Investigation of Crayfish Control Technology

FINAL REPORT

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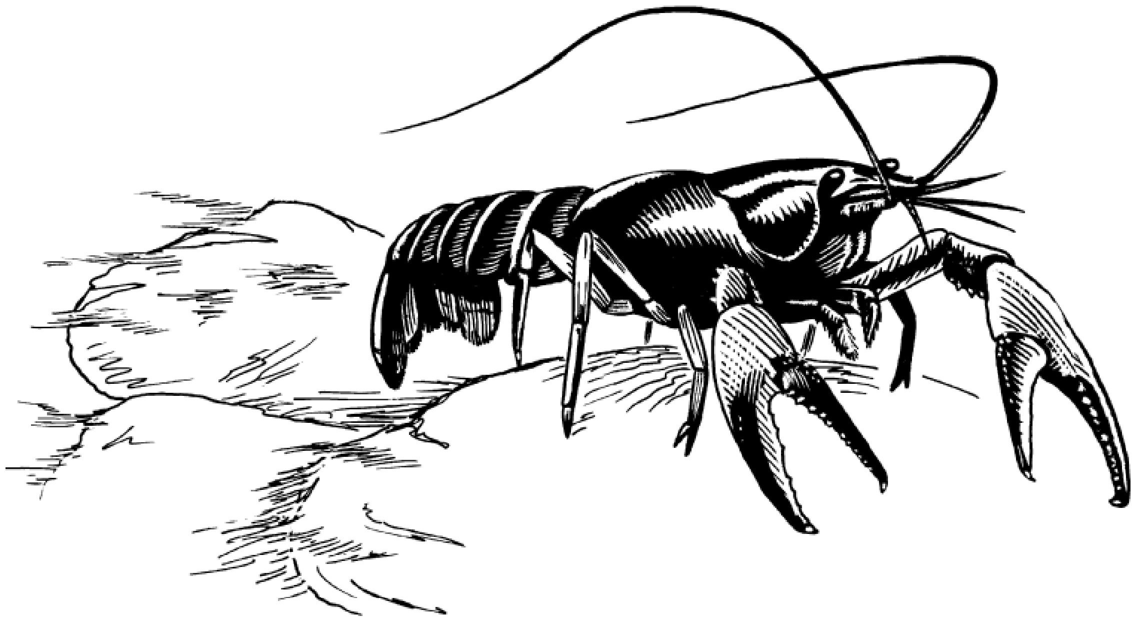

Matthew W. Hyatt

Arizona Game and Fish Department
Wildlife management Division / Research Branch
2221 W. Greenway Road
Phoenix, AZ 85023

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EXECUTIVE SUMMARY

North America is home to 390 native species of crayfishes, 75% of the world's total. No native crayfish occur in Arizona or the Colorado River basin of western North America; however, they have been widely introduced to this landscape and have become widespread and abundant throughout the Colorado River basin. Nonindigenous crayfishes have greatly altered North American lake and stream ecosystems, harmed fisheries, extirpated many populations of native crayfishes, and contributed to the global extinction of at least one native crayfish species. The economic cost alone of a small subset of freshwater Nonindigenous species in the United States has recently been estimated at 4.1 billion dollars annually. In Arizona, crayfish pose a serious threat to the long-term survival of many species of native fishes and amphibians. Due to the potential harmful effects to native flora and fauna, there is a need for the development of methods to control or eradicate Nonindigenous species.

This report provides a complete literature review of methods that have been tested for the purpose of controlling or eradicating nonindigenous crayfishes and methods that have not been tested, but have potential. Five broad categories of control were considered: legislative, mechanical, biological, physical, and chemical. Legislative control, while in effect at both the state and national level, has been unsuccessful. Mechanical control methods include manual removal, trapping, and electrofishing. Trapping, despite being the most common method used, has failed in every case to eliminate or even control crayfish. Biological control includes the use of fish predators, diseases, and microbial insecticides. Although some cases demonstrated an inverse relationship between the presence of fish predators and crayfish numbers, in no case did fish predators eradicate a population of crayfish. Crayfish plague is lethal to non-North American crayfish, but not to North American crayfish. If a strain of this disease lethal to North American crayfish could be developed, it might prove to be an effective method of control. Physical methods include de-watering, habitat destruction, and barriers. The ability of crayfish to travel over-ground for long distances and to survive for long periods of time in their burrows during dry periods, renders physical methods useless in most cases. Chemical methods include biocides, rotenone, and pheromones. Although rotenone will kill crayfish, any dosage sufficient to cause crayfish mortality results in the death of almost all other living organisms first. Research on the potential of using pheromones as a means of control has just recently begun. Early results of these studies do not look promising, but pheromones may prove effective in helping detect low density crayfish populations. Biocides proved to be the only method with any potential for eradicating or controlling crayfish.

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INTRODUCTION

North America is home to 390 native species of crayfishes, 75% of the world's total (Lodge et al. 2000). There is at least one native crayfish species in each of the 48 continental United States except for Arizona, which has no native species (Hobbs 1989). Moreover, there are no crayfish species native to the Colorado River basin of western North America, including the Gila River drainage of Arizona and New Mexico. However, crayfish have been widely introduced to this landscape and have become widespread and abundant throughout the Colorado River basin. In several well documented cases, nonindigenous crayfishes have greatly altered North American lake and stream ecosystems, harmed fisheries, extirpated many populations of native crayfishes, and contributed to the global extinction of at least one native crayfish species (Lodge et al. 2000). The economic cost alone of a small subset of freshwater nonindigenous species in the United States has recently been estimated at 4.1 billion dollars annually (Pimentel et al. 1999). In Arizona, crayfish pose a serious threat to the long-term survival of many species of native fishes and amphibians.

Introductions of nonindigenous crayfish around the world can be attributed to a variety of vectors (Table 1). Crayfish first appeared in Arizona waters about 30 years ago when they were stocked by Arizona Game and Fish Department (AZGFD) and U.S. Fish and Wildlife Service (USFWS) for the purposes of aquatic weed control (Dean 1969) and as forage for sport fish. It has also been suggested that the appearance of non-native crayfish in other states is a result of deliberate stockings by crayfish trappers, who wished to expand their operations (Bills and Marking 1988). Other mechanisms by which crayfish are introduced to the wild include their discard by aquarium enthusiasts and escape or release from bait buckets, both reasonable explanations for the present widespread distribution of nonindigenous crayfish in the state (Inman et al. 1998).

Table 1. Differential importance[1] of different anthropogenic vectors of crayfish introductions in Europe and North America (Lodge et al. 2000).

Vector of crayfish introduction	Europe	North America
1. Canals	Decreasing importance	Decreasing importance
2. Legal stocking in natural waters	Decreasing importance	Decreasing importance
3. Illegal stocking in natural waters	Remains important	Decreasing importance
4. Aquaculture	Increasing importance	Increasing importance
5. Live food trade	Increasing importance	Increasing importance
6. Aquarium and pond trade	Remains important	Increasing importance
7. Biological supply trade	Not important	Increasing importance
8. Live bait	Decreasing importance	Increasing importance

[1]In the absence of data comparable across vectors, we relied on expert opinion. Collecting data to quantify the importance of different vectors should be a priority.

Due to the potential harmful effects to native flora and fauna, there is a need for the development of methods to control or eradicate nonindigenous crayfish species.

According to Peay and Hiley (2001), the feasibility of eradicating, or even controlling, a population of crayfish is dependent on a number of factors:

- Is there any method of determining whether or not a control method has been effective?
- Is there a method capable of killing/ removing all the alien crayfish in a target area, or at least sufficient to prevent the population from spreading?
- Is there a method specific to alien crayfish, and if not, is its use acceptable?

Peay and Hiley (2001) suggest that unless the endpoint is known and identifiable, there is a risk of very large expenditure of resources without achieving eradication, or even control. Consequently, basic understanding of crayfish population dynamics is needed in order to assess the potential for eradication.

The fundamental problem of any attempt to eradicate a population is the difficulty of achieving and detecting 'zero' population (Peay and Hiley 2001). In order for any methodology designed for the eradication of nonindigenous crayfish to be judged successful, it must be capable of removing sufficient crayfish to ensure extinction of the population, and loss of this population must be demonstrable. This idea is centered on the concept that a density threshold exists for all animal populations, below which the population will be lost. Minimum Viable Population Density, MVDP, is the number of individuals that must be present in a population to ensure the continued existence of that population. Therefore, any methodology with the potential for achieving eradication or control must reduce the population density to below a threshold level, the MVPD below which extinction can be expected (Peay and Hiley 2001).

Any attempt to eradicate nuisance populations must take into account the impact such actions might have on the ecosystem, as other species may also be eliminated or new ones introduced. The pros and cons of doing nothing, trying to control the nuisance population (thus leaving the threat), or trying to eradicate it (and possibly adversely affecting other organisms) must be taken into account (Holdich et al. 1999).

In order not to make the situation worse, Holdich et al. (1999) suggested the following criteria be considered in any control or eradication program:

- The method should be safe for the environment and cause as little damage to other biota as possible,
- The method should have a good chance of achieving its goal,

- The method should be inexpensive,
- The method should involve little labor,
- The method should not cause danger to humans, e.g. by contaminating ground water,
- The method should be justifiable to the public.

A survey of relevant literature found few references directly relating to the control or eradication of nuisance crayfish populations. Predatory fish, intensive trapping, and biocides were used, with none conducted on a large-scale basis. According to Holdich et al. (1999) there have been no legal attempts in Europe to control crayfish on a large-scale using predatory fish or biocides, most of the experiments confined to small ponds or laboratory tanks. Efforts to control or eradicate crayfish in the United States have been similarly limited to small ponds and short sections of streams.

Based on control methods used for insects, there are five broad control categories that can be considered (modified from Fernald and Shepard 1955):

1. Legislative – local and national regulations,
2. Mechanical – control by hand or with traps,
3. Biological – disease and predators,
4. Physical – environmental manipulation,
5. Chemical – biocides, rotenone, pheromones.

Each of these will be examined separately below. In addition, a number of methods that are theoretically possible, but not, as yet, scientifically tested or evaluated, will be discussed.

CONTROL CATEGORIES

LEGISLATIVE

The problems caused by invasive species and government involvement to address these problems is far from new. In the United States, state laws requiring the eradication or control of invasive weeds have been on the books for over 100 years (National Invasive Species Council 2001). Since then, many Federal laws, authorities, and programs, as well as international agreements and treaties have been established for the purpose of preventing, controlling, and managing invasive species and their impacts. Today more than 20 Federal agencies are directly involved with some aspect of the invasive species issue (National Invasive Species Council 2001).

In North America, nonindigenous species combined with various global changes threaten a much greater proportion of the biota in freshwater than in terrestrial ecosytems (Master 1990). This is particularly true for North American fishes (Williams et al. 1989), mussels (Williams et al. 1993), and crayfishes (Taylor et al. 1996). Of these three groups, crayfishes have received by far the least attention from North American biologists, policy makers, and the general public (Lodge et al. 2000).

Crayfish are often a central component of freshwater foodwebs and ecosystems (Lodge et al. 2000); thus, additions or removals of crayfish species often lead to large ecosystem effects, in addition to changes in fish populations, and losses in biodiversity (Lodge et al. 1998a; Covich et al. 1999). Numerous studies have documented changes (usually reductions) caused by nonindigenous crayfishes in many different freshwater taxonomic groups in North America: algae (Weber and Lodge 1990); Lodge et al. 1994; Charlebois and Lamberti 1996; Luttenton et al. 1998); macrophytes (Feminella and Resh

1989; Chambers et al. 1990; Lodge et al. 1994; Hill and Lodge 1995; Lodge et al. 1998b); macroinvertebrates (Crowl and Covich 1990; Hanson et al. 1990; Lodge et al. 1994; Hill and Lodge 1995; Perry et al 1997; Lodge et al. 1998a); native crayfish (Lodge et al. 1986; Olsen et al. 1991; St. John 1991; Light et al. 1995; Taylor and Redmer 1996; Hill and Lodge 1999); amphibians (Gamradt and Kats 1996; Gamradt et al. 1997); and fishes (Horns and Magnuson 1981; Rahel and Stein 1988; Hobbs et al. 1989; Savino and Miller 1991; Miller et al. 1992).

In a summary of crayfish introductions around the world, Hobbs et al. (1989) listed 20 crayfish species that have been introduced into new river drainages, states, or continents, and documented a long history of intentional and accidental introductions. In many cases, the establishment of introduced crayfishes is enhanced by ongoing global changes that create environments less favorable for native species and more favorable for introduced species (Hobbs et al. 1989; Holdich et al. 1997; Lindqvist and Huner 1999).

Lodge et al. (2000) identified the vectors most likely responsible for introductions of nonindigenous crayfishes: aquaculture; aquarium and pond trade; biological supply trade; and the live bait trade.

In the United States, current federal and state regulations are inadequate for several reasons to prevent introductions of nonindigenous species (U.S. Congress 1993), including nonindegenous crayfishes (Lodge et al. 2000). First, the most relevant pieces of legislation, the Federal Noxious Weed Act and the Lacey Act, focus primarily on terrestrial plants and insects that are potential pests in agriculture, giving little attention to aquatic species. In addition, recent federal acts directed specifically at aquatic nonindigenous species (Nonindigenous Aquatic Nuisance Prevention and Control Act of

1990, National Invasive Species Act of 1996) primarily address ballast water as a vector, rely on voluntary guidelines, and therefore do not address the vectors listed above that are of greatest importance for crayfishes and many other freshwater organisms (Bean and Rowland 1997).

Second, even though many harmful nonindigenous species come from within the United States, federal laws deal primarily with importation into the United States, with no regard to interstate or intrastate transport or movements within states (Lodge et al. 2000).

Third, the relevant regulations take a "black list" approach, i.e., species can be imported into the United States unless they are on a list of prohibited species (Lodge et al. 2000). Currently, the U.S. Fish and Wildlife Service (USFWS) prohibits importation into the United States of two families of fishes; 18 genera or species of mammals, birds, reptiles, and shellfish; and two fish pathogens (U.S. Congress 1993), leaving the door open for most species, including most potentially invasive ones, simply because few data relevant to invasiveness exist for most species, including crayfish (Lodge et al. 2000)

At the state level, regulation of nonindigenous species varies widely. In some states, Florida for example, a permit is required for possession of any species not native to Florda, but thousands of permits are issued annually for nonindigenous fishes and other aquatic species (Cox et al. 1997). In other states, there are no regulations applicable to freshwater nonindigenous species.

In February 1999, President Clinton mandated the development of an Invasive Species Management Plan for the United States, emphasizing in Executive Order 13112 the severity of the economic, human health, and ecological threats posed by nonindigenous species (Lodge et al. 2000). The plan was mandated to include a review of the anthropogenic vectors that move species, and to recommend measures to minimize future introductions.

Lodge et al. (2000) addressed the various vectors of nonindigenous crayfish introduction and made recommendations to protect native crayfish faunas, fisheries, and freshwater ecosystems in the United States from the impacts of nonindigenous species. These included two general recommendations and specific recommendations for each of four vectors implicated in the introduction of nonindigenous crayfishes.

Their first general recommendation is the adoption of a white list approach that would preclude moving any species from one body of water to another within a state, between states, and from other countries until adequate screening of the characteristics of a given species was conducted (Lodge et al. 2000). Furthermore, they suggest states be required to appoint a lead agency to develop white lists to govern species movements between catchments within states and between states. Assessments for proposed white listing should include information on invasiveness in any other locations in which the species has been introduced, diseases, parasites, commensals, environmental tolerances, and life history characteristics. In addition, they also recommend results of assessments be reviewed by independent scientists under the coordination of the American Fisheries Society (AFS).

Their second general recommendation is for research on methods to eradicate localized populations of crayfishes while minimizing impact on nontarget species (Gherardi and Holdich 1999), and on methods for maintenance control of more widespread nonindigenous crayfishes. Lodge et al. (2000) suggest that each state identify a lead agency with the authority to respond quickly to eradicate newly established populations of nonindigenous crayfishes, and to manage those that cannot be eradicated.

As aquaculturists experiment with crayfishes from other locations within North America and from other continents (Semple et al. 1995), there is a potential of accidental species introductions. In the United States, current state laws governing aquaculture range from extensive permit applications under a white listing approach (Tennessee, Illinois), to no regulations (Arkansas). Even in states where commercial aquaculture is regulated, it is legal for anyone to import and culture a nonnative species in a noncommercial enterprise (Lodge et al. 2000). Because crayfishes invariably escape from outdoor aquaculture facilities, Lodge et al. (2000) advocate that the most stringent possible criteria should govern white listing proposals for aquaculture..

Escapes from outdoor culture facilities, and intentional releases by aquarium hobbyists have been responsible for the establishment of many nonindiginous fishes (Lodge et al. 2000). Although no crayfish introductions by this vector have been documented, nonindigenous crayfish are being sold in many aquarium and pond shops and the potential for their release into the wild is great. Lodge et al. (2000) recommend these trades be brought under a white list approach, with all sales accompanied by educational materials and warnings to hobbyists about the dangers of releasing nonindigenous species. They also recommend proposals for outdoor culture facilities be held to the same criteria advocated above for aquaculture facilities.

Several species of crayfishes, including some know to be invasive, are currently sold live by many biological supply companies and legally shipped into many states. Lodge et al. (2000) recommend that in addition to bringing this trade under a white listing approach, educational materials, and warnings to teachers and students about the dangers of releasing nonindigenous species be required to accompany all shipments.

The live bait trade has resulted in introductions of numerous nonindigenous fishes and other organisms, including crayfishes (Ludwig and Leitch 1996). Lodge et al (2000) believe the release of live bait to be the most important vector for introductions of nonindigenous crayfishes. Importation of bait across state lines is at best loosely regulated, with most states requiring nothing more than an easily obtained bait dealer's license (Meronek et al. 1995). To put an end to this avenue of nonindigenous species introduction, Lodge et al. (2000) advocate making the use of live crayfish as bait illegal in all states.

MECHANICAL

Manual

Manual removal of crayfish involves actively searching a pond or stream and removing (typically by hand) all observed crayfish. Sweep netting is commonly used in areas with an abundance of aquatic vegetation. Some projects have involved using surveyors to kick the substrate, across the full cross-section of a channel, while nets held immediately downstream are used to catch the fleeing crayfish. In some cases there has been excavation of crayfish burrows. The rationale for manual removal assumes that all or nearly all the crayfish in a particular system can be found and removed, making all size classes available for capture and thereby eliminating the size-bias associated with other techniques (Peay and Hiley 2001).

A program of intensive manual removal was carried out in May-June 1998[1], October-November 1998[2], May-July 1999[3], October-November 1999[4] and May-june1998[5] on the River Gwash in the United Kingdom (Peay and Hiley 2001). Efforts one, three, four, and five consisted of 100 man-days of work. Effort two consisted of 60 man-days of work. Survey methodology involved turning over stones and capture of exposed crayfish in areas of clear water. Where high levels of suspended solids rendered this method ineffective, a modified form of kick sampling was used. This method involved drag netting, with a line of large hand nets each staggered a foot behind the next. Teams of four or five people worked upstream within a 25 m section, and some sections were trawled many times in succession until no more crayfish were caught. Overhanging banks were searched by pushing a net under the overhang and dragging up the bank and along the roof of the overhang. Although catch decreased from 2227 total crayfish captured in effort one to 1009 total crayfish captured in effort five, the authors caution against inferring from this data that a reduction in population size caused by the capture scheme is necessarily responsible for these results. (Peay and Hiley 2001) suggest the observed decrease in number of crayfish captured could possibly be attributed to (1) a change in survey methodology, (2) possible inexperience of additional surveyors used during effort five, or alternately, (3) population decrease due to unrelated causes e.g. flooding, pollution incident.

Trapping

Many types of traps are used to catch crayfish for the purposes of harvest, population control, and scientific research. These traps are typically cylindrical traps, seine nets and fyke nets. Differences among traps include construction materials and mesh sizes, physical dimensions, number of entrance funnels and the presence or absence of support rods, bait holders and retainer bands or collars (Huner and Barr 1991).

A considerable body of information exists on the effects of harvesting on the structure of crayfish populations (e.g. Huner et al. 1991; Momot 1992, 1993; Skurdal & Taugbøl 1994). However, these mostly focus on ways of sustaining production, not reducing it, although there are a number of instances where sustained trapping has been shown to reduce crayfish populations.

In Sweden, Svärdson (1948) found that intensive trapping of an overpopulated crayfish lake reduced the number of *A. astacus* by 50% over three years, although the average size of the crayfish increased.

In the United States, Bills and Marking (1988) trapped a nuisance population of *Orconectes rusticus* continuously for six weeks, with catches declining from 6500 crayfish to 206 over the trial period, and males dominating the catches. Their trapping was ineffective in removing small-sized crayfish, as they did not seem to enter the traps. They suggested that trapping by itself might suppress the crayfish population, but would be unlikely to control it.

In France, Roqueplo et al. (1995) used standard cylindrical traps and also a trap shaped like a tambourine with funnels in the sides, to trap a nuisance population of *Procambarus clarkii* from a pond. By using different mesh sizes they were successful in catching both juveniles and adults. They also found the color of the trap to be important – black catching more crayfish than white. The tambourine-type trap was more effective than the cylindrical one. Similar to other studies, they found that regular use of traps substantially reduced the population, but did not eliminate it.

In England, a number of attempts have been made to control nuisance crayfish populations. First, a population of *A. leptodactylus* that was interfering with angling in a lake was heavily trapped, at one time 70 fyke nets were being used, over five months using Swedish trappies and fyke nets (Holdich et al. 1995; Rogers 1996). The Swedish trappy (Figure 1) consists of a plastic mesh sheet that is folded into a cylinder 50 cm long and 20 cm wide and clipped into place. Funnels fit into each end and have an inner opening 4.5 cm wide. The mesh is diamond-shaped with a size of 2.5x3.5 cm. A metal clamp secures bait to the center of the trap (Harlioğlu 1991). Although this reduced the adult population considerably and solved the problem in the short-term, this effort involved considerable cost and manpower.

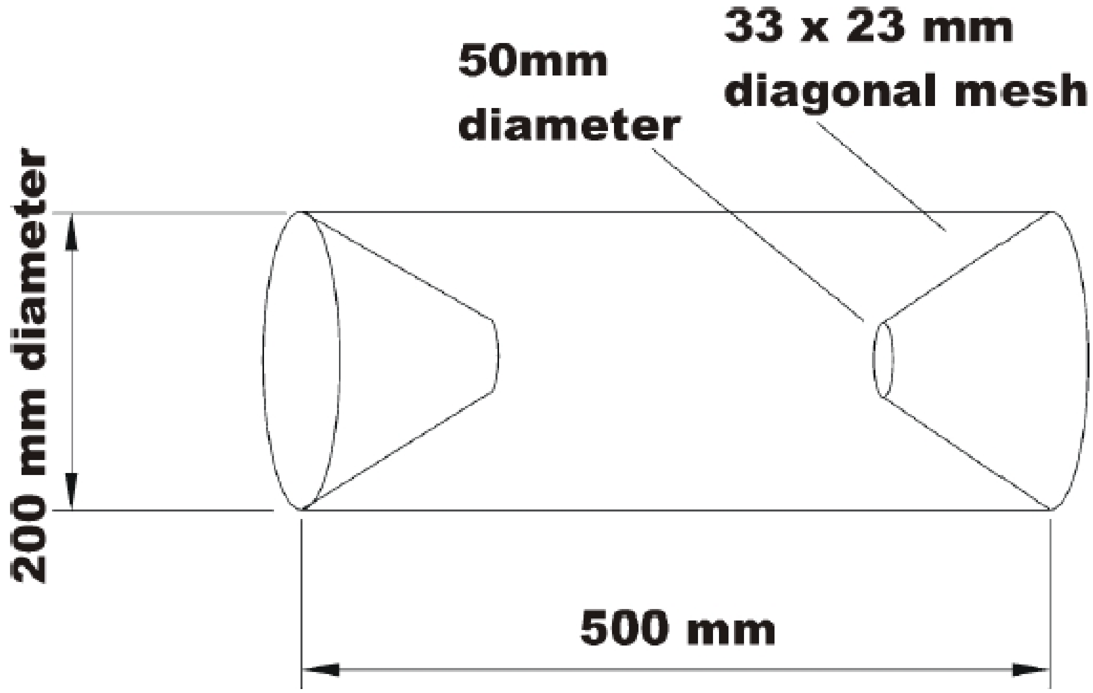

Figure 1. Schematic diagram of commercial Swedish Trappy (Peay and Hiley 2001).

Second, a rapidly expanding population of *P. leniusculus*, which was at the point of eliminating, probably through competitive exclusion a population of *A. pallipes* in the same lake, was heavily trapped and seine-netted in February of two succeeding years and all trapped ovigerous females were removed (Holdich & Domaniewski 1995; Holdich et al. 1995). This reduced recruitment considerably and, if combined with removal of other trappable individuals throughout the year, could have had a significant impact on the population, especially in the face of predation pressure from the fish population. In this population *P. leniusculus* less than 40 mm carapace length proved very difficult to trap, a finding similar to that of others in Britain (e.g. Guan & Wiles 1996), even when mesh size of traps was significantly reduced. This is possibly due to the cannibalistic tendencies of this species and avoidance of large crayfish by small crayfish because of this (Holdich et al. 1999b).

Third, a population of *P. leniusculus* was heavily trapped from carp ponds using Swedish trappies and the population was estimated to have been reduced from 4000 to 1500 over the equivalent of 900 trap nights (Rogers et al. 1997). They suggested if regular trapping of large individuals had been continued, fish predation on smaller individuals may eventually have eliminated the population.

In the cases above, a considerable amount of time and effort was employed, the problems were only solved in the short term and the populations were not eliminated. It is likely that within a few breeding seasons, crayfish populations returned to their former levels, despite the considerable amount of time and effort employed (Holdich et al. 1999b).

Some of the examples above illustrate that improvements in trap design should be considered. Westman (1991) reviewed the wide variety of traps used in Finland. Westman et al. (1979) stated that crayfish are very skilful at escaping from standard traps and as a consequence developed the 'Evo-trap,' which has narrow slit-like apertures, that make it much more difficult for crayfish to escape. Fjälling (1995) assessed the efficiency of seven commercial crayfish traps used in Sweden and found that crayfish catch differed significantly with trap design. He also found that minor modifications of traps could improve their performance significantly. He designed a new collapsible trap, consisting of terylene webbing stretched over a galvanized steel ring and a buoyant plastic ring with three stiff plastic entrance funnels, which he found to be more effective than those already in use, although more expensive to make. Holdich (in Harlioğlu 1996) has shown that the Swedish trappy commonly used in Britain is not very effective at retaining crayfish once captured and that traps needed to be emptied frequently. Edsman and Söderbäck (1999) recommended for the standardized sampling methodology setting the traps just before dusk and removing them around 0600 h. Romaire and Pfister (1983) recorded a maximum catch of crayfish per trap after 6-12 h with no visible effect on catches with an increase in time. Conversely catches decreased when traps were deployed for less than 6 h. Kozak and Policar (2003) examined the extent to which crayfish escaped from 'Evo-traps' and found that an unexpectedly high (39.7 ± 29.03%) frequency of crayfish escaped from the traps with 90% maximum and 0% minimum. No effect of length, weight, or sex was found. In agreement with the data of Holdich et al. (1999b), they recommended traps be set before dusk and harvested in early morning (Edsman and Söderbäck 1999), or at least 6 hours after setting them up, as stated by Romaire and Pfister (1983).

Morgan et al. (2001) accomplished another improvement in trap design. They found that although standard minnow traps effectively capture crayfish, they capture fish as well. In an effort to reduce fish capture rates, they modified standard minnow traps by connecting trap funnels with a PVC “T” fitting (see Figure 2). A comparison between modified and unmodified traps showed the modified traps did not compromise the capture efficiency of crayfish ($P=0.34$), but significantly reduced the number of fish captured ($P<0.0001$). These results suggest that crayfish can be removed from aquatic systems using modified traps with minimal fish capture.

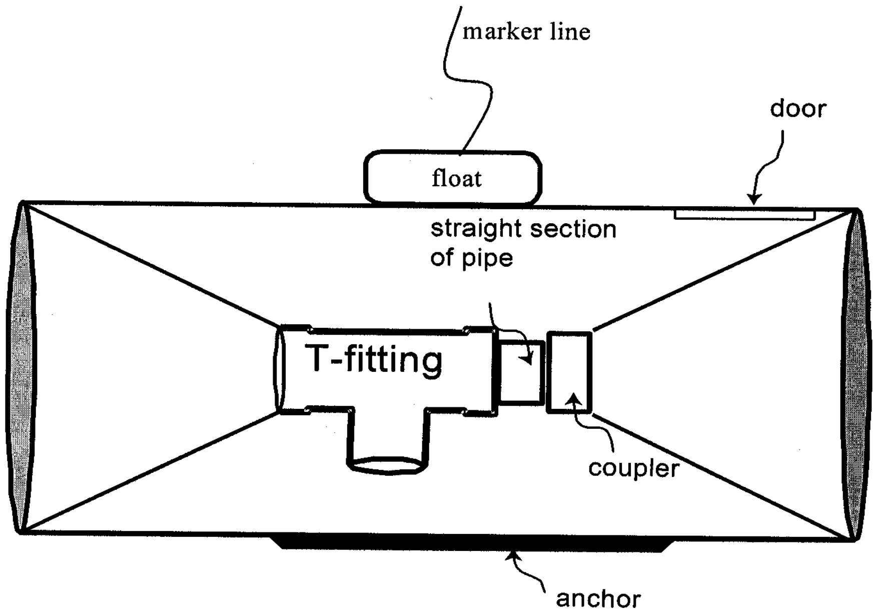

Figure 2. Modification of standard minnow trap used to harvest crayfish and reduce unwanted fish capture in lakeside ponds used to rear endangered native fish at Lake Mohave, Arizona/Nevada (Morgan et al. 2001).

A new development with respect to trap design is the recent introduction of the refuge trap. Described by Peay and Hiley (2001), these traps differ from Swedish trappies and small mesh traps in that crayfish can enter and leave the traps at will. This removes the need for baiting and reduces the frequency with which traps must be checked. Refuge traps (Figure 3) consist of black plastic pipes of different diameters and are used to provide habitat for a wide range of size classes. One end of each tube is blocked by a piece of perforated plastic, to allow draining of water, and the trap is weighted with a steel chain. These traps are not intended to capture active crayfish, but rather to provide preferential habitat for resting crayfish. Trials are currently underway to assess the effectiveness of refuge traps (Peay and Hiley 2001).

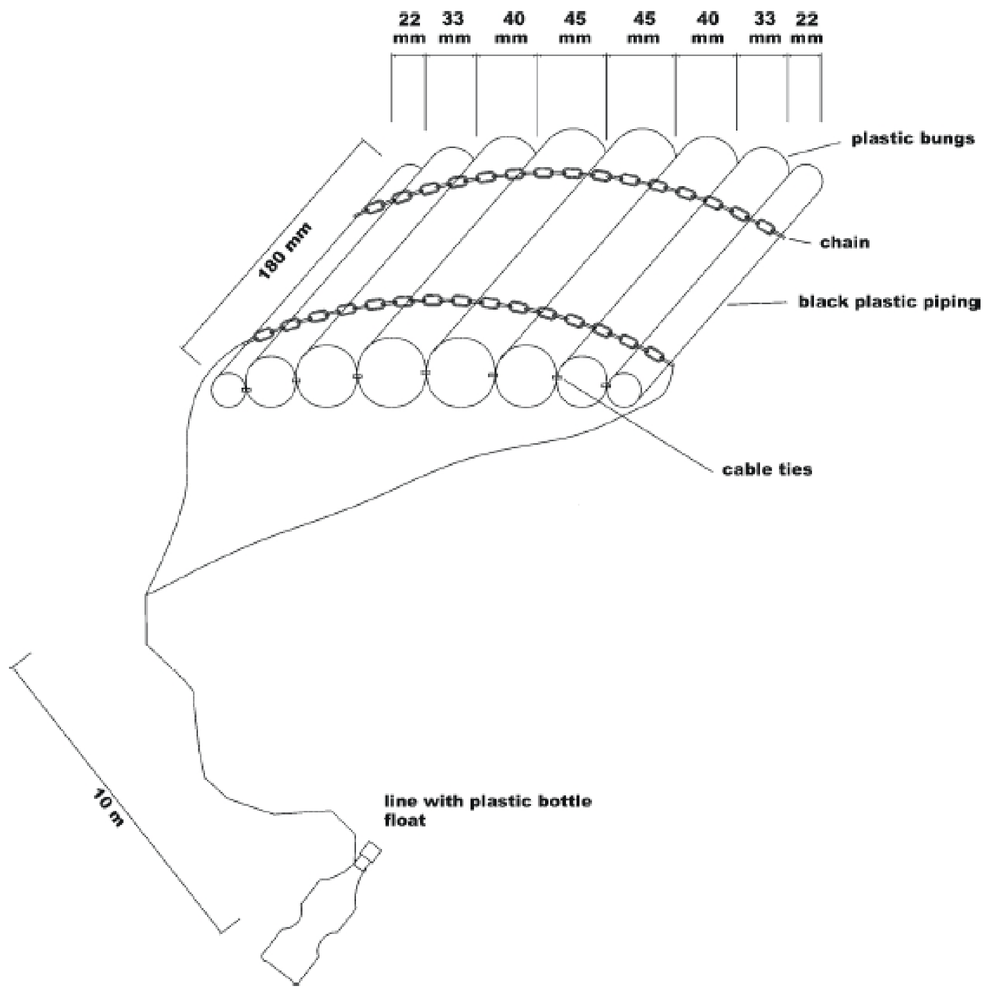

Figure 3. Schematic diagram of a refuge trap (Peay and Hiley 2003).

Laurent (1988) found the number of crayfish caught in a trap to be dependent on time of day and season. In addition, juveniles and ovigerous females may be trap shy and more effectively caught with seine and fyke nets (Rogers 1996).

Cullen et al. (2003) conducted experimental trapping of crayfish on the Kilchreest River in east County Galway, Ireland, utilizing three methods of trapping. The first method involved the use of specifically built pipe traps that were baited with beef liver. These pipe traps were constructed from a 0.5 m length of PVC piping, 160 mm in diameter. The pipe ends were then covered with wire mesh (15 mm x 19 mm chicken wire netting) funnels, which allowed a 5 cm opening into the trap. Bait was suspended in the center of the trap. The second method involved the use of wire traps baited with beef liver. The wire traps were similar in overall dimensions and design to the pipe traps, except that instead of PVC, chicken wire (15 mm x 19 mm mesh size) was used to form the 'pipe' component of the trap. The third method, hand collections, involved turning over large stones and rocks and collecting by hand any crayfish that were exposed. Cullen et al. (2003) found differences between the trapping methods used, both in terms of numbers and sexes of individuals trapped. In general, males dominated the catches, with ovigerous females, making up between 0% and 50% of the trapped individuals on any occasion (overall average, excluding hand collections specifically aimed at ovigerous females). These results reflect the natural habits of crayfish, with female crayfish, in particular ovigerous females being less active than males (Lowery 1988). Juvenile crayfish were generally absent from the samples, due, according to Cullen et al. (2003), mostly to their small size and associated difficulty of capture using the trapping methods employed during this study. This greater trapability of males has been recorded in many other studies (Moriarty 1973; Reynolds and Matthews 1993).

Peay and Hiley (2003) found that small mesh traps (Figure 4) caught crayfish across a broader size range (19-72 mm) than Swedish trappies (38-76 mm). The modal size for small mesh traps was 30 mm CL (carapace length) with the majority of the catch in the range of 20-40 mm CL. In contrast, Swedish trappies caught very few crayfish less than 40 mm CL.

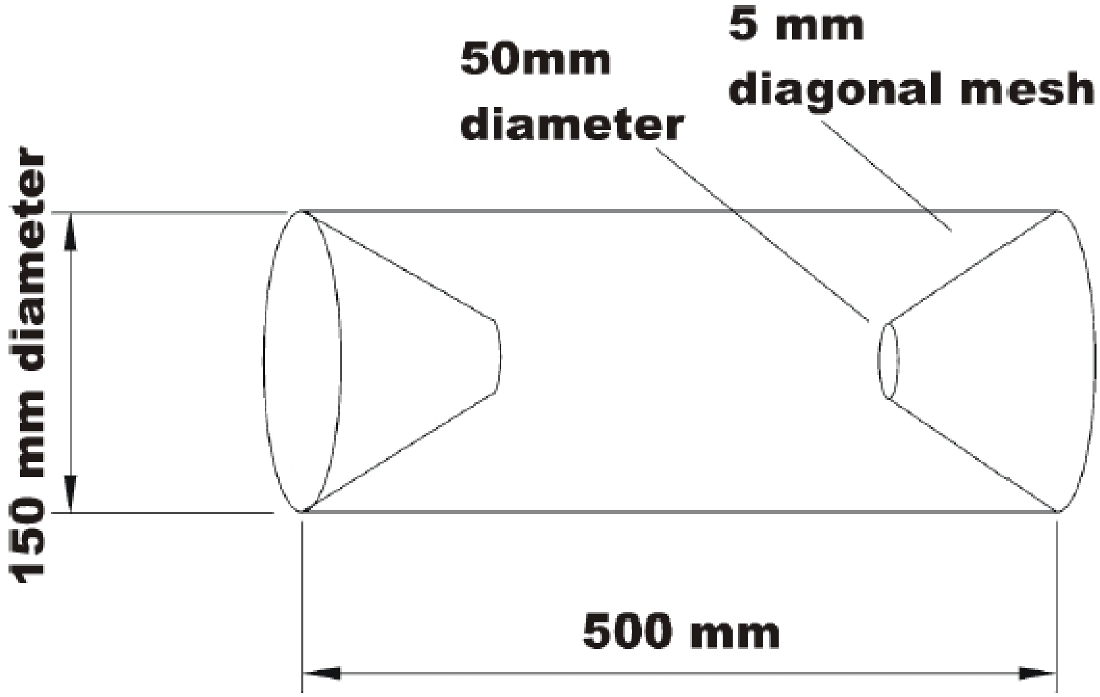

Figure 4. Schematic diagram of a small mesh trap (Peay and Hiley 2001).

According to Lodge and Hill (1994), there is very little evidence of crayfish stocks being over fished by man. In fact, heavy predation has sometimes been found to increase production and yield in a number of populations (Morgan and Momot 1998; Svärdson et al. 1991; Westman 1991; Momot 1993). For example, populations of *Orconectes virilis* can withstand exploitation rates of 60% of age 1 and older individuals (Momot 1993). This phenomenon acts through reduced competition between young of year (YOY) and older males (Holdich et al. 1999b). Dominance hierarchies exist in some species, e.g. *P. leniusculus*, with large males dominating females and juveniles. Removing such males by trapping reduces pressure on smaller individuals, allowing them to grow, and often leading to a large population of individuals whose growth is stunted due to competition for resources (Skurdal and Qvenlid 1986). Ibbotson et al. (1997) in a study of *P. leniusculus* in the River Thame in England suggested that intensive trapping of one section of river in the middle of a population acted like a drain on the larger individuals in the population; the areas alongside the section being trapped were thus depleted of larger crayfish and this enhanced population expansion in these adjacent sections by reducing competition for the younger year classes.

As with fish predation (see below), long-term trapping may affect a greater number of individuals in a population and may be more important in controlling population size and production than short-term intensive trapping. However, it is probably impossible to trap out a population of crayfish because of the difficulty of trapping juveniles (Holdich et al. 1999b). Trapping is only effective on a limited portion of a population. Literature data vary in the minimum size of crayfish that can be caught in traps, stating sizes from 40 to 80 mm (Abrahamsson 1966; Edsman and Söderbäck 1999; Holdich et al. 1999; Kozak and Policar 2003; Westman et al. 1999). Sustained trapping can be used to reduce the population to a low level, but this must be done regularly over the length of time reduction is desired.

In Switzerland, Frutiger et al. (1999) attempted to control a population of *P. clarkii* in a pond by trapping and although they achieved a slight reduction in the segment of the population susceptible to trapping, they estimated this was less than 20% of the total population and concluded no control could be achieved by this method.

In the Czech Republic, Kozak and Policar (2003) attempted to eradicate a population of signal crayfish, *P. leniusculus*, from a 0.16 ha experimental pond by trapping. They found traps to not be very effective, catching only a part of the crayfish population bigger than 80 mm. Similar to Bills and Marking (1988) they suggested small-sized crayfish did not enter traps. They concluded that trapping may have suppressed the crayfish population, but did not eliminate it.

In order to enhance trapping, specialized baits or attractants can be used. Huner and Paret (1995) observed increased catch rates in traps containing baits rich in fish oil. However, artificial baits can be expensive to produce. In Louisiana, the cost of bait figures high in the annual operating costs in crayfish culture (Huner et al. 1994). Cange et al. (1986) evaluated 18 artificial crayfish baits against gizzard shad (*Dorosoma cepedium*), but even the most attractive baits (those containing catfish meal and oil) only caught slightly more than the control bait. In non-commercial operations, the cheapest bait available tends to be used, the type depending on the choice of the trapper. Holdich et al. (1999) identified punctured cans of cat food, herring, coarse fish, liver, and mammal carcasses as baits commonly used by trappers in Europe. In Arizona, trappers use baits such as bacon and hotdogs (Sue Sitko personal communication), dry dog food and meat scraps (Jerry Hobbs personal communication), and when available, green sunfish (Jim Walters personal communication). Based on his trapping experience, Walters (personal communication) claimed green sunfish to be a slightly better bait than meat scraps which were slightly better than dry dog food.

Electrofishing

Crayfish are often caught during electrofishing surveys to study fish populations, but the method has also been used specifically for catching crayfish. Huner (1988) reported that special boats with a bow-mounted trawl and a pulsed, direct current electrofishing unit are sometimes used to harvest soft-shelled crayfish in Louisiana, and are particularly effective amongst vegetation. Westman et al. (1978) found all sizes of crayfish could be trapped by electrofishing, but only in shallow, clear water, when the weather was calm. They recommended using non-pulsating, direct current equipment rather than pulsating, battery-fed equipment as used for fish capture. Laurent (1988) also stated that electrofishing was a good method for catching crayfish but, due to their predominantly nocturnal activity, results varied depending on time of day. Westman et al. (1978) suggested that nighttime electrofishing can be more productive than during day-time. Eversole and Foltz (1995) used weighted nets to form cells within a river and then successfully electrofished the crayfish out of each cell.

BIOLOGICAL

Crayfish have many predators (Hogger 1988; Westman 1991; Lodge and Hill 1994) and suffer from a number of diseases (Alderman and Polglase 1988), most notably the crayfish plague fungus, *Aphanomyces astaci.* The use of predators, diseases, and microbial insecticides as control agents will be discussed next.

Fish Predators

Many studies suggest that fish predators reduce crayfish populations and that they may consume a large proportion of crayfish production (Westman 1991; Rabeni 1992; Mather and Stein 1993; Roell and Orth 1993; Lodge and Hill 1994; Blake and Hart 1995a). Holdich et al. (1999b) suggests that a significant inverse relationship may exist between densities of predaceous fish and crayfish. Svärdson (1972) found that crayfish were less abundant in Swedish lakes containing large populations of eels and vice versa.

When eels were excluded by dams, the crayfish population increased in size. Fürst (1977) suggested that predation by eels and perch were the most important factors in limiting the establishment of newly introduced crayfish in 44 Swedish waters. While European eels have an impact on native crayfish species, it is not known if they would have the same impact on American crayfish, especially ones which burrow. Westman (1991) mentioned eels, burbot, perch and pike as being partial to crayfish, particularly when the crayfish were moulting. Eel, recently introduced into the Rumensee in Switzerland, substantially reduced an expanding *P. clarkii* population to less than 10% within 3 years, whereas pike, introduced at the same time had no obvious effect (A. Frutiger, personal communication). Hickley et al. (1994) found that *P. clarkii* introduced into Lake Naivasha, Kenya became the principle food item of another introduced species, largemouth black bass. Similarly, Elvira et al. (1996) found that *P. clarkii* introduced into Spain, became the main prey item of pike, another introduced species. The impact of fish predators on crayfish can be shown when fish are removed; an experiment to remove fish using rotenone in Finnish lakes resulted in a dramatic increase of crayfish numbers (Westman 1991). Under experimental conditions, crayfish densities have also been found to be inversely related to fish density (Rickett 1974; Rach and Bills 1989). However, these experiments were relatively short-term.

Fish predation can have an impact on crayfish populations (Table 2). However, this is not always the case. For example, very little correlation was found between the presence of largemouth bass and yellow perch and crayfish abundance in 21 lakes in northern Wisconsin (Lodge and Hill 1994). Gowing and Momot (1979) found that brook trout at different densities had little effect on recruitment of *O. virilis* in experimental lakes in Canada. Holdich and Domaniewski (1995) recorded an increasing density of signal crayfish, *P. leniusculus*, with time in an English lake heavily stocked with brown and rainbow trout, perch, and carp.

Table 2. Effect of fish predators on adult (A) and juvenile (J) crayfish population size (Lodge and Hill 1994, Holdich et al. 1999).

Crayfish stage species	Fish	Predator	Type	Impact study	Authors
Astacus astacus	A	Eel	C	+	Svärdson (1972)
Orconectes rusticus O. sanborni	A	Smallmouth and rock bass	C	+	Mather and Stein (1993)
Orconectes rusticus O. propinquus O. virilis	A	Largemouth bass and yellow perch	C	+	Lodge and Hill (1994)
Orconectes nais	A	Largemouth bass	E	+	Rickett (1974)
Orconectes virilis	A	Largemouth bass	E	+	Saiki and Tash (1979)
Orconectes immunis	A	Largemouth bass	E	+	Rach and Bills (1989)
Orconectes virilis	A	Brook trout	E	-	Gowing and Momot (1979)
Pacifastacus leniusculus	J	Perch	C & E	+	Blake and Hart (1995a)

E = experimental and C = field studies. - = no impact; + = impact.

Cover has been shown to be an important factor in crayfish survival, especially for young life stages when molting is more frequent (Capelli and Magnuson 1983; Lodge and Hill 1994). Blake and Hart (1993) found under both experimental and field conditions that predation by perch on juvenile *P. leniusculus* was linked to the substrate type, i.e. crayfish survival increased as the number of hiding spaces increased. Saiki and Tash (1979) found that as weed cover decreased, predation by largemouth bass on *O. virilis* increased. Even in the absence of fish predators, cover is important for young crayfish, as most species are cannibalistic (Holdich et al. 1995). Reduction in cover, therefore, may increase the chances of crayfish being eaten by predators (Holdich et al. 1999b). However, despite these observations, Lodge and Hill (1994) have shown that invading *O. rusticus* populations can survive at high densities, even after they have eliminated all the aquatic macrophytes.

Crayfish have been shown to alter their behavior in the presence of fish predators by increasing utilization of shelter and decreasing their post-dusk peak in activity (Hamrin 1987; Blake and Hart 1995a, b). This may have some implication for increasing fish numbers in order to control crayfish populations (Holdich et al. 1999b).

Although the results of the majority of studies seem to indicate that fish predators reduce crayfish populations, the potential exists, as with trapping, for such predation to increase crayfish production (Rabeni 1992). Fish predation may have more sublethal effects, which, in the long-term, reduce crayfish growth, reproduction and survival. Continued predation pressure may affect a greater number of individuals in a population than direct predation and be more important in controlling population size and production (Lodge and Hill 1994). Very few attempts have been made to control crustaceans with fish, although suggestions have been made that the deep water sculpin, *Myoxocephalus thompsoni*, might be used as a form of biological management of the opossum shrimp, *Mysis relicta*, which has proved an undesirable introduction in some North American lakes and reservoirs (Martinez and Bergersen 1989).

<u>Diseases</u>

Crayfish suffer from a number of diseases, mainly caused by bacterial, fungal, protistan and helminthes infections (Alderman and Polglase 1988, Edgerton et al. 1995). Thune et al. (1991) also found that some large-scale mortality among farmed *P. clarkii* were caused by viral infections.

Most crayfish diseases are sublethal, but one, crayfish plague, caused by the oomycete fungus, *Aphanomyces astaci*, has been shown to have a dramatic effect and is usually 100% lethal to susceptible species (Smith and Söderhäll 1996). All non-North American crayfish tested so far have proved to be susceptible to crayfish plague (Unestam 1975), and the disease has had a disastrous effect on European crayfish populations since the 1860s (Alderman 1996). Crayfish plague is endemic in North American crayfish, where it occurs as a chronic infection, but these species are relatively immune to its effects unless put under stress (Svärdson et al. 1991). As a vector gets older, it presumably carries more of the chronic infection and the immune system is constantly challenged. Additional environmental stressors, such as changes in water temperature and quality, sudden changes in light levels and increased intrapopulational competition (as occurs under rearing conditions) may result in mortality. A chronic infection of crayfish plague may challenge the immune system to such an extent that a crayfish would be unable to cope with any additional parasitic load, such as *Psorospermium haeckeli,* which, on its own, may not prove lethal (Thörnqvist and Söderhäll 1993). The same may prove true for another protistan parasite, *Thelohania contejeani* (Henneguy) (Alderman and Polglase 1988). Söderhäll (1989) has suggested that *P. leniusculus* is not suitable for aquacultural purposes because of these possible problems. There are a number of recorded cases of mass mortalities of wild and farmed *P. leniusculus* in Sweden, which have been attributed to stress in combination with crayfish plague. However, not all populations of North American crayfish harbor the crayfish plague fungus. This has led to some mixed species populations becoming established in European waters, at least in the short-term (Westman et al. 1993; Holdich and Domaniewski 1995; Söderbäck 1995). Crayfish plague could in theory be used to eliminate nuisance populations of susceptible species, although this has never been tried. One danger is that the disease could be spread to other populations of susceptible crayfish. Genetically altering the crayfish plague fungus, so that it can overcome the defense system of North American crayfish, might be a possibility if funds were available (K. Söderhäll personal communication), but at present, very few laboratories have the know-how and facilities to do this. Again, this might present an increased danger to native populations as spores of the crayfish plague fungus are easily transported in water and on damp equipment (Alderman & Polglase 1988). According to Reynolds (1988), the crayfish plague outbreak in central Ireland in the 1980s was thought to have been caused by contaminated fishing equipment belonging to foreign anglers. In addition, predators of crayfish such as birds and otters could in theory move infected crayfish from one body of water to another. Although this method of transfer is poorly documented, there is anecdotal evidence to indicate that it happens (Holdich et al. 1999).

Microbial Insecticides

Varieties of the, bacterium, *Bacillus thuringiensis*, such as *israeliensis* Berliner (H-14) have been developed as natural insecticides to kill insect pests (Pedigo 1989). By itself, *Bacillus thuringiensis* is harmless, but is converted to a potent toxin in the gut of certain insects. As a result, the insect stops feeding and starves to death. To date, no crayfish-specific strain has been developed, but if it were, it might be a new method for eradicating crayfish (Holdich et al. 1999). However, it would need to be specific to nuisance crayfish species, or it might also affect native crayfishes. Jarboe (1988) records a 96-h LC_{50} of 103 mg /l for *P. clarkii* exposed to *Bacillus thuringiensis* var. *israeliensis*, which is used as an insecticide in rice fields.

PHYSICAL

Physical methods of crayfish population control include draining lakes or ponds, diverting streams or rivers, or creating obstacles such as weirs. However, I found very little in the literature relating to actual use of these techniques. Holdich et al. (1995) suggested that a natural event such as drought could be effective in eliminating crayfish populations. Crayfish are very adaptable animals (McMahon 1986) and are capable of living out of water for long periods, provided some moisture is available, and particularly if they are in burrows. Holdich et al. (1995) reported live *P. leniusculus* from under rocks on the bed of a British river three months after it had dried up. There is one instance of the same species surviving for over six months, including a British winter, under an outdoor aquarium tank (P.R. Wiles personal communication).

Although burrowing is more associated with cambarid (Huner et al. 1994) and parastacid crayfish (Mills et al. 1994), astacid crayfish can also burrow, although there are few references to this activity in native European crayfish in the literature (e.g. Huxley 1879). There is nothing in the literature to suggest that *P. leniusculus* burrows, even in North America (although apparently it does to a minor extent in Oregon -S.D. Lewis personal communication), but when introduced to Britain, it did so extensively in suitable substrata. Holdich and Reeve (1991) reported large numbers of burrows in the banks of a pond on a fish farm, where the owner thought that he had eliminated the crayfish by trapping, seine netting and draining the pond. The pond was refilled soon after, but when it was drained again a year later, almost as many adult crayfish were found again, having survived the first drain down in their burrows. Guan (1994) and Harris and Young (1996) have also reported extensive damage to river banks caused by the burrowing activities of *P. leniusculus* in England. A lake in Wales was recently (1997) found to be infested with *P. leniusculus* and the banks riddled with burrows (W.D. Rogers personal communication). Healthy, ovigerous females were found in burrows three months after the drain-down.

An alternative to trapping is to use barriers, such as weirs, which might act as a focus for crayfish to congregate in. Crayfish can then be manually removed at regular intervals. However, hand trapping is unlikely to be an effective method of controlling crayfish, except after a drain down or isolation of a riverbed (see below). Manual removal of crayfish from burrows may prove effective if sufficient labor is available and the population is not too extensive.

Holdich et al. (1999) suggested that nuisance populations of crayfish in rivers could in theory be isolated if the river was diverted via a channel or pipeline and the remaining water pumped out. The isolated stretch could then be thoroughly searched for crayfish and, if necessary, burrows could be chemically treated (see below) or crayfish could be removed from their burrows by hand.

Various other physical methods have been suggested, but not tested. There is some anecdotal evidence that crayfish in tanks exposed to vibrations from aerators and pumps show higher mortality than normal. Holdich et al. (1999) suggests this might prove to be a valid management option.

De-watering

This method involves removing the water from a pond or small body of water by draining or drawing the water off. The rationale behind this technique is that crayfish need water to survive and thus by removing the water the crayfish will die. However, in practice it is very difficult to remove all the water from an area. Even the best efforts to drain a pond leave the ground soil moist, which is more than adequate to provide for the survival of crayfish.

Peay and Hiley (2001) observed the survival of signal crayfish in a dried up streambed for more than 12 weeks and similar survival has been found by Holdich et al. (1995). There is one instance of the same species surviving for over six months, including a British winter, under an outdoor aquarium tank (P.R. Wiles personal communication).

Kozak and Policar (2003) failed to eliminate a population of signal crayfish from a small pond after repeatedly drawing the water off and removing all visible crayfish by hand. Even after draining the pond and allowing it to remain empty over the winter in temperatures as low as minus 20 ^{o}C, when the pond filled in the spring, the presence of crayfish was confirmed. While de-watering may not eliminate a population completely, the authors contend that repeated drying of a pond in combination with some other eradication method, such as the application of toxic chemicals, may be a viable method of eradicating a population of crayfish from a pond.

Habitat Destruction

Habitat destruction involves removal of crayfish and habitat, typically by mechanical excavation (Peay and Hiley 2001). Sometimes this includes making some aspects of the habitat unsuitable. The goal is to destroy all crayfish and crayfish burrows and to eliminate potential refuge areas. If applied rigorously, this method has potential to eradicate localized populations of crayfish by physical removal of animals and habitat (Peay and Hiley 2001).

The only available case study involved an attempt to eradicate crayfish from a small pond at the headwaters of the River Vyrnywy in the United Kingdom (Peay and Hiley 2001). The pond contained a dense population of signal crayfish, which exhibited burrowing behavior. The pond was drained and enlarged to improve it as a fishery. Prior to the dredging operation, crayfish were observed escaping into a nearby stream. Left over soil from the enlargement process was transported far away from the pond in the hopes that this would destroy all crayfish and crayfish burrows. Some time later, the presence of a sizable population of signal crayfish was confirmed in both the pond and stream. Due to the possibility that crayfish from the stream re-colonized the pond, it is unknown whether or not the eradication effort in the pond was successful.

Barriers

Physical barriers include reservoir dams, in-channel weirs, canal locks, screens, catchpit outfalls, and fencing. The rationale for the use of barriers is that even if crayfish cannot be eradicated, it might be possible to put some kind of barrier in place that would prevent a population from spreading.

The potential of barriers to limit the spread of crayfish was investigated at Durford Bridge on the River Rother and at West Tanfield Fishery in the United Kingdom (Peay and Hiley 2001). At Durford Bridge, a population of signal crayfish was believed to be separated from an upstream population of white-clawed crayfish by two small weirs. Trapping surveys conducted in 1997 showed that the signal crayfish population had spread upstream of the downstream weir, a structure about 0.3 m high, but were not detected upstream of the upper weir, a higher structure up to 1 m in height. In 1999 signal crayfish were detected upstream of the upper weir suggesting any barrier effect of the weir was only temporary (Peay and Hiley 2001).

At West Tanfield Fishery, a 3 ha fishing lake a few hundred meters from the River Ure, a population of alien signal crayfish was found to be escaping via an outfall and long drainage pipe into an open section of stream within a nearby fish farm, where they then escaped to the River Ure, a large upland river containing a robust population of native white-clawed crayfish. In Summer 2000, a catchpit system was installed between the lake and the fish farm in an attempt to prevent the escape of signal crayfish from the pond to the fish farm. The catchpit consists of a bell-mouth outlet pipe running from the lake to a chamber with a vertical bell-mouth outlet. Figure 5 illustrates the proposed catchpit, as designed by Scott Wilson staff. The design of the catchpit is intended to ensure that no crayfish could, by swimming, walking, or passive carriage, pass through the chamber and subsequently colonize downstream waters.

The main features of the design, described in Peay and Hiley (2001), are:

- smooth plastic interior to prevent climbing;

- a vertical bell-mouth with a sufficiently long vertical arm to prevent a crayfish reaching up to the top;
- a tank size designed for the on site flow, maximum internal velocity $0.05ms^{-1}$;
- a baffle to reduce velocity at the inlet;
- removable baskets with material suitable for providing crayfish refuge, to be lifted and emptied of crayfish regularly.

The catchpit actually installed at West Tanfield Fishery was slightly less complex than the Scott Wilson design, but remained fundamentally and functionally similar. No results from this study are available as of yet, but if successful, the catchpit may have the potential to prevent the escape of crayfish populations in similar situations specifically where a water body is well-removed from the nearest open water (Peay and Hiley 2001).

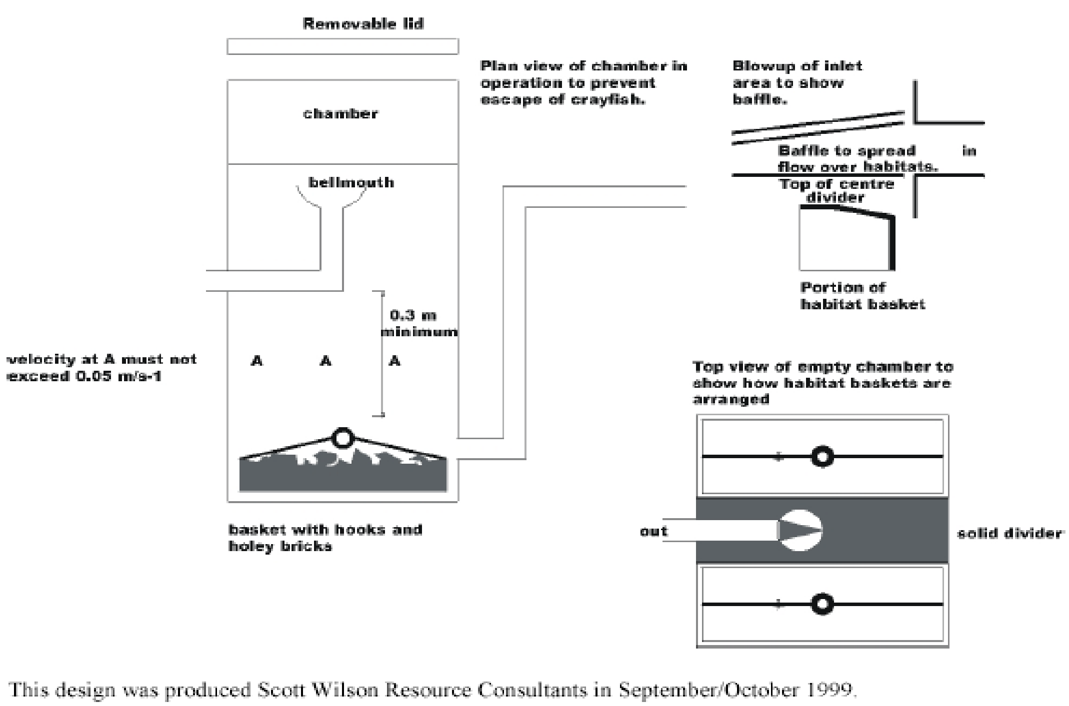

Figure 5. Proposed design of catchpit at West Tanfield Fishery (Peay and Hiley 2001).

Fencing is another barrier that has been considered as a method of preventing crayfish from escaping from a pond. To be effective, a fence would need to be constructed of a material that crayfish are incapable of climbing. Peay and Hiley (2001) suggest fencing might be used as a short-term barrier to enclose a crayfish population during the use of biocides in an enclosed waterbody, similar to temporary drift fencing which is regularly used to contain populations of amphibians. It consists of heavy duty polythene sheeting stretched between posts 1 m apart, with the lower edge of the sheeting buried underground. To date, no fencing methods have been trialed (Peay and Hiley 2001).

Other

Bureau of Reclamation (1956) suggests mixing cinders or gravel with the soil in places of crayfish infestation as a form of control. This suggestion is based on the idea that as a matter of self-preservation, crayfish will not burrow in substrates containing sharp materials since the slightest cut could result in bleeding to death. I found no references discussing the actual implementation of this method.

CHEMICAL

Fisheries managers rely on a wide variety of chemicals, including piscicides and biocides, for the management of aquatic systems. In the United States and Canada, as many as 30 piscicides have been used for fisheries management. Only four are currently registered for use, two lampricides, Lamprecide® and Bayluscide® and two general piscicides, antimycin and rotenone (Finlayson 2001).

Biocides

No biocide has yet been found which is completely specific to crayfish (Rogers 1998; Peay and Hiley 2001). The effectiveness of those that have been tried appears to be very dependent on water parameters such as pH, temperature, and age of crayfish, with younger stages usually being more susceptible.

Pesticides

In a literature review of potential methods for controlling alien crayfish species, Holdich et al. (1999) discusses the potential use of organophosphate and organochlorine insecticides, pyrethroid insecticides, ivermectin, and surfactants as agents for crayfish control and eradication.

Organophosphate and Organochlorine Insecticides

There is a wealth of literature relating to the development and use of organophosphate and organochlorine insecticides (Matsumura 1985; Pedigo 1989); only information relating to crayfish is reviewed below.

Some studies have shown organophosphate insecticides such as fenthion and methyl parathion to be highly toxic to crayfish (Muncy and Oliver 1963; Grigarick and Lange 1965). One of the first studies on biocides as a means of eliminating crayfish was by Chang and Lange (1967), who tested a variety of insecticides with a view to controlling *P. clarkii* in California rice fields. They too found fenthion and methyl parathion to be the most effective. This study was one of very few to involve large-scale trials, in this case aerial spraying of caged crayfish in rice fields. Fenthion proved effective in that case, but only early on in the rice-growing season when plant cover was low.

Ray and Stevens (1970) tried to control nuisance populations of *Procambarus simulans* and *Orconectes nais* in channel catfish rearing ponds. They found that Baytex® (active ingredient fenthion) at 100 µg/l or greater was very effective at killing crayfish in a few hours, if sprayed over the surface of a pond. Baytex® was found not to be harmful to fish at concentrations as high as 250 µg/l, but at 100 µg/l aquatic insects, cladocerans and copepods were killed, although rotifers survived.

Ludke et al. (1971) assessed the impact of Mirex® (an organochlorine insecticide) on *Procambarus spp*. They recorded almost 100% mortality in juveniles exposed to 1 µg/l of Mirex® in six days and 71 % mortality with 0.5 µg/l after four days. An important finding was that crayfish bioaccumulated Mirex® to levels many thousand times that in the water. In one experiment, the hepatopancreas of four individuals that survived exposure to Mirex®, had concentrations 126,603 times that in the water. As crayfish are eaten by many predators, this level of bioaccumulation is obviously an issue in terms of biomagnification through the food chain.

Hobbs and Hall (1975) provided a review of the effects of various insecticides on crayfish, most relating to cambarid crayfish such as *Procambarus*. Jarboe (1988) listed a wide variety of insecticides, herbicides and fungicides that might have an impact on *Procambarus clarkii* if applied to rice fields. Indiscriminate use of insecticides against invasive *P. clarkii* in Spain, however, led to the loss of other fauna, especially birds (Mackenzie 1986). Huner (1988) cited endrin, malathion (organophosphate) and propanil (amide) as being toxic to crayfish. Other studies in the United States involving *P. clarkii* include those of Brown and Avault (1975) on antimycin, Cheah et al. (1979,1980) and Ekanem et al. (1983) on the effects of rice pesticides on *P. clarkii*, Gaude (1987) on the thermal effects of pesticide toxicity and Hyde et al. (1975) on the effect of mirex-impregnated bait.

Eversole et al. (1995) and Eversole and Sellers (1997) listed 97 chemical compounds and their associated 96-h LC_{50} values for nine cambarid crayfish taxa. Of these chemicals, hexachloroethane (an organophosphate insecticide) and methoxychlor (an organochlorine insecticide) are listed as being extremely toxic to crayfish with 96-h LC_{50} levels of between 1-10 μg/l. Among the insecticides, the organophosphate and organochlorine compounds were found to be 17 times more toxic than carbamates (a broad spectrum of insecticides derived from carbamic acid, see Pedigo 1989). The purpose of these experiments was to evaluate effects of agricultural pesticides on farm-raised crayfish, not to evaluate the use of such chemicals for eradicating crayfish. No mention is made of their effect on other organisms, although they are likely to be equally effective on most other arthropods.

Laurent (1995) tested various organophosphate insecticides on *Orconectes limosus* from Lake Geneva in France and found that Baytex PM 40 (active ingredient fenthion) was effective at low doses. Laboratory experiments indicated a 24-h LC_{50} of 46 μg/l and 48-h LC_{50} of 12 μg/l. Total mortality was achieved after 24 h with concentrations of 90-100 μg/l and after 48 h with 50 μg/l. These levels are much less than those required to kill fish (Anonymous 1979). Laurent (1995) also found that toxicity of the insecticide lasted several weeks. Field trails with Baytex® applied by hand or from agricultural atomizers over the surface of ponds were equally effective at levels as low as 60 µg/l (total mortality being achieved after 87 hours). Fish, frogs and mammals appeared not to be affected, but insects and other crustaceans were killed with the exception of some species of copepods, although many species of rotifers survived. Molluscs appeared to suffer no ill effects. Laurent (1995) suggested that the relatively long time needed for total mortality of crayfish would limit the use of Baytex® as an astacicide in standing waters, because even at levels harmful to fish, it took several hours to kill crayfish. He also warned that studies on the fenthion residue in the food web (i.e. biomagnification) must be considered before using it for crayfish eradication. Apparently, there are a number of commercial formulations of Baytex, making comparisons with the results of other workers difficult (cf. Ray and Stevens 1970, Eversole et al. 1995). Indeed, Eversole et al. (1995) stated that the 96-h LC_{50} in their experiments with crayfish was 350 µg/l, although this is still much less than that required to kill fish (e.g. carp: 96-h LC_{50} = 2900 µg/l, Anonymous 1979).

In France, attempts have been made to eliminate an expanding population of *P. clarkii* from a pond using the organophosphate insecticide Dipterex® (Roqueplo et al. 1995). However, experiments only involved laboratory tests, and relatively high concentrations of Dipterex® were needed to kill crayfish compared to other insecticides (i.e. ppt rather than ppm or ppb). However, a short exposure to Dipterex® appears to be enough to kill the majority of crayfish some time later. For example, exposing juveniles to 5 g/l for 30 minutes was sufficient to kill 50% after 20.5 hours. At 25 g/l, exposure of adults for 30 minutes resulted in 100% mortality after 27 hours. Even exposure for 1 minute at 25 g/l resulted in 33% mortality after 60 hours. The effects were found to be temperature dependent, with higher temperatures resulting in a faster response time. Despite the apparent effectiveness of Dipterex®, the authors warn against its use, as the active molecule persists in the environment and kills other arthropods as well. Presumably, like Mirex® (see above), it can be bioaccumulated and biomagnified through the food chain.

Fornstrom et al. (1997) pointed out that during rain events, pesticides can be transferred into aquatic ecosystems via agricultural runoff. They found that terebufol, an organophosphate insecticide used to control corn rootworm, caused aberrant behavior in *P. clarkii* at concentrations 1000 times less than the expected theoretical runoff concentrations. They also found terebufol to be lethal to crayfish with a 96 h LC_{50} value of 5.9 µg/l in aqueous experiments and a LC_{50} value of 4.4 µg/l in 12-h dietary experiments, with aberrant behavior starting at 50% and 80% of these concentrations, respectively. They concluded that, as crayfish are keystone species, any decrease in their populations due to pesticides might cause adverse ecosystem changes.

Pyrethroids

Pyrethroids are synthetic derivatives of pyrethrin I, one of several active components in pyrethrum, which can be extracted from dried flower heads of *Chrysanthemum spp*. grown in countries such as Kenya and Ecuador (Pedigo 1989). Natural pyrethrins in the form of powders are widely used as contact insecticides, acting primarily on the nervous system. Pyrethrum breaks down quickly in sunlight. The first generation of pyrethrum analogues (e.g. allethrin) was developed in the 1950s and showed higher environmental stability than the natural product and low toxicity to birds and mammals. More effective second-generation pyrethroids (e.g. resmethrin) were developed and these were followed by third (e.g. fen valerate, permethrin) and fourth (e.g. cypermethrin, flucythrinate, fluvalinate, deltamethrin) generation products, with exceptionally low application rates compared to other insecticides (Pedigo 1989).

The toxicity of pyrethroids increases with increasing temperature and they degrade quickly at high environmental temperatures, rapidly becoming transformed to various isomers and binding to dissolved substances in water and soil (Matsumura 1985; Muir et al. 1985; Landrum et al. 1987; National Research Council of Canada 1986; Smith and Stratton 1986; Anderson 1989; Haya 1989; Day & Maguire 1990, Day 1991). Ecosystem recovery is fairly rapid with the toxic effect of pyrethroids lasting from days to months with all major faunal groups recovering within a year (Kaushik et al. 1985; Gydemo 1985, Smith and Stratton 1986).

Pyrethroids are highly toxic to fish, particularly cold-water species (Haya 1989), aquatic insects (Anderson 1989) and crustaceans, although soft-bodied invertebrates such as molluscs are generally unaffected (Anderson 1982; Jolly et al. 1978). During acute and/or chronic exposure, pyrethroids can be bioaccumulated by individual organisms but levels rapidly return to normal after exposure ceases (MacLeese et al. 1980; Ohkawa et al. 1980; Anderson 1982; Spehar et al. 1983; Smith & Stratton 1986). Mammals are more sensitive to pyrethroids than birds, but LD_{50} values are > 1000-fold higher for aquatic insects and crustaceans. Most crustaceans are extremely sensitive to synthetic pyrethroids with toxicity values close to or less than 1 µg/l. For lobsters, deltamethrin was more toxic than cypermethrin, fenvalerate or permethrin (Zitko et al 1979; MacLeese et al. 1980).

Jolly et al. (1977, 1978) found that body size influenced the susceptibility of *P. clarkii* to permethrin, while Thurston et al. (1985) found permethrin to be highly effective against *Orconectes immunis* with a 96-h LC_{50} of < 1.2 µg/l compared to > 89 µg/l for the organochlorine insecticide endrin. Jarboe and Romaire (1991) tested permethrin against *P. clarkii* and found that the 96-h LC_{50} ranged between 0.44 and 0.81 µg/l depending on the size of the crayfish, smaller individuals being less tolerant. Jarboe and Romaire (1995) also tested permethrin against procambarid crayfish in rice ponds and found it to be acutely toxic at concentrations ranging from 1.0 to 3.0 µg/l.

Bills and Marking (1988) tested 19 chemicals on the invasive crayfish, *O. rusticus*, and bluegill in the United States (see Table 3) and found that a synthetic pyrethroid, Baythroid®, was by far the most effective, a complete kill of crayfish being recorded with 0.05 µg/l in laboratory tests. They found it to be fairly selective for crayfish, although they warned that it would be an expensive method of eliminating crayfish as much higher concentrations (25 µg/l) were needed for a complete kill in field trials. Overall, they found most of the chemicals were much more toxic to fish than to crayfish. Although Baythroid® holds promise for control of crayfish populations, it is not currently registered for any aquatic use in the USA.

From field analyses of crayfish kills and experiments, Gydemo (1995) reported that deltamethrin has the capacity to kill *A. astacus* at concentrations as low as 0.1 µg/l, the level allowable in drinking water by the European Union.

Eversole et al. (1995) and Eversole and Sellers (1997) listed permethrin as being extremely toxic to cambarid crayfish with 96-h LC_{50} levels of between 1-10 µg/l.

Table 3. Concentrations (mg/L, except µg/L for Baythroid) that produced 100% mortality for rusty crayfish and bluegills in static tests at 12°C (Bills and Marking 1988).

Toxicant	A Crayfish (mg/L)	B Bluegill (mg/L)	Selectivity Index (B/A)
Baytex 73	5.00	0.20	0.04
Baytex	0.80	0.20	0.25
Baythroid (µg/L)	0.05	2.00	40.0
Carbaryl	20.0	6.76	0.34
Chlorine	1.00	0.10	0.10
Copper sulfate	3.00	0.88	0.30
Cyanide	5.00	1.00	0.20
Endothall	10.0	0.94	0.09
Fenitrothion	10.0	3.80	0.38
Fensulfathion	10.0	1.38	0.14
Fintrol	0.60	0.15	0.0003
Juglone	2.00	0.18	0.09
Malathion	1.00	0.10	0.10
Potassium permanganate	10.0	2.00	0.20
Pydrin	0.02	0.01	0.50
Noxfish	10.0	0.02	0.002
Salicylanilide I	0.02	0.005	0.25
Sodium azide	1.00	3.00	3.00
TFM	20.0	6.23	0.31

Ivermectin

Ivermectin is a synthetic derivative of abamectin, a natural fermentation product of the actinomycete fungus, *Streptomyces avermitilis*. It is used as an anthelminthic drug to kill parasites in cattle, pigs, horses and humans (Campbell 1989). It might have some potential for eradicating crayfish, as it is also effective against fish lice on farmed salmon (Palmer et al. 1987). Ivermectin has been used by cattle farmers and it is possible that the chemical enters the aquatic environment via their urine (or direct run-off from pour-on applications) when cattle drink from water courses. It may also be present in cattle manure spread and plowed into the land as fertilizer; however, due to its low water solubility and tight soil binding it is unlikely to be translocated very far (Halley et al. 1989). Halley et al. (1989) have reviewed the environmental effects of ivermectin. They state that ivermectin quickly becomes suspended in soil particles in water, thus reducing its impact on freshwater organisms. However, they quote laboratory tests, which show that daphniid crustaceans (48-h LC_{50} 0.025 µg/l) and rainbow trout (96-h LC_{50} 3.0 µg) are highly sensitive to low doses of ivermectin.

Ivermectin can now be used under license on Scottish salmon farms as long as they are not within 3 km of shellfish operations (Scottish Fish Farmer 08/08/96). The Scottish Environmental Protection Agency (SEPA) has stated that ivermectin is not a problem as a food safety or environmental issue. However, others take a different view and workers at the University of East Anglia consider that its use should be banned until its environmental effects are better understood, as even very small amounts can affect crustaceans and worms important in marine food webs (Times 23/02/98). Ivermectin was not licensed or approved for aquaculture in any country in the world until SEPA sanctioned its use in 1996, although it has been widely used in the Republic of Ireland in recent years. Ivermectin is usually applied by injection, by drenching, in feed or as a pour-on. The active ingredient is absorbed into the blood of the animal under treatment and is ingested by the parasite, which is then paralyzed. There are also very narrow safety margins between therapeutic levels and toxic levels in salmon. Irish studies have shown that it takes approximately 120 days at 10°C for all traces of ivermectin to be excreted from salmon flesh. Until more is known about the environmental effects of ivermectin, it is unlikely that permission would be given to add it directly to an aquatic system to kill crayfish.

Diflubenzuron

Diflubenzuron is a member of the benzoylphenyl urea group of insecticides used on forest and field crops to selectively control insects and parasites (http://ace.orst.edu/info/extoxnet/pips/difluben.htm). It acts by inhibiting the production of chitin which prevents the formation of a new exoskeleton and shedding of the old one (http://infoventures.com/e-hlth/pesticide/difluben.html). Common product names include Dimilan® 4L, Dimilan® 2F, Dimilan® 25W, Micromite®, and Vigilante®.

Registered by the U.S. Environmental Protection Agency (EPA) as an insecticide for use on forests and rangelands in the United States, diflubenzuron is used to control gypsy moths, Nantucket pine tip moths, douglas-fir tussock moths, and forest tent caterpillars (http://infoventures.com/e-hlth/pesticide/difluben.html). Due to its toxicity to aquatic invertebrates, some formulations of diflubenzuron may be classified as Restricted Use Pesticides (RUPs). In the U.S., RUPs may be used only by certified and licensed applicators, and then only under specific conditions (http://pesticideinfo.org/Docs/ref_regulatoryUS.html).

Diflubenzuron is practically non-toxic to birds, mammals and fish. However, it is extremely toxic to crabs, shrimp, and other aquatic invertebrates (http://infoventures.com/e-hlth/pesticide/difluben.html). Diflubenzuron bioaccumulates in aquatic animals, but is reversible when exposure ends. Chronic exposure of minnows to diflubenzuron did not have significant effects on survivability, growth or reproduction during exposure for 10 months at a concentration of up to 0.10 ppm. A study of bass exposed to diflubenzuron showed no effects of exposure. Two other chronic exposure studies showed slight effects on fish.

Dimilan® 25W has been suggested for use in controlling introduced populations of crayfish. Although, Dimilan® 25W does not fall under the RUP restrictions, diflubenzuron is not registered for use in aquatic systems. Currently, the EPA requires additional study of the effects of diflubenzuron on aquatic animals in the field. Any use of Dimilan® 25W to control crayfish would have to be weighed against the potentially harmful affect it might have on aquatic invertebrates.

Surfactants

P. clarkii has become a serious problem in Portugal, particularly in rice fields and wetlands, since its introduction in the 1980s from Spain. Various pesticides (e.g. parathion) have been used illegally by farmers; meanwhile, scientists are working to develop more environmentally friendly control methods (Fonseca et al. 1997). Consequently, biodegradable surfactants have been examined as an ecotechnological control method. Surfactants are normally used to improve emulsifying, wetting, and spreading properties of pesticides (Pedigo 1989).

A number of surfactants inhibit oxygen consumption by crayfish (Fonseca et al. 1997) through morphological and physiological changes to the surface of the gills, thus leading to decreased activity. Crayfish, however, quickly recover from this treatment. In a related study, Cabral et al. (1997) tested the same surfactants on three non-target animals, *Gambusia affinis* (Pisces), *Physa acuta* (Mollusca) and *Daphnia magna* (Cladocera) to assess the risk, if applied to waters containing *P. clarkii*. They found that, at concentrations required to reduce oxygen consumption in crayfish, these non-target animals were more adversely affected. The authors suggested that this method might have some potential in rice fields, which have an impoverished fauna, but would have an adverse effect in systems with a higher faunal diversity.

Non-specific Toxicants

The objective of any chemical treatment is to achieve 100% mortality of alien crayfish, but the need to avoid or minimize impacts on non-target species means it is necessary to use biocides which can readily be de-natured after use. In 2000, Stephanie Peay and Peter D. Hiley began a multi-phase project to demonstrate that 100% of the crayfish inhabiting a confined waterbody can be killed economically and reliably within 48 hours. The study was divided into three stages: a laboratory test, a preliminary trial in the field and full-scale treatment in a small farm reservoir.

In stage one, Peay and Hiley (2001) conducted laboratory trials of poisoning with common chemicals which could be degraded rapidly by chemical or physical means within an hour or two of application. Chemicals tested included: chlorine (sodium hypochlorite); high pH (sodium hydroxide); low pH (hydrochloric acid); potash alum; ammonium sulphate/ sodium hydroxide; papain (an enzyme in meat tenderizer); deoxygenation with sucrose/ soil suspension; deoxygenation with sodium sulphite; permethrin. Some of these were also tested in various combinations. These chemicals were selected for testing based on the literature review by Rogers et al. (1998) and the personal experience of Pete Hiley (Scott Wilson Resource Consultants). The methodology employed by Peay and Hiley (2001) was to first use an adjuvant to stimulate crayfish to leave their refuges, then use a toxicant to kill the crayfish, and then neutralize or denature the toxicant. A brief summary of the authors findings for each chemical tested is presented below.

Chlorine

Between 10 and 100 mg/l was found to kill signal crayfish within 24 hours of a 1 hour exposure period. Dechlorination is carried out using sodium thiosulphate saturated solution. Since chlorine is inactivated by organic sediments, the authors recommend chlorine only be used in clean water conditions, with little or no organic matter.

pH 12 or higher

Using sodium hydroxide to elevate water pH to 12 or higher was found to be lethal to crayfish following 1 hour of exposure. The water was neutralized using mineral acid. Because aeration of water of high pH tends to create foams, the authors recommend neutralization be carried out before final aeration.

Ammonia

Ammonia was not effective at neutral pH, but a concentration of 100 mg/l (from addition of ammonium sulphate) at pH 9 (following addition of sodium hydroxide) provided 100% kill within 24 hours, following a 1 hour exposure. The addition of mineral acid to reduce the pH to neutral reduces toxicity immediately.

Deoxygenation

Deoxygenation with more than 500 mg/l sodium sulphite produced behavioral responses in the crayfish within 15 minutes of exposure (crayfish actively attempted to climb out of the water). Crayfish were killed within 12-24 hours. Soil and sucrose solution was found to be ineffective in laboratory conditions. Deoxygenation can be neutralized by reaeration.

Other chemicals

Low pH, potash alum, and papain/salt were found to be ineffective.

Based on the results of these trials the authors identified four possible methods, each of which could be used on its own to kill crayfish: (1) pH 12 or higher (sodium hydroxide); (2) 10-100 mg/l chlorine (sodium hypochlorite bleach); (3) 10 μg/l permethrin; and (4) zero oxygen, from sodium sulphite or organic addition (sucrose). However, using a combination of methods may produce the best results. Peay and Hiley (2001) recommend the following procedure: (1) encourage crayfish into movement by deoxygenation with sodium sulphite; (2) add a mixture of ammonium sulphate and caustic to provide un-ionized ammonia in conditions of high pH; (3) allow 1-24 hours exposure, remove or treat any crayfish which climb out; and (4) neutralize pH and un-ionized ammonia by addition of mineral acid.

Stage two, preliminary field trials carried out in August 2003 at the reservoir site, involved the use of selected biocides at different concentrations and combinations, in conditions as close as possible to those in the farm reservoir. The aim of stage two was to demonstrate that eradication of crayfish could be achieved by a process of chemical addition and detoxification, economically without any specialized equipment and without causing any environmental damage outside the target area. Treatments tested included: deoxygenation using sodium sulphite saturated solution; ammonia with and without high pH; chlorine; high pH; natural pyrethrum (in and out of water). The authors also discuss methods to prevent crayfish from escaping the treatment area and cost analysis of each treatment.

Deoxygenation

Sodium sulphite in aqueous solution was the primary chemical used to achieve deoxygenation, but a suspension of farmyard cattle manure was also tested. Since sodium sulphite denatures in reaction with oxygen, aeration can be used to restore a treated area to an oxygenated state.

Deoxygenation alone was only effective when dissolved oxygen could be reduced to 0.5% saturation or less and kept at that level for an extended period of time. Even after four hours under these conditions, signal crayfish were able to recover when placed in a well-oxygenated environment. The authors recommend full deoxygenation for a period of 20 hours to achieve 100% mortality.

In response to deoxygenation, crayfish attempted to escape by breathing at the surface or climbing completely out of the tank. In some cases, crayfish in tanks lacking a climbing fabric swam to the surface and turned on to their backs with the entry to their gill chambers at the surface. These actions confirm observations made by the authors of crayfish climbing out of rivers during pollution incidents and flood events (Hiley and Peay 2003).

This study confirmed the effectiveness of deoxygenation in getting crayfish out of their burrows and actively moving around in the water. For field applications where crayfish may be inside burrows, the authors suggest a period of up to 4 hours between the start of deoxygenation and the application of the toxicant, when using deoxygenation prior another treatment (Hiley and Peay 2003).

Ammonia + High pH

Ammonium nitrate (in solution) was used to provide unionized ammonia, in combination with sodium hydroxide (in solution) to increase pH. Ammonia can either be left alone to degrade on its own, or the process can be accelerated with aeration. High pH resulting from sodium hydroxide can be denatured with sulphuric acid.

Ammonia concentrations of 20 mg/l or higher at pH 9.5 or higher consistently achieved 100% mortality of crayfish. Allowing for variability in field conditions, the authors recommend 30 mg/l at pH 10-12 to ensure 100% mortality.

Ammonia was not effective at neutral pH because there was not enough of the toxic agent, unionized ammonia, available. In situations where it is difficult to achieve a pH level of 9.5 or greater, this problem can be overcome by using very high concentrations of ammonia. This study found that pH needed to be increased to at least pH 9.5 for the ammonia treatment to be effective and the toxic effects appeared to be more rapid when the pH was raised to pH 11 (Hiley and Peay 2003). The authors note that trials in this study were carried out under warm conditions, with water temperature ranging from 22-30°C. Under cooler conditions, the dissociation of ammonia is much slower which might allow the required toxicity to be achieved either at lower concentrations, or less elevated pH.

Chlorine

Domestic bleach (5% sodium hypochlorite by volume), without detergent or other additives, was used as the source for chlorine. Sodium sulphite can be used to denature chlorine, however the available chlorine is also rapidly removed by simple aeration.

Chlorine was found to only be effective when concentrations greater than 15 mg/l could be achieved and sustained. Sustainability of available chlorine proved to be a major obstacle to successful treatment in this study as sodium hypochlorite broke down very quickly and the available chlorine was lost rapidly, even when large doses were used (Hiley and Peay 2003).

The effectiveness of chlorine, inactivated by organic sediments, is greatly reduced in waters containing peat, or in ponds with a thick accumulation of organic silt. In the latter case, the authors warn there is a risk that crayfish in submerged burrows would not be adequately exposed to the toxicant.

High pH

The condition of high pH alone was not found to cause crayfish mortality. Crayfish exposed to pH 10.5-11.0 for a period of three hours suffered no apparent toxic effects. Even in the presence of low doses of ammonia, crayfish were able to survive pH levels of 11.5-12.0 in tank tests.

Natural pyrethrum

'Pyblast' (Agropharm Ltd), a natural pyrethrum, was used as a toxicant both in and out of the water. 'Pyblast' is a formulation of 3.0% (30 mg/l) pyrethrins (natural pyrethrum). This formulation is used as an insecticide in food storage and food processing areas and is also approved for outside use, such as control of insects at waste disposal sites (Hiley and Peay 2003). Degradation of natural pyrethrum occurs within 48 hours of application, faster in sunlight.

In the water, natural pyrethrin was found to be extremely effective against crayfish, with the time required to achieve 100% mortality decreasing substantially as pyrethrum concentration increased. For the pond water tested in this study, pyrethrum concentrations of 0.05 mg/l achieved total mortality within 4 hours, while a concentration of 0.10 produced the same results in half the time.

Out of the water, 'Pyblast' was also found to be an effective toxicant when placed directly on crayfish and when used to treat the ground shortly prior to contact by the crayfish. Sprayed directly on the crayfish, 'Pyblast' resulted in 100% mortality within ten minutes. For the ground tests, a single application of 'Pyblast' was made, applied as a fine mist from a hand-held sprayer at a rate at which the droplets were still separated from each other when the spray settled. All crayfish placed on the 'treated' ground died within 1 hour. 'Pyblast' was found to degrade rapidly on the ground. This was confirmed when only 20% of crayfish placed on the 'treated' ground 1 hour after application suffered mortality.

Preventing crayfish from escaping during treatment

Faced with adverse environmental conditions, crayfish will attempt to escape. It is vitally important to take measures to prevent the escape of crayfish during any attempt to eliminate a population. Crayfish are capable of surviving for several months out of water in humid air (Hiley and Peay 2003). Crayfish sometimes leave the water at night to feed and have also been known to migrate overland (Peay and Hiley 2001). In Arizona, Blomquist (2003) documented individual northern crayfish (*Orconectes virilis*) traveling overland up to 6,060 meters as they moved from one pond to another. Crayfish escapees pose two serious problems: (1) if they escape treatment and survive out of water, they might move back into the waterbody as soon as conditions improve, and (2) there is a significant risk that if emerging crayfish are not controlled, an attempted eradication could stimulate overland movement of crayfish to new waterbodies.

This study demonstrated that spraying the margins of a waterbody with pyrethrum is an effective method of preventing crayfish from escaping the target area. The authors suggest using a backpack sprayer set so that a virtually complete film of toxicant is created on all surfaces. For surface spraying, the manufacturers recommendation is for a 1 in 10 dilution of 'Pyblast' to be applied at a rate of 0.5 l of product per 100 m^2. Results from this study suggest that the surface, the ground, may need to be damp for the pyrethrum to be effective. Therefore, repeated applications are required until it is clear that all the crayfish have been killed.

In addition to the direct action of the pyrethrum spray, physical barriers surrounding the target area should also be used. Hiley and Peay (2003) recommend one-way temporary amphibian fencing (TAF). While keeping crayfish confined to the target area, the TAF also serves as at least a partial barrier to prevent non-target animals from wandering onto the treated area.

Cost analysis

Cost is an important consideration when selecting a treatment for eradication. Factors influencing treatment cost include the cost of materials, amount of effort required, and the speed of the treatment. The methods described above by Hiley and Peay (2003) make use of materials that are widely obtainable and simple techniques that could be used readily by landowners or fishery managers. Speed of treatment is important in keeping labor cost at a minimum. Table 4 provides estimates of the chemical costs associated with the various methods for treatment of a pond containing $1000m^3$ of water.

Table 4. Estimated cost of chemical treatments (Hiley and Peay 2003).

Treatment	**Unit Cost of Chemicals/ Quantity**	**Chemical Requirements per $1000m^{3*}$**	**Approximate Cost Per $1000m^3$**
Ammonia, 30 mg/l at pH 9.5 or above Neutralize with sulphuric acid, 10%	Urea, granular at $295/ metric tonne, or $28/50kg. Sodium hydroxide 32% wt. by vol. at $350/200 liters, or $612/1000 liters. Sulphuric acid 10% at $313/ 1000 liters	65 kg urea + approx. 675 kg sodium hydroxide 32% wt. by vol. Acid similar volume, depending on conditions	$664 (+ approx. $184 to neutralize?)
Deoxygenation with sodium sulphite	Anhydrous sodium sulphite at $22/25kg	Approx. 160 kg	$157
Chlorine, starting target of 50 mg/l	14.5% sodium hypochlorite at $203/200 liters	275 liters minimum, needed, but could be 5x more	$608 - $3,040
Natural pyrethrum, in solution 0.1 mg/l	'Pyblast' 3% w/w pyrethrins at $409 for 5 liters or $107/liter	3.3 liters	$359
Natural pyrethrum, minimum of 2 applications to ground, all treatments	Pyblast at $107/liter	0.5 liters per 100 m^2 perimeter, 2 applications	$110

*based on the water chemistry at Barmbyfield irrigation reservoir.
Note: The dollar amounts appearing in this table were converted from United Kingdom pounds based on the live mid-market rate for March 2, 2004 (16:50:57 GMT) of 1 GBH (United Kingdom Pound) = 1.84249 USD (United States Dollar).

After analyzing the cost of each chemical and the time and effort associated with each treatment, Hiley and Peay (2003) found the use of 'Pyblast' in the water and as a spray for treatment of the shoreline to be the most practical and economical. Compared to the bulk chemicals required by the other treatments, 'Pyblast' has the advantage of relatively low volumes of a single product.

Rotenone

Rotenone is a toxin associated with certain leguminous plants, e.g. Derris, and has long been used as a fish poison by tropical communities and as an insecticide (Pedigo 1989). A powdered form was developed in the United States for use as an insecticide, however, it was almost insoluble in water. Later, water-soluble emulsions containing 5% rotenone were developed and the modern products are reputed to work well as piscicides for fishery management at temperatures from 1.5-30°C in both acid and alkaline water (Morrison 1988). Rotenone is by far the most commonly used piscicide in North America today with a current average annual use of 9,474 kg (as active ingredient) (McClay 2000). Very few studies have mentioned the effect of rotenone on crayfish, although the levels used to kill fish have been reported not to be harmful to them (Berzins 1962; Bills and Marking 1988). Westman (1991) reported an increase in crayfish numbers after fish had been removed with rotenone.

In fish, rotenone acts as a vaso-constrictor narrowing the blood vessels in the gill, thus preventing the normal uptake of oxygen (Hamilton 1941). Biochemically, rotenone prevents the transfer of electrons along the respiratory pathway (Oberg 1967). It has been used to reduce recruitment of an overpopulated trout lake (Walker 1975), as well as to remove nuisance fish such as perch (Amey 1981) before stocking with game or sport fish. A concentration of 0.5 mg/l for 30 minutes has been successfully used to eradicate trout and 0.05 mg/l has proven effective for pike, perch and eels (Holdich et al. 1999b). Morrison (1988) reviewed the effect of rotenone on vertebrates other than fish and found it had a low toxicity to birds and mammals, although it has been found to be toxic to amphibians at low doses (Chandler 1982), particularly gill-breathing tadpoles.

Studies in Sweden have shown that the efficiency of rotenone is highest in waters with a low temperature and sparse aquatic vegetation (Almquist 1959; R. Gydemo personal observation). Marking and Bills (1976), however, found that its toxicity to fish was reduced in cold water. It is believed that silt and organic matter absorbs rotenone, thus reducing its concentration (Lindgren 1960). Leonard (1939) found that rotenone rapidly lost its toxicity to fish in 41 hours. Rotenone supposedly degrades rapidly (a few days) in strong sunlight, but Bills and Marking (1988) quote unpublished work suggesting that rotenone residues may persist for over 40 days in cold water (5O°C), but for only five days in warm water (24°C). They also found that, although Noxfish (5% rotenone) was toxic to fish in laboratory tests at a concentration as low as 30 μg/l, the manufacturer recommended using 5 mg/l for field treatments. They attributed this to numerous physical and chemical factors that could affect its toxicity in the natural environment.

Effects of rotenone on aquatic invertebrates have been variously reported. Invertebrates may be affected by rotenone in open water (Almquist 1959; Anderson 1970) but benthic invertebrates seem to be partly protected (Lindgren 1960). Almquist (1959), in a review of the effect of rotenone on fish food organisms in Sweden, found that most invertebrates, including planktonic crustaceans, were killed by a concentration of 0.5-0.6 mg/l. Lindgren (1960) suggested that, although many benthic invertebrates were likely to be affected by a level of 0.5 mg/l rotenone, they were less susceptible than fish, and the survivors would guarantee their continued existence. Even populations of sensitive species have been found to make a full recovery after a few months (Hockin et al. 1985). Morrison and Struthers (1975) and Morrison (1977) found little effect of rotenone application on the benthos of lakes and streams in Scotland. Amey (1981) found no mortality of invertebrates when exposed to 2-4 mg/l rotenone (0.5 mg/l being lethal to many fish species).

Few studies have investigated effects of rotenone on benthic crustaceans. However, Lindgren (1960) found that *Gammarus pulex* in experimental cages in a lake were not affected by exposure to1-2 mg/l rotenone for 40 hours, and Engstrom-Heg (1987) showed that brown shrimp and blue crab were tolerant of 1.8 and 4.0 mg/l rotenone respectively. As crayfish are also benthic, higher concentrations may be required to kill them and this may adversely affect other invertebrates. Leonard (1939) showed that *Cambarus propinquus* and a number of other freshwater invertebrates could survive exposure to 1 mg/l rotenone for 96 hours. Hamilton (1941) found *Cambarus immunis* to be much more tolerant to rotenone than other freshwater crustaceans. Berzins (1962) carried out a series of experiments on *A. astacus* and concluded that a normal dose, (0.7 mg/l), would not harm crayfish. Bills and Marking (1988) found that 10 mg/l Noxfish® (a rotenone-based product) killed 100% of *O. rusticus* by 96 hours in static tests at 12°C, although a dose of only 0.02 mg/l was needed to kill bluegill under the same conditions.

Wujtewicz et al. (1997) conducted laboratory and field tests with 5% non-synergized emulsifiable rotenone to define the maximum non-lethal concentration (LC_0) for white river crayfish *Procambarus acutus acutus* and the minimum lethal concentration (LC_{100}) for white perch *Morone americana*. Acute LC_0 toxicity for *P. acutus acutus* was determined to be 3.0 mg/l. Acute LC_{100} toxicity for *M. americana* was determined to be 0.15 mg/l. In the final phase of the study a 1.0 mg/l concentration of rotenone was applied to a pond containing both species held in cages. All white perch were dead within 24 h; no crayfish mortality was observed for the 96-h duration of the trial.

Morrison (1988) provides protocols for applying rotenone to still and running waters. However, he warns that it is difficult to forecast precisely what the effects of rotenone treatment will be. As shown above, opinions differ on the effect of temperature. For rotenone to be effective, adequate dispersal is essential and this will be hindered if plant material is abundant (Holdich et al. 1999b).

Pheromones

The term 'pheromone' was coined in 1959 by Karlson and Lüscher to describe chemical signals transmitted between members of the same species that elicits a stereotypical response (Agosta 1992).

Ideal control methods have a maximum impact on the target species with a minimum impact on indigenous species, while also being economically viable. Pheromones have been used as a method for controlling insect pest species for a number of years, and largely fulfil the necessary environmental and economic criteria of an ideal control method. With recent developments in the field of aquatic chemical ecology, the potential application of pheromones as a method of controlling aquatic pests is becoming a reality (Stebbing et al. 2003).

Crustaceans use a range of water-borne chemicals, pheromones, for many forms of communication, particularly during courtship and mating, agonistic behavior, maternal behavior, aggregation, and stress-related conditions (Ameyaw-Akumfi and Hazlett 1975; Itagaki and Thorp 1981; Hazlett 1985; Rose 1986; Dunham 1988; Bechler 1995). Recently, several crayfish species have been shown to utilize a number of pheromones in a wide range of activities, such as aggressive interaction, inter- and intra-species recognition, shelter choice and predator avoidance (Blake and Hart 1995b; Chivers et al. 1998; Zulandt Schneider and Moore 2000; Hazlett 2000; Bouwma and Hazlett 2001; Nisikawa et al. 2001; Breithaupt and Eger 2002; Gherardi 2002).

Male crayfish tend to be very active during the mating season and may locate females by means of pheromones. However, evidence for presence of such chemicals in crayfish is inconsistent, having been found in some species but not others (Dunham 1988, Bechler 1995). It has been shown conclusively that newly released juveniles communicate with their mothers by pheromones to prevent them from being cannibalized (Little 1975, 1976). Neither the source nor the chemical nature of such pheromones in crayfish has been characterized (Bechler 1995). However, work with annelids and crabs has shown that this is possible (Zeek et al. 1988, 1998, J.D. Hardege personal communication).

If a mating pheromone could be isolated and synthesized from crayfish, then it could be used in traps as an attractant. By such a method, many males could be removed from the population at the start of the mating season, so that less mating takes place (Holdich et al. 1999b). Coupled with standard trapping, this could quickly reduce the population, although it should be noted that males are able to mate with many females.

Stebbing et al. (2003) conducted experiments on the use of pheromones as a method of controlling signal crayfish. This research focused on four categories of pheromones: sex, stress, alarm and avoidance pheromones. The sex pheromone investigated is a female-released chemical that attracts and stimulates mating behavior in males during the breeding season (Ameyaw-Akumfi and Hazlett 1975; Cowan 1991; Gleeson 1991; Bamber and Naylor 1997; Jones and Hartnoll 1997; Asia et al. 2000; Kamio et al. 2002; Stebbing et al. 2003). Stress, alarm and avoidance pheromones are all repellents, in extreme cases stimulating an escape response; the difference between the categories is their source of release. Stress pheromones are released from stressed but undamaged conspecifics; alarm pheromones are released from a damaged conspecific; while avoidance pheromones are released directly from a repellent stimulus, i.e. a predatory fish (Zulandt Schneider and Moore 2000).

The pheromones were field-tested using standard Swedish ‘trappy’ traps, which were left out for 24 hours. All pheromones tested were freeze-dried samples of active water placed into a slow release gel matrix. Traps were baited with either: (a) sex pheromone water, (b) stress or alarm pheromones with an attractant (food bait) which allowed the testing of the repellents against a known and quantified attractant, (c) food, and (d) a blank gel matrix (as a control for the sex pheromones and repellents). Trapping took place year round (except for sex pheromones which were only tested during the breeding season) at two field sites, the River Clyde in Scotland and Lartington Ponds in Teesdale, North Yorkshire.

The results showed that the sex pheromone baited traps caught significantly more males than females, with on average 10.25 males being found in each trap compared to 0.167 females. There were significantly more crayfish, in total, in both the stress and alarm traps than in the sex pheromone traps. Significantly more crayfish were found in the sex pheromone traps than in the blanks, but no significant difference was seen in the number of crayfish caught in the sex pheromone traps when compared to the food baited traps. There were no significant differences, however, in the number of males in the sex pheromone traps when compared to the stress, alarm or food baited traps, the significant differences in total numbers of animals being caught in the stress and alarm baited traps being due to the number of females. No significant differences were seen in the number of males compared to females for either the stress or alarm baited traps. There was also no significant difference in the number of total crayfish found in either of the treatments (stress vs. alarm). Neither was there a significant difference in the total number of crayfish found in the stress nor alarm baited traps compared to the food-baited traps. Significantly more animals were found in both the stress and alarm pheromone baited traps than in the blank traps.

These preliminary results suggest that the sex pheromone baited traps may be effective at trapping male signal crayfish during the breeding season. Although the sex pheromone baited traps did not appear to be any more effective than food baited traps, the authors suggest that purification and concentration of the sex pheromones may improve their success rate. The failure of the stress and alarm pheromones to repel individuals from the traps may have more to do with the design of the experiment than the chemicals being tested. It is possible that the food placed into the traps was a greater attractant than the repellents were a deterrent. This idea is supported by the fact that there was no significant difference between the numbers of crayfish found in the stress and alarm baited traps and the food baited traps.

According to the authors, future research will focus on concentrating, purifying, isolating, and identifying the pheromones so as to improve the effectiveness of the traps. In addition, habitat data collected from the trapping sites will be incorporated into a model that will predict the effectiveness of these traps as well as the best location to the place the traps for optimal effect (Stebbing et al. 2003).

Perhaps the greatest potential for the use of pheromone baited traps is the possibility of detecting low-density populations of crayfish (S. Peay personal communication).

CONCLUSIONS

Bills and Marking (1988) state that no single method is likely to be effective for solving crayfish problems in all situations and that multiple approaches need to be developed. This literature review supports that conclusion. Each nuisance population must be considered separately and the most appropriate techniques applied to it for control or eradication purposes. As with insect control, whatever the method and its effectiveness, the cost of control is often considered to be the deciding factor (Fernald & Shepard 1955).

When assessing the effectiveness of any methodology to eradicate or control a crayfish population, it is important to keep in mind the concept of minimum viable population density. To be successful, artificial control of a population will have to reduce the density to less than the MVPD and keep it there. Any method that does not achieve this will allow the population to expand in both density and range (Peay and Hiley 2001).

Current federal and state regulations are inadequate to prevent the spread of non-indigenous species, including crayfish (U.S. Congress 1993). The role of legislation in crayfish control is to protect native faunas by imposing regulations to minimize the impacts of non-indigenous crayfishes and to prevent their spreading. Lodge et al. (2000) recommended the adoption of a white list approach that would preclude moving any species between catchments within a state, between states, and from other continents until the characteristics of a given species is known. They also recommend making the use of live crayfishes as bait illegal in all states. Until suitable regulations are enacted across the board, the control of non-indigenous species, including crayfish, will remain a difficult task as these populations continue to spread out of control.

Based on all the studies to date, manual removal crayfish cannot achieve eradication or even control a population at any level of effort. There are almost always areas within a site that cannot be searched effectively and even experienced surveyors will miss a proportion of the juvenile crayfish. In addition, intense manual efforts, such as repeated trampling of the substrate, can cause noticeable alterations to the habitat and damage to the environment

Trapping, although environmentally acceptable, does not appear to be a viable method for eradicating crayfish. Studies have shown that even intensive trapping catches less than 10% of the active population. While trapping may be used to remove a portion of the adult population, the resulting reduction in predation will favor growth in the smaller size classes, and crayfish biomass is unlikely to be affected. There is also a possibility that reduction in the predation by large crayfish and the dominance of the largest individuals in breeding may even increase population size. The one positive aspect of trapping is that traps are relatively cheap, although their design could be improved so they are more effective, particularly for catching juveniles. Crayfish traps rarely catch anything other than crayfish, although it is possible that small fish and mammals may be caught. It appears the only way to control a nuisance crayfish population through trapping is to have a sustained effort over a number of years. However, it is unlikely that such methods would eradicate a population, unless coupled with some of the other methods below. According to Peay and Hiley (2001), there are no known circumstances under which trapping has any value as a method for controlling alien crayfish populations.

Development of more attractive baits has been carried out in Sweden and the United States. Comparison would need to be made to see if they are any more effective than using fish or other meat-based baits, as commercially produced baits would greatly add to the cost of any control or eradication program. It is unlikely that even the most attractive bait would improve the efficiency of traps to a level where trapping could be used as viable means of control.

Electrofishing has been used successfully as a method to harvest crayfish from ponds, but not as a method of control. Electrofishing is only effective at catching a limited portion of the population and is therefore not a viable method of control.

In some cases, there appears to be an inverse correlation between numbers of predaceous fish and crayfish in the natural environment and this is borne out by experiments. However, there have been no large-scale attempts at using predaceous fish to control nuisance crayfish populations. The impact such fish might have on other wildlife, especially when they have consumed all the crayfish, would likely result in strong opposition to this method. Westman (1991) suggested using eels because they do not breed in freshwater and they may be able to enter the hiding places of crayfish. Frutiger and Müller (2002) concluded that the type of substrate will influence the effect of predatory fish and is highest if shelter is sparse. Another possibility for avoiding the establishment of introduced predators would be the use of monosex fish. Peay and Hiley (2001) concluded that fish predators have no possibility of eradicating an established crayfish population and little chance of reducing it. Even if this method proved effective in controlling crayfish, it is unlikely to garner the approval of regulatory agencies.

In Europe, the use of *Aphanomyces astaci* might be an effective method of eradicating susceptible species, particularly if a more virulent strain could be developed. Different strains of the *Aphanomyces astaci* fungus are known and may differ in their pathogenicity (Lilley et al. 1997); however, it would take time and money to develop one specific and more virulent to nuisance crayfish, but likely wouldn't be effective in controlling North American crayfish species. There is no known disease, which is selective to American species of crayfish. Even in Europe, this is unlikely to be a very environmentally acceptable method, due to its possible impact on native crayfish. Although no other organisms are affected by known strains of crayfish plague, this is not to say that a genetically modified strain would be so specific. Varieties of *Bacillus* *thuringiensis* such as *israeliensis* (Bti) capable of killing insect pests have been developed. Although Bti is relatively ineffective against crayfish, the development of a variety that is effective might be worth exploring.

Draining and drying out a pond or lake, or isolating a section of river, after intensive netting or electro-fishing, is another possible method for eradicating crayfish. However, in the majority of instances this would be impractical for burrowing species, unless followed by chemical treatment or a lengthy period (over one year) before refilling. However, the use of biocides (see below) might be severely hampered by the protection afforded to crayfish in burrows. Control of burrowing crayfish could be accomplished by dosing individual burrows with 'Pyblast', although density of burrows may make such a method impractical. Even after intensive trapping, a viable population may exist in burrows that can recolonize the area.

There is evidence that a variety of organochlorine, organophosphate, and pyrethroid insecticides are capable of killing crayfish, although few large-scale, controlled experiments have been carried out except in rice fields (e.g. Chang and Lange 1967), and none, so far, in rivers. If a quick kill is required, then biocides may be the only answer. However, few field trials have been carried out in the wild, other than in experimental, enclosed ponds. Since there is no specific toxicant against crayfish or even crustaceans, major damage to other aquatic organisms is an inevitable consequence of crayfish control using chemicals (Hiley 2003b). There would likely be public and private opposition to the use of biocides. This was the case in Switzerland a few years ago where a plan was put forward to use an organophosphate insecticide to eliminate a *Procambarus* *clarkii* population, after trapping was found to be ineffective (A. Frutiger personal communication).

However, organophosphate insecticides, some of which have been found to be effective against crayfish, have been successfully used to control other aquatic organisms in the field, such as Cladocera and Copepoda (Balvay 1981) and flies (Ray and Stevens 1970, Roqueplo et al. 1995). Pyrethroids appear to have the greatest potential for eradicating crayfish, due to their rapid breakdown and low doses needed, although their impact on other crustaceans would be equally severe. Baythroid, a synthetic pyrethroid, was found to be highly toxic to and selective for crayfish, at least with respect to bluegill. Unfortunately, Baythroid is not registered for any aquatic use in the United States and it is unlikely the manufacturer (Mobay Chemical Company) will seek registration for aquatic use. The greatest worry about the use of biocides is their potential to be bioaccumulated and biomagnified through the food chain, although this is less of a problem with pyrethroids. The use of such substances, while likely effective, is unlikely to be accepted until more research is done on their environmental impacts. As no biocide known is specific to crayfish, other invertebrates, particularly arthropods, would also be eliminated from any watercourse to which these poisons were applied. This might not necessarily be a problem, as re-seeding could be undertaken, but the residence time of the poison in the environment must be known before this is done.

Peay and Hiley (2001) concluded that biocides offered the only practical option for the elimination of unwanted populations of crayfish. Ideally, a biocide should be highly selective to crayfish and have a very low persistence in the environment. In addition, for a control method to be seen as practically acceptable, it should employ chemicals that are reliably available commercially in quantities and costs that are not prohibitive (Hiley 2003b). Since no biocides have been found which are selective to crayfish, they focused their efforts on chemicals that were capable of killing crayfish, were not persistent in the environment, were readily available, and were relatively inexpensive. This research led to the discovery of two methods capable of eradicating a crayfish population from small bodies of water.

The use of 'Pyblast', a natural pyrethrum, in the water and as a spray for treatment of the shoreline was found to be the most cost effective and methodologically simplistic. The alternative approach was the use of ammonium in the presence of high pH with prior deoxygenation.

Since these methods will affect non-target organisms their uses will be limited. Desirable fish and plant species would need to be temporarily removed prior to the chemical application. The most likely candidate for this type of treatment would be small enclosed ponds.

The use of surfactants to control crayfish activity (Cabral et al. 1997, Fonseca et al. 1997), while useful as a means to limit damage in rice fields, has no value as a method of crayfish eradication.

Ivermectin may have some potential for eradicating crayfish, but no work has been carried out and it is unlikely that permission for its general use would be given before much more is known about its environmental impact.

The use of rotenone might be acceptable for crayfish eradication, although it is toxic to fish and amphibians at levels lower than those needed to kill crustaceans, so these taxa would have to be removed before its use was considered. Rotenone is widely used as a piscicide in fisheries management, but has rarely been tested on crayfish (Bills and Marking 1988). As crayfish appear more tolerant to rotenone than fish, considerable cost would be involved in applying sufficient levels to eradicate them.

Sexual attractants are widely used to control insect pests. Crustaceans use similar pheromones, particularly in the mating season. However, this method has not been used as a means of controlling crayfish and more research is needed in this area. Initial testing found no difference in the number of crayfish caught in sex pheromone baited traps compared to traps baited with food, but the authors suggest that purification and concentration of the sex pheromones may improve their success rate.

There are other methods not considered above which have been used effectively on insect pests, such as introducing sterile males into the population (Gherardi and Holdich 1999). No such work has been done with crustaceans, but it might be worth considering. However, a single male crayfish can mate with many females in a short space of time and it would be difficult to be sure all males had been sterilized. Another method worth considering might be the use of molt-inhibiting hormones (Gherardi and Holdich 1999). However, it is unlikely that hormones specific to crayfish could be developed and consequently other arthropods would also be affected.

Based on this literature review, only two methods appear capable of achieving control of a crayfish population, and then only in a very limited number of circumstances.

Crayfish are very adaptable animals, even capable of moving across land if conditions become unfavorable in their environment. With the increasing spread of alien crayfish, there is an urgent need to develop methods for controlling and, if feasible, eradicating nuisance populations. Of course, the best method is not to introduce them in the first place. However, for many countries it is too late and in such cases the cost of eradication (i.e. the ecosystem cost) should be weighed against the costs and risks of merely attempting to control the problem, as well as not doing anything (Gherardi and Holdich 1999).

Comments on Crayfish Control in Arizona

Two species of crayfish, *O. virilis* and *P. clarkii*, both non-indigenous, currently exist in Arizona. Since their introduction to Arizona during the 1960's, crayfish have become abundant throughout the state. Virtually every piece of water in the state, from the smallest creek to the largest impoundment, can include at least one of these crayfish species in its inventory of life. Unfortunately, Arizona ecosystems did not evolve with crayfish and their presence appears to be wreaking havoc in these systems. Fernandez and Rosen (1996) studied the impacts of *O. virilis* on two Arizona aquatic ecosystems and were able to quantify how crayfish reduce the abundance and diversity of native aquatic species of plants, invertebrates, and vertebrates. Not surprisingly, the need to eradicate or at the very least control these crayfish is vital to the preservation of native species and to the general health of aquatic ecosystems around the state.

Although Arizona enacted regulations in 2001 prohibiting the transport of live crayfish within most of Arizona (R12-4-316), this legislation probably came about too late. Successful eradication of crayfish in Arizona at this point in time is highly unlikely. Since the majority of Arizona waters are connected in some manner, even if crayfish are eradicated from an area, the area will almost certainly be re-colonized from an adjacent area. The only possibility of eradication is in small, geographically isolated ponds.

Attempts to control crayfish in Arizona have focused primarily on trapping and manual removal. Based on the information presented in this report, it may be time for Arizona to re-examine its' current strategy for crayfish control. As natural resource managers it is imperative we recognize the limitations of our tools and stop trying to fit square pegs into round holes.

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