Literature Review for Candidate Chemical Control Agents for Nonnative Crayfish

Open-File Report 2021–1048
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.
Literature Review for Candidate Chemical Control Agents for Nonnative Crayfish

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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 (in³) |
| **Mass** |    |                            |
| microgram (µg) | 3.5274 × 10⁻⁸ | ounce, avoirdupois (oz) |
| milligram (mg) | 3.527 × 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:

\[ °F = (1.8 × °C) + 32. \]

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

LC₅₀    lethal concentration to produce fifty percent mortality in test species
EPA    United States Environmental Protection Agency
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; Mumert 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)). Pyrethrins 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 [USOF.R, 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 | 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 | 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 | Pyrethrins (Pyblast) | Permethrin | Cyfluthrin | 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 | 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 | N/A | Yes | N/A | 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 | 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                                           | Pyrethrins (Pyblast) | Permethrin | Cyfluthrin | 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        | N/A        | N/A       | 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–myisid 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; Sanddoden 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 LC50 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, desulfynyl fipronil, fipronil sulhide, 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). Desulfynyl 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 LC50 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 mg/L, required 72-hours to kill rusty crayfish. Rotenone was not toxic to *Dreissena polymorpha* (Clonal mussels) (Wujtewicz and others, 1997). 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 LC50 values of 6.2 and 7.5 mg/L were determined for *Macrobrachium rosenbergii* (giant freshwater prawn) (Ogunsanya and others, 2011).

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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; 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–aqua...
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,               |                                 |
|                                     |                                         | Photodegradation 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).

| Species                  | Life stage   | LC₅₀ Concentration (µg/L) |
|--------------------------|--------------|---------------------------|
| Signal crayfish          | Stage 1 hatchling | 48-hr | 5.23 |
| Signal crayfish          | Stage 2 hatchling | 48-hr | 6.43 |
| Signal crayfish          | Juvenile     | 48-hr | 57.95 |
| Signal crayfish          | Adult        | 48-hr | 118.25 |
| Red swamp                | Adult        | 24-hr | 50.0  |
| Red swamp                | 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.

| Species                  | Common name  | LC₅₀ Concentration (µg/L) |
|--------------------------|--------------|---------------------------|
| *Daphnia magna*          | Water flea   | 48-hr | 17.0  |
| *Ictalurus punctatus*    | Channel catfish | 96-hr | 114.0 |
| *Lepomis macrochirus*    | Bluegill     | 96-hr | 49.0  |
| *Oncorhynchus kisutch*   | Coho salmon  | 96-hr | 39.0  |
| *Oncorhynchus mykiss*    | Rainbow trout | 96-hr | 24.6  |
| *Perca flavescens*       | 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 $^c$     | 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\textsubscript{50}, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

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

\textsuperscript{a}Yang and others, 2007  
\textsuperscript{b}Harwood and others, 2009  
\textsuperscript{c}Schleier and Peterson, 2013  
\textsuperscript{d}Finto, 1990  
\textsuperscript{e}Anderson and others, 2006  
\textsuperscript{f}Zhang and others, 2010  
\textsuperscript{g}Dwyer and others, 2005  
\textsuperscript{h}Fojut and others, 2012  
\textsuperscript{i}Holcombe and others, 1982  
\textsuperscript{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 $^d$   | Adult      | Cypermethrin 24-hr | 0.14                            |
| Red swamp crayfish $^d$   | Adult      | Cypermethrin 48-hr | 0.10                            |
| Red swamp crayfish $^d$   | Adult      | Deltamethrin 24-hr | 0.22                            |
| Red swamp crayfish $^d$   | 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 | 96-hr 0.683 |
| Daphnia magna $^b$  | Water flea | Cypermethrin | 48-hr 0.161 |
| Lepomis macrochirus $^c$ | Bluegill   | Cyhalothrin | 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 $^{b}$ | Zebrfish    | 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 | pH 5 | pH 7 | pH 9 | 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, 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).

[EC₅₀, 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                    | EC₅₀ (mg/L) | LOEC (mg/L) | NOEC (mg/L) |
|----------------------------|-------------|-------------|-------------|
| Anabaena flos-aquae        | 62.3        | 25          | 10          |
| Microcystis flos-aquae     | 87.0        | 10          | 5           |
| Microcystis aeruginosa     | 34.6        | 20          | 10          |
| Selenastrum capricornutun  | 3.4         | 0.5         | 0.2         |
| Scenedesmus quadricauda    | 2.4         | 0.5         | 0.2         |
| Scenedesmus obliquus       | 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 | Juvenile | Fipronil            | 19.5                |
| Red swamp    | Juvenile | Fipronil            | 14.3                |
| Red swamp    | Juvenile | Fipronil Sulphone   | 11.2                |
| Red swamp    | Juvenile | Fipronil Sulfide    | 15.5                |
| Red swamp    | Juvenile | Desulfinyl fipronil | 68.6                |
| Red swamp    | Adult    | Fipronil            | 180                 |
| Red swamp    | Adult    | Fipronil (+)        | 81.7                |
| Red swamp    | Adult    | Fipronil (−)        | 163.5               |
| Red swamp    | Adult    | Fipronil (±)        | 124.9               |
| Grass shrimp | Embryo   | Fipronil            | >512.0              |
| Grass shrimp | Larvae   | Fipronil            | 0.68                |
| Grass shrimp | 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 |
|--------------------------|--------------|----------------|-------------------------|
| *Ceriodaphnia dubia*     | Water flea   | Fipronil       | 48-hr 17.7              |
| *Ceriodaphnia dubia*     | Water flea   | Fipronil (+)   | 48-hr 10.3              |
| *Ceriodaphnia dubia*     | Water flea   | Fipronil (–)   | 48-hr 31.9              |
| *Ceriodaphnia dubia*     | Water flea   | Defulfinyl fipronil | 48-hr 355           |
| *Daphnia magna*          | Water flea   | Fipronil       | 24-hr 240               |
| *Daphnia pulex*          | Water flea   | Fipronil       | 48-hr 15.6              |
| *Hyalella Azteca*        | Scud         | Fipronil       | 96-hr 1.593             |
| *Hyalella Azteca*        | Scud         | Fipronil sulphone | 96-hr 0.748       |
| *Hyalella Azteca*        | Scud         | Fipronil sulfide | 96-hr 1.359           |
| *Palaemonetes pugio*     | Grass shrimp | Fipronil       | 96-hr 320               |
| *Danio rerio*            | Zebrafish    | Fipronil       | 24-hr 220.4             |
| *Lepomis macrochirus*    | Bluegill     | Fipronil       | 24-hr 83                |
| *Oncorhynchus mykiss*    | Rainbow trout| Fipronil       | 24-hr 246               |
| *Pimephales promelas*    | Fathead minnow| Fipronil | 24-hr 398               |
| *Pimephales promelas*    | 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 of 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.

[LC₅₀, lethal concentration to produce fifty percent mortality; µg/L, micrograms per liter; hr, hour]

| Species                  | Species type                        | LC₅₀  | Concentration (µg/L) |
|--------------------------|-------------------------------------|-------|----------------------|
| Rhithropanopenis harrisii | Mud crab (larvae)                   | 48-hr | 10                   |
| Mysis bahia b            | Mysis 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 (LC₅₀) values. Molted crayfish have lower LC₅₀ values. Smaller juvenile crayfish have lower LC₅₀ 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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