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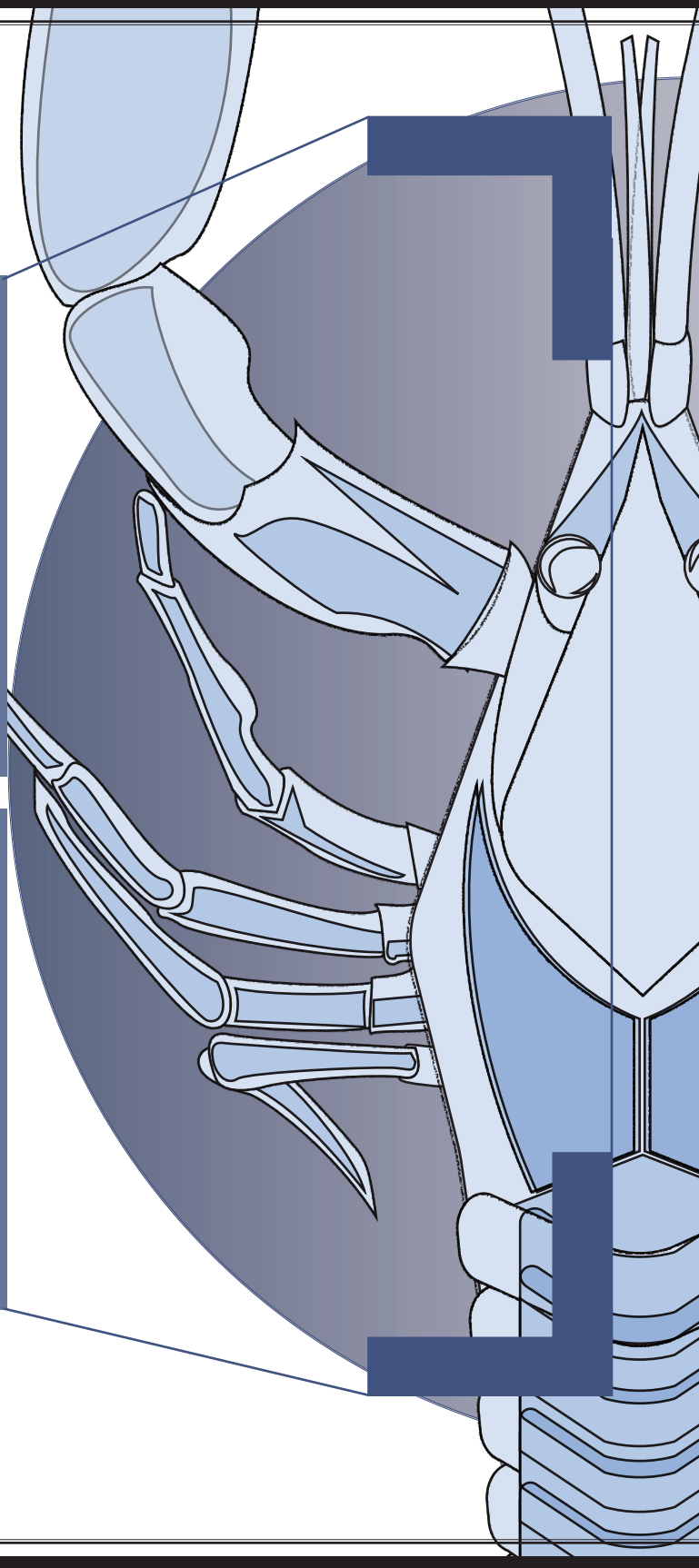
Literature Review for Candidate Chemical Control Agents for Nonnative Crayfish



Open-File Report 2021–1048

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Front cover. Crayfish Illustration by David Bruce, U.S. Geological Survey, Science Publishing Network. Upper inset photograph of *Procambarus clarkii* (red swamp crayfish) by Justin Smerud, biologist, U.S. Geological Survey. Lower inset photograph of gnawed tree in the Agashashok River, Alaska, by Michael Carey, research fish biologist, U.S. Geological Survey.

Back cover. Background photograph of Sugar Creek, Indiana, by Megan Saksa, hydrologist, U.S. Geological Survey. Upper inset photograph of Pole Bridge Creek, Georgia, by Alan Cressler, hydrologic technician, U.S. Geological Survey. Lower inset photograph of Kettle Lake, Colorado, by Laura Hempel, hydrologist, U.S. Geological Survey.

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By Justin R. Schueller, Justin R. Smerud, Kim T. Fredricks, and Joel G. Putnam

Prepared in cooperation with the U.S. Fish and Wildlife Service

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
	Mass	
microgram (µg)	$3.5274 \times 10 -8$	ounce, avoirdupois (oz)
milligram (mg)	$3.527 \times 10 -5$	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F = (1.8 \times °C) + 32$.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Absorption values of chemicals to sediment are given in micrograms per gram (µg/g).

Molecular weight values of chemicals are given in grams per mole (g/mol).

Abbreviations

LC_{50}	lethal concentration to produce fifty percent mortality in test species
EPA	United States Environmental Protection Agency

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Abstract

Nonnative crayfish are an immediate and pervasive threat to aquatic environments and their biodiversity. Crayfish control can be achieved by physical methods, water chemistry modification, biological methods, biocidal application, and application of crayfish physiology modifiers. The purpose of this report is to identify suitable candidates for potential control of nonnative crayfish through a comprehensive literature review. This review focuses on control methods, specifically on the available data to support registration of a crayfish pesticide. The literature search resulted in 28,058 documents, which were searched to determine if they contained information on physical, chemical, biological, and (or) biocidal approaches to control crayfish. Pesticides directly toxic to crayfish in this literature review include: pyrethroids (natural pyrethrins and synthetic), fipronil, mirex, antimycin-A, and rotenone. Some chemicals, such as diflubenzuron and emamectin benzoate, alter crayfish physiology resulting in a lower pesticide dose needed to control crayfish. Environmental damage, application rate, exposure duration, nontarget effects, environmental persistence, and registration data gaps were used as criteria to define which pesticides are potentially selective to crayfish, along with which have the greatest amount of data to support registration by the U.S. Environmental Protection Agency.

Synthetic pyrethroids were identified as the most likely candidate to be developed into a crayfish pesticide. A type-2 synthetic pyrethroid, cyfluthrin, has the greatest potential for eradicating nonnative crayfish. Although other invertebrate species will be negatively affected at the concentrations required for crayfish control, compared with other pyrethroids and other potential control chemicals, cyfluthrin offers rapid ecosystem recovery due to being more selective, having fewer effects on native fish, and having a short aquatic persistence. Cyfluthrin also has few data gaps for U.S. Environmental Protection Agency registration purposes.

Introduction

Nonnative crayfish are an immediate and pervasive threat to aquatic environments and are listed under the Species Action Framework as species that pose a significant threat to biodiversity and catastrophic regime shift (Hill and Lodge, 1999; McCarthy, 2006; Gladman and others, 2009; Matsuzaki and others, 2009; Hansen and others, 2013; Twardochleb and others, 2013; James and others, 2015). Nonnative crayfish can reduce aquatic plant diversity by consuming shoreline vegetation (Schuytema, 1977); decrease length and growth of certain macrophytes (Chambers and others, 1990); and cause declines in native fish, amphibian, and invertebrate species populations (Schuytema, 1977; Bills and Marking, 1988; Chambers and others, 1990; Hanson and others, 1990; Gamradt and others, 1997; Dorn and Mittelbach, 2004; Griffiths and others, 2004; Kerby and others, 2005). Additionally, lacustrine and riverine environments contain endemic and rare crayfish species that contribute to ecosystem biodiversity (Griffiths and others, 2004) and that are threatened by the introduction of nonnative crayfish (Kerby and others, 2005). At least ten crayfish species have been introduced across the United States and four are considered widespread nonnative species (https://nas.er.usgs.gov/): *Procambarus clarkii* (red swamp crayfish), *Faxonius rusticus* (rusty crayfish; previously *Orcenectes rusticus*), *Orcenectes virilis* (virile crayfish), and *Pasifastacus lenusculus* (signal crayfish). Several approaches to nonnative crayfish control have been explored including physical removal, alterations to habitat, biological controls, and chemical controls.

Attempts to eradicate nonnative crayfish have included habitat destruction, establishment of barriers, and trapping. Habitat destruction typically reduces populations of crayfish (Peay, 2001) but does not eradicate populations and affects endemic and rare species (Stebbing and others, 2014). Barriers are designed to prevent or slow the spread of crayfish into new areas but are not successful for permanent control (Peay 2001; Hyatt, 2004). Trapping can remove large numbers of nonnative crayfish but is very labor intensive, does not eradicate populations, and can have size and sex catch bias (Bills and Marking, 1988; Holdich and Gherardi, 1999; Peay and others, 2006; Stebbing and others, 2014; O'Reilly, 2015; Longshaw and Stebbing, 2016).

Modifications to water quality has been identified as a nonnative species management strategy. By adjusting ammonia, pH, and oxygen concentration, nonnative species can be potentially controlled without persisting negative environmental effects (Hyatt, 2004). However, altered water chemistry may also negatively affect nontarget populations. Adjusting water pH and ammonia can cause nontarget organism mortality (Tarazona and others, 1987; Bergerhouse, 1992; Mummert and others, 2003). Deoxygenation can be used in tandem with a pesticide to control crayfish; deoxygenation stimulates crayfish to leave their burrows, exposing the crayfish to higher chemical concentrations (Peay 2001; Peay and others, 2006). Carbon dioxide, a pesticide approved by the U.S. Environmental Protection Agency (EPA) for control of other aquatic nuisances (Cupp and others, 2020), causes avoidance behavior in several fish species (Donaldson and others 2016) and is effective in altering behavior of nonnative crayfish in water (Bierbower and Cooper, 2010; Fredricks and others, 2020). Concentrations of carbon dioxide required to alter crayfish behavior may cause nontarget organism mortality (Cupp and others, 2020). Methods to modify water quality to control nonnative crayfish would require further research for EPA registration. Also, most states have water quality standards for pH and ammonia that cannot be violated, and these standards may not allow for crayfish control using pH and ammonia or may require coordination with state agencies to utilize these types of control technique.

Biological controls (such as parasites, pathogens, and predators) also have potential to be used as invasive species control tools (Meyer and Fourdrigniez, 2011; Gherardi and others, 2011). Parasites have reduced crayfish populations (Sargent and others, 2014; Imhoff and others, 2012). Pathogens such as fungi, bacteria, and viruses have been linked with selective crayfish mortality and may be useful to control their populations (Alderman, 1996; Aquiloni and others, 2011; Freeman and others, 2010; McMahon and others, 2013; Martin-Torrijos and others, 2019).) The use of biological controls such as parasites and disease would require substantial research for registration for crayfish control.

Predation to control populations of invasive species is dependent on habitat, water quality, and management of predators but may improve the overall success of control (Hein and others, 2007; Freeman and others, 2010). The use of biological controls such as predation require additional research to identify the potential ecological effects of introducing a new species or disease.

Many existing integrated pest management strategies used to control nuisance species rely on the use of chemicals (Peay, 2001; Kasai and others, 2016). These chemicals (pesticides) may play an important role in nonnative crayfish control, but unfortunately no chemical has been registered for use in the United States to control crayfish. Several chemicals (such as pyrethroids, fipronil, diflubenzuron, mirex, antimycin-A, rotenone, and emamectin benzoate [avermectin]) have been reported to kill crayfish and may have existing data that could be used to support registration. The objective of this report is to identify chemicals for which data on (1) selectivity to crayfish and (2) pesticide registration exist that together warrant further research to develop as a nonnative crayfish pesticide. We completed an intensive literature review for pyrethrins, pyrethroids, fipronil, diflubenzuron, mirex, antimycin-A, rotenone, and avermectin to determine their potential to be registered through EPA as a crayfish-specific pesticide.

Methods

We performed a preliminary literature search for chemicals that could be rapidly developed into crayfish pesticides and identified eight chemicals as potential crayfish pesticides. Then we completed a comprehensive literature search focused on the potential to register pyrethrins, pyrethroids, fipronil, diflubenzuron, mirex, antimycin-A, rotenone, and avermectin as nonnative crayfish pesticides. Our comprehensive search focused on chemical selectivity to crayfish and requirements for EPA registration as a potential pesticide. We searched the Web of Science and Scopus databases using multiple search terms related to selectivity and registration (appendix 1). Search terms were developed from the data requirements for pesticide registration (U.S. Office of the Federal Register [USOFR], 2017). Information identified in the literature search was reviewed for potential to fill identified registration data gaps. We screened through Reregistration Eligibility Decisions for each chemical. The Master Record Identifiers (MRID) was reported when it existed for a specific guideline (guidelines from the US Code of Federal Regulations Title 40:Protection of Environment, Chapter 1:Environmental Protection Agency, Subchapter E:Pesticide Programs, Part 158:Data Requirements for Pesticides, Subparts: F:Toxicology, G: Ecological Effects, K: Human Exposure, and N: Environmental Fate).

We screened EPA's ECOTOX Knowledgebase (https://cfpub.epa.gov/ecotox/) to identify if the chemicals were toxic to crayfish and nontarget species to assess if levels of toxicity were similar (appendix 2). We searched the database for pyrethrins (Pyblast, and pyrethrins) type-1 pyrethroids (permethrin), type-2 pyrethroids (cyfluthrin), fipronil, diflubenzuron, mirex, antimycin-A, rotenone, and emamectin benzoate (avermectin). Pyrethrin was used as a surrogate for Pyblast. Permethrin was selected as a representative from the pyrethrin type-1 synthetic pyrethroid data and cyfluthrin was selected as a representative for the pyrethrin type-2 synthetic pyrethroid data. Data from the ECOTOX database were downloaded on April 25, 2019.

The preliminary search indicated mirex as a potential crayfish pesticide. Mirex is an organochloride that was used to control ants. Its use was prohibited by EPA in 1978 and Stockholm Convention on Persistent Organic Pollutants due to its environmental persistence and bioaccumulation concerns (Eisler, 1985). Mirex is not included in the results section because the actions by EPA and the Stockholm Convention make it unlikely to be registered as a crayfish control tool.

Results

Potential nonnative crayfish pesticides (including pyrethrins, pyrethroids, fipronil, antimycin-A, rotenone, diflubenzuron, and emamectin benzoate) are discussed in the following sections. Previous uses, crayfish toxicity, nontarget toxicity, and environmental fate data are reviewed. EPA registration data gaps, and the potential for the reviewed literature filling these data gaps are discussed. Tables 1–4 contain a list of data requirements (located in 40 CFR Part 158 [USOFR, 2017]) for pesticides, if there are data accepted by the EPA for the requirement, and if relevant data were identified to potentially fill an identified data gap.

Pyrethroids

The insecticide Pyblast is produced naturally by the flower *Chrysanthemum cinerariefolium* (Matsuda, 2011). Pyblast (pyrethrins) is separated from the synthetic pyrethroids based on their environmental persistence and toxicity. Pyrethroids were separated into two categories: type-1 and type-2. Type-1 pyrethroids lack an α-cyano group (Wolansky and others, 2006), and produce repetitive nerve discharge in target organisms (Palmquist and others, 2012).

Pyblast (Pyrethrins)

Pyblast, natural pyrethrins, are separated from synthetic pyrethroids based on differences in environmental persistence and toxicity.

Aquatic Toxicity

Pyblast has been used to control nonnative crayfish is Scotland and Italy (Peay and others, 2006; Cecchinelli and others, 2012; O'Reilly, 2015). Much of the crayfish toxicity data available for Pyblast is from signal crayfish (table 2.1). Pyblast seems more toxic to hatchlings (less than 1-year-old crayfish) than adults (O'Reilly 2015; table 2.1). Crayfish evacuated water when Pyblast was applied (Hyatt, 2004). Treatment efficacy might be increased if the area surrounding the waterbody is treated, because crayfish placed on Pyblast treated ground were dead within 1 hour (Hyatt, 2004). It is important to note that Pyblast loses much of its terrestrial application efficacy after one hour (Hyatt, 2004).

The concentration of Pyblast needed for complete adult crayfish mortality is greater than concentrations likely to cause significant mortality to other aquatic invertebrates and fish species (table 2.2). The use of Pyblast may affect other aquatic organisms such as amphibians. The life history of amphibians suggests that they may recolonize treated ponds through overland movements from refugia (Hall and others, 2013). Pyblast has low mammalian and avian toxicity (Peay and others, 2006).

Environmental Persistence

Literature values for the environmental persistence of Pyblast varies. Peay and others (2006) report a half-life of 48 hours in water compared to the environmental persistence varying from hours to several days prior to degradation reported by Gerberding (2003). Hyatt (2004) reported even more rapid degradation with significant chemical losses within an hour after application. Photodegradation and sediment binding occur at extremely rapid rates (O'Reilly, 2015). Pyblast has a strong binding affinity to sediment where microbial degradation rapidly occurs (Gerberding, 2003; Todd and others, 2003). It has not been determined to biomagnify (Peay and others, 2006; O'Reilly, 2015).

Registration Data Gaps for Pyblast

Data gaps for Pyblast are identified in tables 1–4**.** Pyrethrin is registered with EPA as a terrestrial insecticide. Potential data have been reported for guideline 835.1230–adsorption/desorption (Antonius and others, 2011). No relevant data were identified for: guideline 835.1230–adsorption/desorption (batch equilibrium) except as noted in tables 1–4**.** The remaining data gaps include: guidelines 835.2240–photodegradation in water, 835.6200–aquatic (sediment) field dissipation, 850.1300–aquatic invertebrate life cycle (freshwater), 850.1400–fish early-life stage (freshwater), 850.4100–seedling emergence, 850.4150–vegetative vigor, and 850.4400–aquatic plant growth.

Type-1 Pyrethroids (Primarily Permethrin)

Type-1 pyrethroids (primarily permethrin) lack an α-cyano group (Wolansky and others, 2006) and produce repetitive nerve discharge in target organisms (Palmquist and others, 2012).

Aquatic Toxicity

The available toxicity data for type-1 pyrethroids for crayfish are primarily for permethrin (table 2.3). Permethrin caused complete mortality of signal crayfish after a 1-hour laboratory exposure at 6 micrograms per liter (µg/L; (Peay, 2001). Type-1 pyrethroids have similar toxicity to crayfish and other aquatic invertebrates thus environmental applications at rates lethal to crayfish would likely be lethal to most other aquatic invertebrates present. Some species of fish are less susceptible than crayfish to permethrin, whereas others are equally susceptible (table 2.4), indicating the potential for effects to some fish species from permethrin applications with permethrin at concentrations needed to eradicate crayfish. *Pimephales promelas* (Fathead minnow) exposed to the type-1 pyrethroid esfenvalerate at 0.455 and 1.142 µg/L displayed impaired swimming and feeding behaviors even after being transferred to clean water, suggesting that some organisms

Table 1. The U.S. Environmental Protection Agency guideline number for Section 835–fate, transport and transformation, type of data requirement. A "Yes" indicates there are data accepted by the U.S. Environmental Protection Agency.

[MRID, Master Record Identifier (indicates the most recent registration has been approved); N/A, no data available; a number indicates the quantity of journal articles that may provide support for approval of that guideline.]

Guideline number	Data requirements	MRID exists							
		Pyrethrins (Pyblast)	Permethrin	Cyflutherin	Fipronil	Diflu-benzuron	Antimycin-A	Rotenone	Emamectin benzoate
835.1230	Adsorption/de-sorption (batch-equilibrium)	N/A	Yes	Yes	Yes	2	Yes	N/A	Yes
835.2120	Hydrolysis	Yes	Yes	Yes	Yes	Yes	Yes	N/A	Yes
835.2240	Photodegradation in water	N/A	Yes	Yes	Yes	N/A	N/A	N/A	Yes
835.4300	Aerobic aquatic	Yes	Yes	Yes	Yes	Yes	N/A	N/A	Yes
835.4400	Anaerobic aquatic	Yes	Yes	Yes	Yes	Yes	N/A	N/A	Yes
835.6200	Aquatic (sediment)	N/A	N/A	Yes	4	N/A	N/A	N/A	N/A

Table 2. The U.S. Environmental Protection Agency guideline number for section 850–ecological effects, type of data requirement. A "Yes" indicates there are data accepted by the U.S. Environmental Protection Agency.

[MRID, Master Record Identifier (indicates the most recent registration has been approved); N/A, no data available; a number indicates the quantity of journal articles that may provide support for approval of that guideline.]

Guideline number	Data requirements	MRID exists							
		Pyrethrins (Pyblast)	Permethrin	Cyflutherin	Fipronil	Diflu-benzuron	Antimycin-A	Rotenone	Emamectin benzoate
850.1010	Acute toxicity freshwater invertebrates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
850.1025	Acute toxicity estuarine organisms	Yes	N/A	Yes	Yes	Yes	N/A	N/A	Yes
850.1035	Acute toxicity marine organisms	Yes	N/A	N/A	Yes	Yes	N/A	N/A	Yes
850.1045	Freshwater fish toxicity	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
850.1300	Aquatic invertebrate life cycle (freshwater)	N/A	N/A	Yes	Yes	Yes	N/A	Yes	N/A
850.1400	Fish early-life stage (freshwater)	N/A	Yes	Yes	Yes	Yes	N/A	Yes	Yes
850.2100	Avian oral toxicity	Yes	Yes	Yes	Yes	Yes	N/A	Yes	Yes
850.2200	Avian dietary toxicity	Yes	Yes	Yes	Yes	Yes	N/A	Yes	Yes
850.2300	Avian reproduction	Yes	Yes	Yes	Yes	Yes	N/A	N/A	N/A
850.4100	Seedling emergence	N/A	N/A	N/A	1	N/A	N/A	N/A	N/A
850.4150	Vegetative vigor	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
850.4400	Aquatic plant growth (algal and aquatic vascular plant toxicity)	N/A	N/A	1	Yes	N/A	N/A	N/A	Yes

Table 3. The U.S. Environmental Protection Agency guideline number for Section 870–health effects, type of data requirement. A "Yes" indicates there are data accepted by the U.S. Environmental Protection Agency.

[MRID, Master Record Identifier (indicates the most recent registration has been approved); N/A, no data available; a number indicates the quantity of journal articles that may provide support for approval of that guideline.]

Guideline number	Data requirements	MRID exists							
		Pyrethrins (Pyblast)	Permethrin	Cyflutherin	Fipronil	Diflu-benzuron	Antimycin-A	Rotenone	Emamectin benzoate
870.1100	Acute oral toxicity-rat	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
870.1200	Acute dermal toxicity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A
870.1300	Acute inhalation toxicity-rat	Yes	N/A	Yes	Yes	Yes	Yes	Yes	N/A
870.2400	Primary eye irritation-rabbit	Yes	Yes	Yes	10	Yes	Yes	Yes	N/A
870.2500	Primary dermal irritation-animal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A
870.2600	Dermal sensitization-animal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A
870.6200	Acute neurotoxicity-rat	Yes	Yes	Yes	Yes	N/A	N/A	8	Yes

Table 4. The U.S. Environmental Protection Agency guideline number for Section 875 –occupational and residential exposure, type of data requirement. A "Yes" indicates there are data accepted by the U.S. Environmental Protection Agency.

[MRID, Master Record Identifier (indicates the most recent registration has been approved); N/A, no data available; a number indicates the quantity of journal articles that may provide support for approval of that guideline.]

Guideline number	Data requirements	MRID exists							
		Pyrethrins (Pyblast)	Permethrin	Cyflutherin	Fipronil	Diflu-benzuron	Antimycin-A	Rotenone	Emamectin benzoate
875.1100	HA dermal outdoor exposure	Yes	Yes	N/A	N/A	N/A	N/A	N/A	N/A
875.1200	HA dermal indoor exposure	Yes	Yes	4	Yes	N/A	N/A	N/A	N/A
875.1300	HA inhalation outdoor exposure	Yes	Yes	Yes	Yes	N/A	N/A	N/A	N/A
875.1400	HA inhalation indoor exposure	Yes	Yes	Yes	N/A	N/A	N/A	N/A	N/A
875.2100	PA human dislodgeable foliar residue and turf transferable residues	Yes	Yes	N/A	N/A	N/A	N/A	N/A	N/A
875.2200	PA human soil residue dissipation	Yes	Yes	N/A	2	N/A	N/A	N/A	N/A
875.2300	PA human indoor surface residue dissipation	Yes	Yes	N/A	N/A	N/A	N/A	N/A	N/A
875.2400	PA human dermal exposure	Yes	Yes	Yes	N/A	N/A	N/A	N/A	N/A
875.2500	PA human inhalation exposure	Yes	Yes	Yes	N/A	N/A	N/A	N/A	N/A

will suffer sublethal effects at concentrations required for crayfish control (Floyd and others, 2008; table 2.3). Primary metabolites of permethrin are less toxic to invertebrates and fish than permethrin (Canadian Council of Ministers of the Environment, 2006).

Environmental Persistence

Permethrin binds strongly to sediment, degrades rapidly in water (Peay, 2001), and degrades by photolysis (Canadian Council of Ministers of the Environment, 2006). Permethrin is metabolized faster than the type-2 pyrethroid cyfluthrin in some species (Fojut and others, 2012). Pyrethroids rapidly bind to organic matter, plants, and sediment (O'Reilly, 2015). Many synthetic pyrethroids have similar bioconcentration factors (table 2.9). Pyrethroids are rapidly metabolized and do not bioaccumulate or biomagnify (Haya and others, 2005; Ros and others, 2005).

Registration Data Gaps for Permethrin

Data gaps for permethrin are identified in tables 1–4**.** Permethrin is registered with EPA as a restricted-use terrestrial pesticide (Palmquist and others, 2012). Information from the literature search did not indicate that data existed to fill gaps identified in tables 1–4 for use as a crayfish pesticide. No relevant data were identified for: 835.6200–aquatic (sediment), 850.1025–oyster acute toxicity test (shell deposition), 850.1035–mysid acute toxicity test, 850.4100–seedling emergence, 850.4150–vegetative vigor, 850.4400–aquatic plant growth, or 870.1300–acute inhalation toxicity.

Type-2 Pyrethroids (Primarily Cyfluthrin)

Type-2 pyrethroids (cyhalothrin, cyfluthrin (Baythroid®), cypermethrin, deltamethrin, etc.) contain an α-cyano group (Wolansky and others, 2006) and produce stimulus-dependent nerve depolarization and blockage in target organisms (Palmquist and others, 2012).

Aquatic Toxicity

Type-2 pyrethroids are more toxic to crayfish than type-1 pyrethroids (Table 2.5). Cyfluthrin and cypermethrin were used to eradicate crayfish in infested ponds treated at 25 µg/L and 20 µg/L, respectively (Bills and Marking, 1988; Sandodden and Johnsen, 2010). Water temperature during treatment can substantially affect toxicity of type-2 pyrethroids (Table 2.6). Dissolved organic material—often present in field settings but not in laboratory water—binds to cyfluthrin, alters the biologically available levels, reduces the uptake, and reduces its toxicological effect (Fojut and others, 2010; Fojut and others, 2012).

Most fishes are less susceptible to cyfluthrin than crayfish, but other aquatic invertebrates are at risk at the required cyfluthrin treatment concentrations (table 2.7). Pyrethroids have low toxicity to mammals and birds (Palmquist and others, 2012). Piperonyl butoxide, a commonly used synergistic additive, is known to increase the toxicity of pyrethroids (Weston and others, 2006; Fojut and others, 2010). As an example, the 48-hour LC_{50} for *Daphnia magna* exposed to cyfluthrin decreased from 0.62 µg/L to 0.46 µg/L when piperonyl butoxide was added to cyfluthrin (Brausch and Smith, 2009).

Environmental Persistence

Type-2 pyrethroids have shorter half-lives (hours to days for deltamethrin) than type-1 pyrethroids (O'Reilly, 2015). The synthetic pyrethroids have low water solubility and have high organic carbon-water partition coefficients. Concentrations needed to eradicate crayfish should be assessed on site before treatment to account for differences in water chemistry. Alkaline conditions aid in the breakdown of pyrethroids (table 2.8), and pyrethroids rapidly bind to organic matter, plants, and sediment (O'Reilly, 2015). Bioconcentration factors are similar for different pyrethroids (table 2.9). Pyrethroids are rapidly metabolized and do not bioaccumulate or biomagnify (Haya and others, 2005; Ros and others, 2005).

Registration Data Gaps for Cyfluthrin

Data gaps for cyfluthrin are identified in tables 1–4**.** Cyfluthrin, commercially named Baythroid®, is registered as a restricted-use pesticide for terrestrial use by EPA. Literature exists that will likely support many of the guidelines required for aquatic use, particularly for guidelines required that are common between terrestrial and aquatic pesticides. Potential data have been reported for guidelines 850.4400–aquatic plant growth (table 2.10; Ma 2005), 875.1200–human applicator dermal indoor exposure, 875.1400–human applicator inhalation indoor exposure and 875.230–post-application human indoor surface residue dissipation (Williams and others, 2003; Berger-Preiß and others, 2009; Keenan and others, 2010). No relevant data were identified for: 850.4400–aquatic plant growth (algal and aquatic vascular plant toxicity), 875.2100–post-application human dislodgeable foliar residue and turf transferable residues, or 875.2200–post-application human soil residue dissipation.

Fipronil

Fipronil, a phenylpyrazole, blocks inhibition sites on the nervous system, leading to the overexcitation of the nervous system (Simon-Delso and others, 2015).

Aquatic Toxicity

Fipronil and its breakdown products are toxic to crayfish (Table 2.11). Fipronil is commonly produced as a racemic mixture of the two enantiomers which vary in their toxicity (Konwick and others, 2005; Overmyer and others, 2007).

Fipronil is toxic to crayfish and other aquatic invertebrates (Table 2.12). Additionally, fipronil's breakdown products are toxic to aquatic invertebrates (Hainzl and Casida, 1996; Walse and others, 2004). Fipronil sulfone is 6.6 times more toxic and fipronil sulfide is 1.9 times more toxic to aquatic invertebrates than fipronil (Connelly, 2001). Concentrations required to eradicate crayfish will affect nontarget fish species (Table 2.12). Fipronil has moderate acute oral toxicity in rats and moderate acute dermal toxicity in rabbits (Keigwin, 2011).

Fipronil may have other toxicological effects. It has been reported that fipronil decreased copepod reproductive rates (Chandler and others, 2004). Fipronil increased thyroid follicular cell tumors in rats, which is why it is classified as a group C potential carcinogen (Keigwin, 2011).

Environmental Persistence

The persistence of fipronil can vary between terrestrial and aquatic environments. The half-life of fipronil on land is 128–300 days (Andrews and others, 2007), while in water is reported between 5.4 to 28 days (Andrews and others, 2007; Jinguji and others, 2013; Kasai and others, 2016). In a lab study, fipronil sediment concentration dropped 40 percent during a 28-day period (Dang and others, 2016). The breakdown products of fipronil, desulfinyl fipronil, fipronil sulfide, and fipronil sulphone (Schlenk and others, 2001) have half-lives of 217–497, 195–352, and 502–589 days in sediment, respectively (Lin and others, 2009). Desulfinyl fipronil is more stable than fipronil (Connelly, 2001). Fipronil sulfone has higher bioaccumulation potential than fipronil (Konwick and others, 2006). Summarized data on fipronil degradation and physical chemical properties is in Table 2.13.

Registration Data Gaps for Fipronil

Data gaps for fipronil are identified in Tables 1–4**.** Fipronil is registered with EPA as a terrestrial insecticide and has a variety of uses in the United States including in agriculture, as a flea and tick control agent, and for household use (Schlenk and others, 2001; Biever and others, 2003; Key and others, 2003). Due to these common uses, many of the guidelines already have published data. Potential data have been reported for guidelines 835.6200–aquatic (sediment; Qu and others, 2016; Wang and others, 2019) and guideline 850.4100–terrestrial plant toxicity of fipronil (Dan and others, 2012). No relevant data were identified for guidelines: 850.4150–vegetative vigor, 870.2400–acute eye irritation, or human exposure (Subpart K).

Antimycin-A

Antimycin-A, a group of molecules created as a byproduct of *Streptomyces spp.* metabolism, is an inhibitor of oxidative phosphorylation, resulting in the breakdown of cellular respiration and ATP synthesis (Kim and others, 1999).

Aquatic Toxicity

The toxicity of antimycin-A varies among crayfish species, and crayfish are generally less sensitive to antimycin-A than fish (table 2.16; Lesser, 1970; Perlman, 1973). Antimycin-A was approved by EPA to control invasive fishes and was commonly used to "reset," (remove all species for native fish restocking) in high mountain streams. The use of antimycin-A to control invasive crayfish will result in the death of most fish species within the pond or stream (table 2.17).

Environmental Persistence

Antimycin-A does not bioaccumulate in organisms (Greselin and Herr, 1974), likely because it rapidly decomposes. The half-life for antimycin-A is 11-hours at pH 6, 7.1 hours at pH 7, and 3.4-hours at pH 9 (Turner and others, 2007).

Registration Data Gaps for Antimycin-A

Data gaps for antimycin-A are identified in tables 1–4**.** Even though antimycin-A was registered as an aquatic pesticide by EPA, data gaps still exist. No relevant data were identified for guidelines: 835.2240–photodegradation in water, 835.4300–aerobic aquatic, 835.4400–anaerobic aquatic, 835.6200–aquatic (sediment), 850.1023–acute toxicity estuarine organisms, 850.1035–acute toxicity marine organisms, 850.1300–aquatic invertebrate life cycle (freshwater), 850.1400–fish early-life stage (freshwater), 850.2100–avian oral toxicity, 850.2200–avian dietary toxicity, 850.2300–avian reproduction, 850.4100–seedling emergence, 850.4150–vegetative vigor, 850.4400–aquatic plant growth (algal and aquatic vascular plant toxicity), or 870.6200–aerobic aquatic. Additionally, no relevant publications were identified for Subpart K–human exposure.

Rotenone

Rotenone, a botanical extracted from the roots of tropical plants, is an inhibitor of oxidative phosphorylation, resulting in the breakdown of cellular respiration and ATP synthesis (Gupta, 2014).

Aquatic Toxicity

It has been reported that rotenone toxicity differed among crayfish species. *Orconectes immunis* (calico crayfish) survived rotenone concentrations as much as 0.5 milligrams per liter (mg/L) when exposed for 72-hours (Ling, 2003) whereas rotenone was not toxic to *Procambarus zonangulus* (White River crayfish) at concentrations up to 3 mg/L (Wujtewicz and others, 1997). Bills and Marking (1988) reported 10 mg/L required 72-hours to kill rusty crayfish. Rotenone 96-hour LC_{50} values of 6.2 and 7.5 mg/L were determined for *Macrobrachium rosenbergii* (giant freshwater prawn) (Ogunsanya and others, 2011).

Rotenone is more toxic to many fish species than it is to crayfish. Rotenone's application rate for fish removal is 0.025 to 0.2 mg/L as active ingredient (EPA, 2019). It has been reported to be toxic to *Morone americana* (white perch) at 0.15 mg/L (Wujtewiczand others, 1997). Rotenone produces 24-hour LC_{50} values between 5 and 100µg/L in fish species (Ling, 2003). The 72-hour LC_{50} value for *Cyclops sp*. isave less than 100 µg/L (Stebbing and others, 2014). A 48-hour LC_{50} of 0.219 mg/L was reported for *Dreissena polymorpha* (zebra mussels) (Stebbing and others, 2014).

Environmental Persistence

Rotenone breaks down quickly in the presence of heat, light, or oxygen. Rotenone has an aquatic half-life of less than one day at 24 °C but 3.5 days at temperatures of 0˚ C (Gilderhus and others, 1986). The fish tissue half-life of rotenone is about 1 day and there is a low potential to accumulate (Robertson and Smith-Vaniz, 2008).

Registration Data Gaps for Rotenone

Data gaps for rotenone are identified in tables 1–4**.** Rotenone is registered by EPA as a restricted-use pesticide due to aquatic, acute oral, and inhalation toxicity. Rotenone is a broad-spectrum pesticide and is not selective to crayfish. Rotenone is used by aquatic resource managers to "reset" some aquatic systems. Because rotenone is already registered for use to control fishes, data to expand its label to include crayfish control would be minimal. Data gaps exist for the following guidelines: all of Section 835–fate, transport and transformation, 850.1025–acute toxicity estuarine organisms, 850.1035–acute toxicity marine organisms, 850.2300–avian reproduction, 850.4100–seedling emergence, 850.4150–vegetative vigor, 850.4400–aquatic plant growth (algal and aquatic vascular plant toxicity), and all of Subpart K-human exposure.

One area of concern is related to guideline 870.6222-acute neurotoxicity rat. Several publications suggest a link between rotenone exposure and Parkinson-like symptoms in humans. The first link between a Parkinson-like neurotoxicity and exposure to rotenone was published in 1997 (Ferrante and others, 1997), and the relation between oxidative stress and exposure is part of this neurodegeneration (Saravanan and others, 2005). The introduction of a mouse neurodegeneration model to the literature was published in 2007 (Inden and others, 2007). More publications on the mouse model exist (Madathil and others, 2013; Ojha and others, 2015; Wu and others, 2015; Nie and others, 2019; and Johnson and others, 2019).

Physiological Modifiers

Diflubenzuron

Diflubenzuron, a benzoylurea, interferes with chitin production and triggers premature molting (Cunningham, 1986).

Aquatic Toxicity

Little data for crayfish toxicity was identified; however, diflubenzuron is extremely toxic to other invertebrates such as shrimp and crabs (Hyatt, 2004). Diflubenzuron was reported to cause behavioral, growth, survival, and reproductive changes in crustaceans at concentrations as low as 0.062–2 µg/L (Eisler, 1992), but no change in red swamp crayfish population size was observed when exposed to these concentrations (Cunningham, 1986). Acute crayfish toxicity data is not available. Toxicity of diflubenzuron to crustaceans is documented in table 2.14.

The U.S. Fish and Wildlife Service reported algae, amphibians, fish, and mollusks are tolerant of diflubenzuron and observed no adverse effects when these organisms were exposed to concentrations as high as 45 µg/L (Eisler, 1992). Diflubenzuron is used at concentrations between 2.5 and 16 µg/L to eradicate dipterans (Eisler, 1992). Populations of cladocerans, copepods, corixids, and springtails were suppressed when exposed to these concentrations but recovered within 80 days (Eisler, 1992).

Registration Data Gaps for Diflubenzuron

Data gaps for diflubenzuron are identified in tables 1–4. Diflubenzuron is registered with EPA as a terrestrial insecticide. Potential data have been reported for guidelines 835.1230–adsorption/desorption (table 2.15; Sundaram and others, 1997), 835.2240–photodegradation in water (Mabury and Crosby, 1996), 835.6200–aquatic (sediment; Mabury and

Crosby, 1996), and 875.1100–human applicator dermal exposure (Roitzsch and others 2019). The data gaps for registration includes: 870.6200–acute neurotoxicity, 158.660–nontarget plant protection data, and human exposure (Subpart K), except 875.240–post-application human dermal exposure and 875.2200–post-application human soil residue dissipation, as identified in tables 1–4..

Emamectin Benzoate

Emamectin benzoate, a second generation avermectin insecticide, prevents electrical impulse transmission in muscle and nerve tissues of invertebrates (El-Saber Batiha and others, 2020).

Aquatic Toxicity

Emamectin benzoate inhibits muscular contraction (Fanigliulo and Sacchetti, 2008). Female *Homarus americanus* (American lobsters) exposed to emamectin benzoate at concentrations 0.22 and 0.39 microgram per gram lost their eggs (Waddy and others, 2007). Premature molting occurred in 89 percent of lobsters dosed at 0.125 microgram per gram (Waddy and others, 2010).

Emamectin benzoate is more toxic to aquatic invertebrates than fishes (Shanaman and Carey, 2008). Reported LC_{50}s for aquatic invertebrates ranged from 0.04 to 490 µg/L, while LC_{50}s for fish ranged from 174 to 1,430 µg/L. *Mysidopsis bahia* (mysid shrimp) are more sensitive than daphnids to chronic exposure (Shanaman and Carey, 2008).

Environmental Persistence

Data for emamectin benzoate environmental fate can be read in table 2.18. Emamectin benzoate binds quickly to soil and has a short soil half-life. Emamectin benzoate has bioconcentration factors of 69 and 98 in whole fish and visceral tissue, respectively (Shanaman and Carey, 2008).

Registration Data Gaps for Emamectin Benzoate

Data gaps for emamectin benzoate are identified in tables 1–4**.** Emamectin benzoate registered by EPA for use as injection and sprayed application on trees to control arthropod pests (Anderson and others, 2009). Potential data have been reported for guidelines 950.2300–avian reproduction (O'Grodnick and others, 1998) and 87.6200–acute neurotoxicity in rats (Wise and others, 1997). Data gaps exist in the following guidelines: 835.6200–aquatic (sediment), 850.1100–aquatic invertebrate acute toxicity test, freshwater daphnids, 850.1300–aquatic invertebrate life cycle (freshwater), 850.4100–seedling emergence, 850.4150–vegetative vigor, 870.1200–acute dermal toxicity, 870.1300–acute inhalation toxicity rat, 870.2400–primary eye irritation rabbit, 870.2500–primary dermal irritation animal, 870.2600–acute neurotoxicity rat, and all of Subpart K–human exposure.

Summary Considerations

The use of pesticides is an important component of an integrated pest management strategy for controlling nonnative crayfish (Bills and Marking, 1988; Hyatt, 2004; Rotherham, 2009; O'Reilly, 2015). Crayfish-specific pesticides are greatly desired so that effects on native fauna are minimized and degradation of the ecosystem is decreased while populations of nonnative crayfish are controlled. The use of multiple pesticides acting on different physiological processes could be used to increase selectivity of the treatment while also decreasing the amounts of pesticides needed to kill crayfish. Life stage is a critical consideration for some pesticides. Molting crayfish are more susceptible to pesticides, and several pesticides are most effective against younger crayfish. In addition, physiological modifiers could potentially force crayfish to prematurely molt. This would significantly lower the required dose to kill crayfish. Emamectin benzoate stimulated premature molting and molted crayfish have shown increased sensitivity to other pesticides (Brown and Avault, 1975; Waddy and others, 2010). Similarly, piperonyl butoxide is commonly used as an additive to increase the toxicity of synthetic pyrethroids. Piperonyl butoxide would also require EPA registration before use in aquatic environments for use as a crayfish pesticide.

Some of the species listed in the review are primary and tertiary burrowers. The act of burrowing by crayfish may limit the crayfish's exposure, interfering with successful chemical treatment. If a pesticide is present in the pond, crayfish are more likely to be exposed to a lethal concentration outside of their burrows. The effects of changes in burrow water chemistry must be considered when trying to control crayfish as some pesticides do not kill crayfish in their burrows. For example, the presence of organic matter decreases bioavailability and efficacy of pyrethroids; carboxylic acid content in organic matter changes the partition coefficient of pyrethroids, altering pyrethroid bioavailability and toxicity (Yang and others, 2007).

Based on this review, pyrethroids have the greatest promise as a crayfish pesticide. Specifically, the synthetic type-2 pyrethroid, cyfluthrin (Baythroid®), seems to be the best candidate for development of a crayfish pesticide. Cyfluthrin has several positive properties desired as a crayfish pesticide, including some potency to crayfish, a margin of safety for some nontarget organisms, and a short aquatic persistence. Cyfluthrin is toxic to other aquatic invertebrates at concentrations needed for crayfish eradication, but it also offers rapid ecosystem recovery compared to other pyrethroids and other candidate chemicals listed in this document in general.

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Appendix 1. Search Terms for the "Literature Review for Candidate Control Agents for Nonnative Crayfish"

This appendix presents keywords searched for the "Literature Review for Candidate Control Agents for Nonnative Crayfish" (table 1.1) The search produced 28,058 documents, which were then evaluated to determine if they contained information on physical, chemical, biological, and biocidal control approaches to crayfish control. Information on potential success as a crayfish control tool, environmental damage, application rate requirements (if applicable), exposure duration, nontarget effects, and environmental persistence were used as criteria to define which chemicals have the most potential to be tested as selective chemical crayfish control chemicals. Table is read as follows. The first keyword is the chemical name, either a product name or common name, used in publications for a specific compound. The next three keywords are combinations of words that are related to specific United States Environmental Protection Agency Guidelines. Databases searched include Web of Science and Scopus.

Table 1.1. Search terms for the "Literature Review for Candidate Control Agents for Nonnative Crayfish."

First keyword	Second keyword	Third keyword	Fourth keyword
Antimycin A or,	Degradation or,	Actual or,	Freshwater or,
Rotentone or,	Aquatic toxicity or,	Adsorption or,	Marine or,
Mirex or,	Avian toxicity or,	Aerobic or,	Post application or,
Pyrethrin or,	Bioavailability or,	Anaerobic or,	Estuarine.
Cyprethrin or,	Dermal or,	Aquatic growth or,	
Pyblast or pyrethrins or,	Dissipation or,	Aquatic organisms or,	
Fipronil or,	Field Testing or,	Aquatic sediments or,	
Diflubenzuron or,	Human or,	Biological monitoring or,	
Emamectin benzoate or,	Life-cycle or,	Dermal or.,	
Avermectin.	Mammalian testing or,	Dermal exposure or,	
	Metabolism or,	Desorption or,	
	Mobility or,	Dietary or,	
	Neurotoxicity or,	Eye irritation or,	
	Phytotoxicity or,	Field trials or,	
	Post application or,	Fish or,	
	Rabbit toxicity or,	Foliar residue or,	
	Rat toxicity or,	Freshwater invertebrates or,	
	Sediment.	Hens or,	
		Hydrolysis or,	
		Inhalation or,	
		Inhalation exposure or,	
		Invertebrates or,	
		Leaching or,	
		Oral or,	
		Photodegredation or,	
		Rats or,	
		Reproduction or,	
		Seedling emergence or,	
		Sensitization or,	
		Simulated or,	
		Soil residue dissipation or,	
		Toxicity or,	
		Turf transferable residue or,	
		Vigor.	

Appendix 2. Chemical Properties and Toxicity Data as Determined from the "Literature Review for Candidate Control Agents for Nonnative Crayfish"

Table 2.1. Pyblast toxicity to invasive *Procambarus clarkia* (red swamp) and *Pacifastacus leniusculus* (signal crayfish).

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Life stage	LC_{50}	Concentration (µg/L)
Signal crayfish [a]	Stage 1 hatchling	48-hr	5.23
Signal crayfish [a]	Stage 2 hatchling	48-hr	6.43
Signal crayfish [a]	Juvenile	48-hr	57.95
Signal crayfish [a]	Adult	48-hr	118.25
Red swamp [b]	Adult	24-hr	50.0
Red swamp [b]	Adult	24-hr	20.0

[a]O'Reilly, 2015

[b]Cecchinelli and others, 2012

Table 2.2. Pyblast toxicity to invertebrate and vertebrate nontarget aquatic species.

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Common name	LC_{50}	Concentration (µg/L)
Daphnia magna [a]	Water flea	48-hr	17.0
Ictalurus punctatus [b]	Channel catfish	96-hr	114.0
Lepomis macrochirus [b]	Bluegill	96-hr	49.0
Oncorhynchus kisutch [b]	Coho salmon	96-hr	39.0
Oncorhynchus mykiss [b]	Rainbow trout	96-hr	24.6
Perca flavescens [b]	Yellow perch	96-hr	<50.1

[a]Oikari and others, 1992

[b]Mauck and others, 1976

Table 2.3. Type-1 pyrethroid toxicity to *Procambarus alleni* (blue crayfish), *Procambarus blandingii* (santee crayfish), *Procambarus clarkii* (red swamp crayfish), and *Faxonius rusticus* (rusty crayfish).

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour; N/A, life stage unavailable]

Species	Life Stage	LC_{50}	Concentration(µg/L)
Blue crayfish [a]	Juvenile	96-hr	0.58
Santee crayfish [b]	N/A [e]	96-hr	0.21
Red Swamp crayfish [c]	N/A	96-hr	0.28
Red Swamp crayfish [d]	New Hatch	96-hr	0.39
Red Swamp crayfish [d]	Juvenile	96-hr	0.62
Red Swamp crayfish [d]	Adult	24-hr	0.49
Rusty crayfish [d]	N/A	96-hr	<1.2

[a]Halstead and others, 2015

[b]Fojut and others, 2012

[c]Schleier and Peterson, 2013

[d]O'Reilly, 2015

Table 2.4. Type-1 pyrethroids toxicity to invertebrate and vertebrate nontarget aquatic species. Toxicity data is for permethrin only.

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Common name	LC_{50}	Concentration(µg/L)
Ceriodaphnia dubia [a]	Water flea	96-hr	0.57
Chironomus dilutes [b]	Midge	96-hr	0.189
Daphnia magna [c]	Water flea	96-hr	0.3
Daphnia magna [d]	Water flea	48-hr	0.32
Hyalella Azteca [e]	Crustacea	96-hr	0.211
Danio rerio [f]	Zebrafish	96-hr	2.50
Erimonax monachus [g]	Chub	96-hr	1.7
Etheostoma fonticola [g]	Darter	96-hr	3.34
Etheostoma lepidum [g]	Darter	96-hr	2.71
Ictalurus punctatus [h]	Channel catfish	96-hr	5.4
Lepomis macrochirus [d]	Bluegill	96-hr	2.52
Menidia menidia [d]	Atlantic silverside	96-hr	2.2
Notropis mekistocholas [g]	Shiner	96-hr	4.16
Oncorhynchus apache [g]	Apache trout	96-hr	1.71
Salvelinus fontinalis [j]	Brook trout	24-hr	4.80
Salvelinus fontinalis [j]	Brook trout	48-hr	3.03
Salvelinus fontinalis [j]	Brook trout	96-hr	2.86
Oncorhynchus clarki [c]	Cutthroat trout	96-hr	1.58
Oncorhynchus mykiss [i]	Rainbow trout	96-hr	7.0
Oncorhynchus mykiss [d]	Rainbow trout	96-hr	0.62
Pimephales promelas [c]	Fathead minnow	96-hr	3.0
Pimephales promelas [d]	Fathead minnow	96-hr	3.5
Salmo salar [h]	Atlantic salmon	96-hr	1.5
Xyrauchen texanus [g]	Sucker	96-hr	5.95

[a]Yang and others, 2007

[b]Harwood and others, 2009

[c]Schleier and Peterson, 2013

[d]Finto, 1990

[e]Anderson and others, 2006

[f]Zhang and others, 2010

[g]Dwyer and others, 2005

[h]Fojut and others, 2012

[i]Holcombe and others, 1982

[j]Paul and others, 2005

Table 2.5. Type-2 pyrethroids toxicity to crayfish at various life stages. Data for four type-2 pyrethroids is displayed for *Procambarus clarkii* (red swamp crayfish), *Procambarus alleni* (blue crayfish), and *Pacifastacus leniusculus* (signal crayfish).

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Life Stage	Chemical	LC_{50}	Concentration (µg/L)
Red swamp crayfish [a]	Adult	Cyfluthrin	24-hr	0.17
Red swamp crayfish [a]	Adult	Cyfluthrin	48-hr	0.08
Blue crayfish [b]	Juvenile	Cyhalothrin	96-hr	0.21
Red swamp crayfish [c]	Juvenile	Cyhalothrin	96-hr	0.16
Red swamp crayfish [a]	Adult	Cypermethrin	24-hr	0.14
Red swamp crayfish [a]	Adult	Cypermethrin	48-hr	0.10
Red swamp crayfish [a]	Adult	Deltamethrin	24-hr	0.22
Red swamp crayfish [a]	Adult	Deltamethrin	48-hr	0.18
Red swamp crayfish [d]	Adult	Deltamethrin	24-hr	0.156
Red swamp crayfish [d]	Adult	Deltamethrin	48-hr	0.099
Red swamp crayfish [d]	Adult	Deltamethrin	96-hr	0.056
Signal crayfish [e]	Adult	Deltamethrin	48-hr	0.86

[a]Morolli and others, 2006

[b]Halstead and others, 2015

[c]Barbee and Stout, 2009

[d]Wu and others, 2012

[e]O'Reilly, 2015

Table 2.6. Fluvalinate toxicity to adult Procambarus clarkii (red swamp crayfish) with differing water conditions (Sorgorb and others, 1988). Toxicity test results are displayed as a 96-hour lethal concentration to produce fifty percent mortality in test species (LC_{50}) values.

[˚C, degrees celcius; µg/L, micrograms per liter;]

Temperature (˚C)	Medium[a]	Concentration (µg/L)
12	Laboratory	0.51
18	Laboratory	0.46
22	Laboratory	0.31
27	Laboratory	0.23
12	Field	1.08
18	Field	0.72
22	Field	0.64
27	Field	0.50

[a]Medium refers to whether the tests were completed in lab water (experimental) or in natural water environment.

Table 2.7. Type-2 pyrethroid lethal concentration to produce fifty percent mortality in test species (LC_{50}) concentrations for nontarget aquatic species. Three type-2 pyrethroids toxicity data is reported. The table is grouped by invertebrate or fish, and then chemical.

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Common name	Chemical	LC_{50}	Concentration (µg/L)
Ceriodaphnia dubia [a]	Water flea	Cyfluthrin	96-hr	0.105
Daphnia magna [b]	Water flea	Cyfluthrin	96-hr	0.16
Daphnia magna [c]	Water flea	Cyfluthrin	48-hr	0.14
Hyalella Azteca [d]	Scud	Cyfluthrin	96-hr	0.017
Hyalella Azteca [e]	Scud	Cyfluthrin	96-hr	0.0015
Ceriodaphnia dubia [f]	Water flea	Cyhalothrin	96-hr	0.200
Gammarus pulex [b]	Scud	Cyhalothrin	96-hr	0.0059
Ceriodaphnia dubia [f]	Water flea	Cypermethrin	48-hr	0.683
Daphnia magna [b]	Water flea	Cypermethrin	48-hr	0.161
Lepomis macrochirus [c]	Bluegill	Cyfluthrin	96-hr	0.68
Oncorhynchus mykiss [c]	Rainbow trout	Cyfluthrin	96-hr	1.5
Oncorhynchus mykiss [b]	Rainbow trout	Cyfluthrin	96-hr	2.09
Pimephales promelas [b]	Fathead minnow	Cyfluthrin	96-hr	2.49
Pimephales promelas [e]	Fathead minnow	Cyfluthrin	96-hr	0.31
Brachydanio rerio [b]	Zebrafish	Cyhalothrin	96-hr	0.64
Gasterosteus aculeatus [b]	Stickleback	Cyhalothrin	96-hr	0.40
Ictalurus punctatus [b]	Channel catfish	Cyhalothrin	96-hr	0.16
Lepomis machrochirus [b]	Bluegill	Cyhalothrin	96-hr	0.106
Leucisus idus [b]	Ide	Cyhalothrin	96-hr	0.078
Oncorhynchus mykiss [b]	Rainbow trout	Cyhalothrin	96-hr	0.19
Pimephales promelas [b]	Fathead minnow	Cyhalothrin	96-hr	0.360
Oncorhynchus mykiss [b]	Rainbow trout	Cypermethrin	96-hr	0.90

[a]Yang and others, 2007

[b]Fojut and others, 2012

[c]Finto, 1990

[d]Weston and Jackson, 2009

[e]Lanteigne and others, 2015

[f]Wheelock and others, 2004

Table 2.8. Type-1 and 2 pyrethroid degradation data (Laskowski, 2002; Dobbs and others, 2007; Fojut and others, 2010).

Chemical	Hydrolysis half-life (days)			Water photolysis half-life (days)	Soil photolysis half-life (days)
	pH 5	pH 7	pH 9		
Cyfluthrin	Stable	183	1.8	0.67	5
Cyhalothrin	Stable	Stable	8.7	25	54
Cypermethrin	619	274	1.9	30	165
Deltamethrin	Stable	Stable	2.2	56	35
Permethrin	Stable	Stable	242.0	110	104

Table 2.9. Physical chemistry data for Type-1 and 2 pyrethroids (Laskowski, 2002).

[LogP[a], partition coefficient, ratio of chemical bound to organic phase (LogP) verses aqueous phase, a higher positive number meaning the chemical concentrates in the lipid phase; µg/L, micrograms per liter; BCF, bioconcentration factor in fish (BCF) tissue compared to water concentration; Koc, soil absorption coefficient]

Chemical	Molecular weight	LogP	Koc (soil sorption)	Water solubility (µg/L)	BCF (Fish)
Cyfluthrin	434.3	5.97	124000	2.3	719
Cyhalothrin	449.9	7.00	326000	5.0	2240
Cypermethrin	416.3	6.54	310000	4.0	597
Deltamethrin	505.2	4.53	704000	2.0	698
Permethrin	391.3	6.10	277000	5.5	558

Table 2.10. Selective cyanobacteria and green algae 96-hour exposure response to beta-cyfluthrin (Ma, 2005).

[EC_{50}, effective concentration to produce effect in fifty percent of individuals; LOEC, lowest observable effect concentration; NOEC, no observable effect concentration; mg/L, milligrams per liter]

Species	EC_{50} (mg/L)	LOEC (mg/L)	NOEC (mg/L)
Anabaena flos-aquae	62.3	25	10
Microcystis flos-aquae	87.0	10	5
Mirocystis aeruginosa	34.6	20	10
Selenastrum capricornutun	3.4	0.5	0.2
Scenedesmus quadricauda	2.4	0.5	0.2
Scenedesmus obliqnus	97.0	10	5
Chlorella vulgaris	4.4	0.5	0.2
Chlorella pyrenoidosa	885.2	20	10

Table 2.11. Toxicity of fipronil and its breakdown products to *Procambarus zonangulus* (Southern White River [SWR] crayfish), *Procambarus clarkii* (red swamp crayfish), and *Palaemonetes pugio* (grass shrimp).

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Age	Chemical	Concentration (µg/L)
SWR Crayfish [a]	Juvenile	Fipronil	19.5
Red swamp [a]	Juvenile	Fipronil	14.3
Red swamp [a]	Juvenile	Fipronil Sulphone	11.2
Red swamp [a]	Juvenile	Fipronil Sulfide	15.5
Red swamp [a]	Juvenile	Desulfinyl fipronil	68.6
Red swamp [b]	Adult	Fipronil	180
Red swamp [c]	Adult	Fipronil (+)	81.7
Red swamp [c]	Adult	Fipronil (–)	163.5
Red swamp [c]	Adult	Fipronil (±)	124.9
Grass shrimp [d]	Embryo	Fipronil	>512.0
Grass shrimp [d]	Larvae	Fipronil	0.68
Grass shrimp [d]	Adult	Fipronil	0.32

[a]Schlenk and others, 2001

[b]Biever and others, 2003

[c]Overmyer and others, 2007

[d]Key and others, 2003

Table 2.12. Toxicity of fipronil and its breakdown products to nontarget aquatic species.

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Common name	Chemical	LC_{50}	Concentration (µg/L)
Ceriodaphnia dubia [a]	Water flea	Fipronil	48-hr	17.7
Ceriodaphnia dubia [a]	Water flea	Fipronil (+)	48-hr	10.3
Ceriodaphnia dubia [a]	Water flea	Fipronil (–)	48-hr	31.9
Ceriodaphnia dubia [a]	Water flea	Defulfinyl fipronil	48-hr	355
Daphnia magna [b]	Water flea	Fipronil	24-hr	240
Daphnia pulex [c]	Water flea	Fipronil	48-hr	15.6
Hyalella Azteca [d]	Scud	Fipronil	96-hr	1.593
Hyalella Azteca [d]	Scud	Fipronil sulphone	96-hr	0.748
Hyalella Azteca [d]	Scud	Fipronil sulfide	96-hr	1.359
Palaemonetes pugio [e]	Grass shrimp	Fipronil	96-hr	320
Danio rerio [b]	Zebrafish	Fipronil	24-hr	220.4
Lepomis macrochirus [f]	Bluegill	Fipronil	24-hr	83
Oncorhynchus mykiss [f]	Rainbow trout	Fipronil	24-hr	246
Pimephales promelas [g]	Fathead minnow	Fipronil	24-hr	398
Pimephales promelas [h]	Fathead minnow	Fipronil	96-hr	450

[a]Konwick and others, 2005

[b]Wu and others 2014

[c]Stark and Vargas, 2005

[d]Weston and Lydy, 2014

[e]Key and others, 2003

[f]Maciorowski, 1994

[g]Beggel and others, 2010

[h]Baird and others, 2013

Table 2.13. Summarized data on fipronil degradation and physical chemical properties (Gunasekara and others, 2007). Molecular weight is reported in grams per mole (g/mol). Solubility is reported as milligrams per liter (mg/L).

[g/mol, grams per mole; mg/L, milligrams per liter; Koc, soil absorption coefficient]

Environmental properties	Values
pH 5.5 half-life	>100 days
pH 7.0 half-life	>100 days
pH 9.0 half-life	32.08 days
Aqueous photolysis half-life	0.33 days
Molecular weight	473.2 g/mol
Solubility	1.90–2.40 mg/L
Koc	825

Table 2.14. Toxicity diflubenzuron to aquatic species. Three species of crab and shrimp are used as crayfish surrogates. Additional toxicity data was available for a copepod and for zebrafish.

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Species type	LC_{50}	Concentration (µg/L)
Rhithropanopens harrisii [a]	Mud crab (larvae)	48-hr	10
Mysidopsis bahia [b]	Mysid shrimp	96-hr	2.1
Palaemonetes pugio [c]	Grass shrimp (larvae)	96-hr	1.44
Palaemonetes pugio [c]	Grass shrimp (adult)	96-hr	>200
Eurytemore affinis [d]	Copepod	48-hr	2.2
Danio rerio [e]	Fish (zebrafish)	96-hr	>200

[a]Christiansen and others, 1978

[b]Nimmo and others 1979

[c]Wilson and Costlow, 1987

[d]Savitz and others, 1994

[e]Doucet and Retnakaran, 2012

Table 2.15. Absorption and desorption values for diflubenzuron. Soil pH was 5.5 and temperature was 20° C. Soil samples collected from boreal forests in Northern Ontario, Canada (Sundaram and others, 1997).

[µg/g, micrograms per gram; hr, hour]

Soil type	Adsorption mass (µg/g)	Maximum adsorption (hr)	Desorption percent (%)
Organic soil	73–88	18	16–27
Silty clay loam	81–92	24	16–27

Table 2.16. Toxicity of antimycin-A to crayfish. Toxicity test results are displayed as a 96-hour lethal concentration to produce fifty percent mortality in test species (LC_{50}) values. Molted crayfish have lower LC_{50} values. Smaller juvenile crayfish have lower LC_{50} values.

[mm, millimeter; µg/L, microgram per liter; N/A, life stage unavailable; Data was obtained from the U.S. Environmental Protection Agency ECOTOX database]

Species	Age	Size (mm)	Molted	Concentration (µg/L)
Cambarus sp. [a]	N/A	N/A	N/A	10
Procambarus sp. [b]	Juvenile	8	No	68
Procambarus sp. [b]	Juvenile	8	Yes	39
Procambarus sp. [b]	Juvenile	19	No	168
Procambarus sp. [b]	Juvenile	19	Yes	60
Procambarus sp. [b]	Juvenile	30	No	735
Procambarus sp. [b]	Juvenile	30	Yes	175

[a]Turner and others, 2007

[b]Brown and Avault, 1975

Table 2.17. Toxicity of antimycin-A to nontarget aquatic species (Turner and others, 2007).

[LC_{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

Species	Species type	Concentration (µg/L)
Chironomus tentans	Midge	0.146
Gammarus pseudolimnaeus	Scud	9.0
Hyalella azteca	Scud	1.4
Carassius auratus	Goldfish	0.18
Lepomis macrochirus	Bluegill	0.034
Lepomis cyanella	Sunfish	0.22
Oncorhynchus mykiss	Rainbow trout	0.012
Oncorhynchus clarki	Cutthroat trout	0.057
Pimephales promelas	Fathead minnow	0.025
Perca flavescens	Yellow perch	0.04

Table 2.18. Summarized data on emamectin benzoate's environmental properties (Shanaman and Carey, 2008).

[g/mol; grams per mole]

Environmental properties	Value
Aquatic photolysis half-life	23 Days
Soil photolysis	5 Days
Hydrolysis pH 5-8 half-life	Stable
Hydrolysis pH 9 half-life	20 weeks
Soil water partition coefficient Koc	265687
Molecular weight	964 g/mol
Aerobic aquatic metabolism half-life	193 days
Anaerobic aquatic metabolism half-life	427 days

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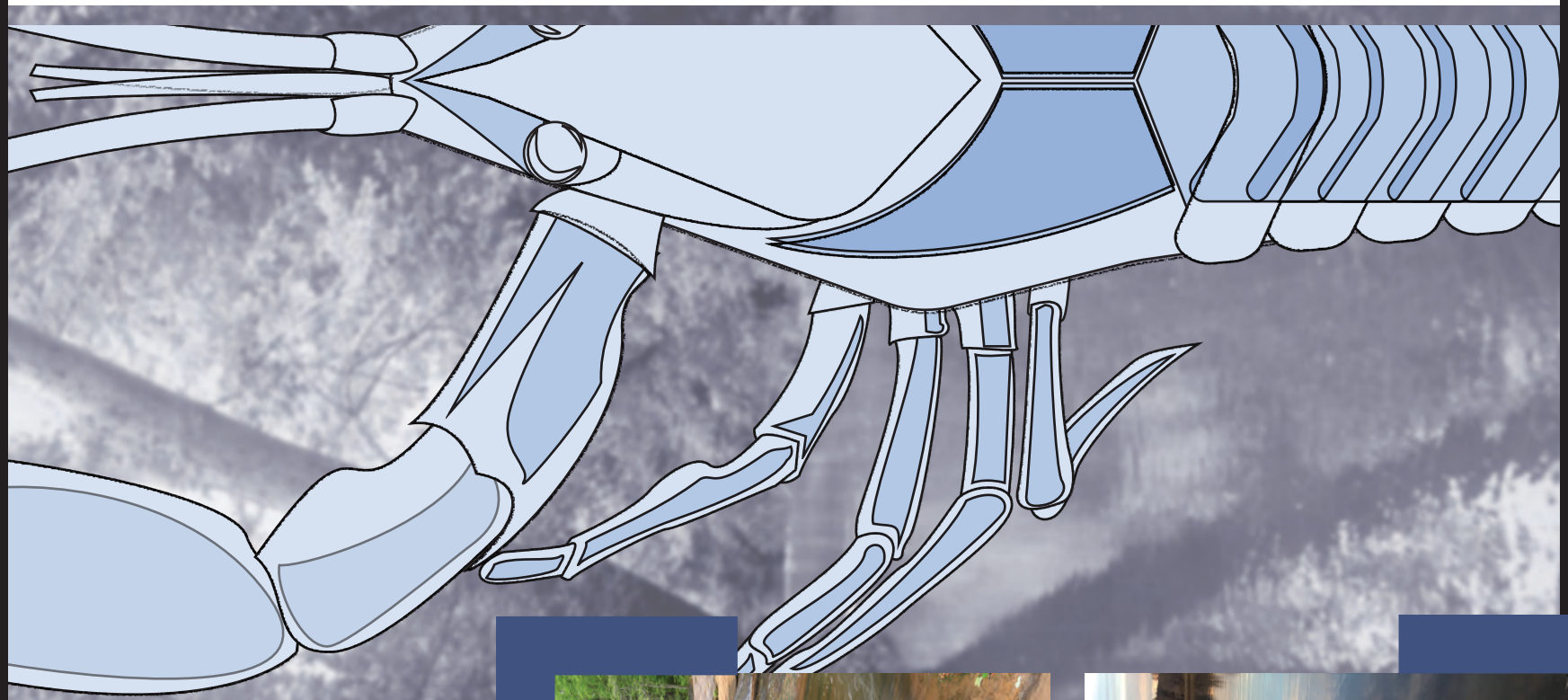

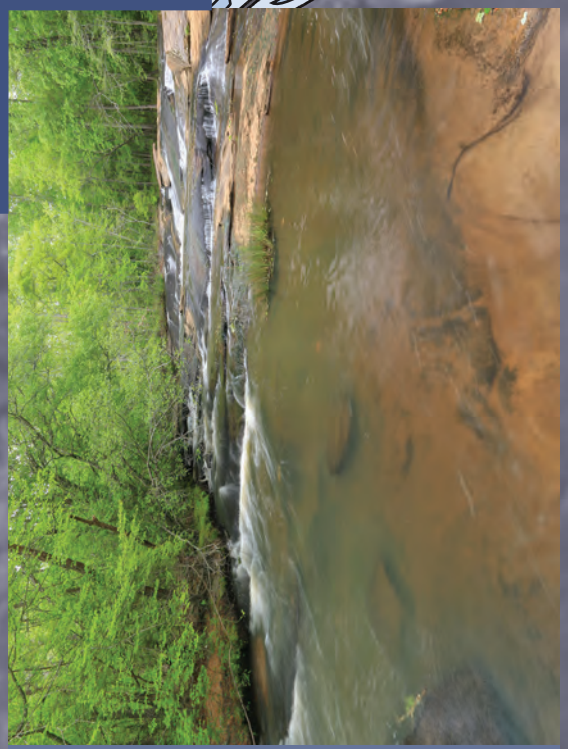

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