupe's coastal environments (Méndez-Fernandez et al., 2018). The authors indicate that
237 these concentrations are much lower than those provided by the literature in organisms living in
238 brackish or fresh waters of this island.

239 For terrestrial ecosystems, contaminated soils could be a possible source of contamination for
240 terrestrial invertebrates and vertebrates. A recent study carried out on domestic pigs whose diet
241 includes soil ingestion gives details on chlordecone contamination by this way (Collas et al., 2023).

Chlordecone effects on biodiversity and ecosystem services

245 Despite more than 15 years of public policy to increase knowledge on chlordecone fate and
246 impacts, little is known on the effect of this insecticide on biodiversity. The main studies about the
247 ecotoxicological effects of chlordecone were mostly performed on mono-specific experiments,
248 mainly carried out under controlled conditions with experimental exposure concentrations
249 generally higher than those detected in contaminated ecosystems (e.g. Moreau et al., 2022). In
250 aquatic invertebrates, proteome analysis of the decapod crustacean *Macrobrachium rosenbergii*
251 exposed to three environmental relevant concentrations of chlordecone (i.e., 0.2, 2 and 20 µg/L)
252 revealed that 62 proteins were significantly up- or down-regulated in exposed organisms,
253 compared to control animals. Impacted proteins are involved in various physiological processes
254 such as ion transport, immune system, or protein synthesis and degradation. Moreover, 6% of the
255 deregulated proteins are involved in the endocrine system and in the hormonal control of
256 reproduction or development processes of *Macrobrachium rosenbergii*, such as vitellogenin or
257 farnesoic acid o-methyltransferase. These results indicate that chlordecone is a potent endocrine
258 disruptor compound for decapod crustaceans (Lafontaine et al., 2017). In fish, various
259 ecotoxicological studies conducted on model species exposed to chlordecone document its
260 capacity to bind to oestrogen (ER α and ER β) and androgen (AR) receptors, to increase the level
261 of expression of numerous genes involved in the oestrogen synthesis pathway (er β , er β , vtg,
262 cyp19a1, cyp17a1, cyp11a1), or to disrupt the histological structure of the female gonad, including
263 decreases in the gonadal-somatic index (Yang et al., 2016). These studies highlighted the impacts
264 of chlordecone on key biological functions such as reproduction and development. While these
265 disturbances at individual level could have an impact on the animal populations concerned, no
266 study provides information on the effects at higher levels of organisation, namely populations,
267 communities, or ecosystems.

268 In terrestrial wildlife, although experimental studies have shown that chlordecone is
269 carcinogenic, reprotoxic and neurotoxic for mammals and birds (Multigner et al., 2016), and
270 despite exposure was demonstrated (see above), the absence of data on the effects of
271 chlordecone contamination on individuals and populations is noted. Only a study conducted on the
272 red-bellied kingfisher (*Megaceryle torquata stictipennis*) in Guadeloupe suggests a link between
273 population decline of this species and the contamination of their habitat by chlordecone but no
274 additional monitoring has been made, for instance on exposure or life-traits, to support this
275 assumption (Villard et al., 2021).

276 To our knowledge, only one study, performed under experimental conditions, investigated the
277 effects of chlordecone at the community level, by considering soil microorganisms. This work,
278 carried out on different soils with or without chlordecone, shows a change in the abundance of
279 Gram-negative bacterial groups and a decrease in sodium acetate mineralisation in contaminated
280 soils, the nature of which allows greater availability of chlordecone (Merlin et al., 2016). Another
281 work showed that a total of 103 fungal strains isolated from different FWI soils contaminated with
282 chlordecone were able to grow on chlordecone-mineral salt media, among which the *Fusarium*
283 *oxysporum* MIAE01197 isolate was found to be tolerant to chlordecone because of its prolonged
284 exposure to this organochlorine in the environment (Merlin et al., 2014).

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

294

Conclusion and research needs

295 The review of the literature shows that both the environment and biota are significantly
296 impregnated by chlordecone and its transformation products in the FWI. The processes involved
297 in the abiotic and biotic transformation of chlordecone in the environment remain poorly described
298 and understood. In addition, little is known about the effects of this insecticide and its
299 transformation products on the biodiversity and the related ecosystem services in the
300 contaminated terrestrial and aquatic environments. In particular, there are almost no studies
301 documenting the effects of chlordecone on groups that ensure key functions within ecosystems,
302 such as pollinators, earthworms or microbial communities, and also on the functions and
303 ecosystem services provided by such engineer species.

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

316 Finally, this knowledge must not be limited to chlordecone alone as this organochlorine is far
317 from being the sole PPP that contaminates ecosystems in the FWI (Pesce et al., 2024).
318 Accordingly, research should also focus on the ecological effects of mixtures containing
319 chlordecone and other PPPs that are reported in these territories.

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

322

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334

Conflict of interest disclosure

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