Eric Larson
Fish 497A
Olden Fall 2007

Pacific Northwest Aquatic Invasive Species Profile:

Red Swamp Crayfish *Procambarus clarkii*

1.) Diagnostic Information

Common Names: Red swamp crayfish, Louisiana red swamp crayfish

Order: Decapoda
Family: Cambaridae
Genus: *Procambarus*
Species: *clarkii*

Figure 1. Red swamp crayfish *Procambarus clarkii*. Top right image is an adult female with hatchlings carried under the abdomen. Bottom image is from the Swedish Board of Fisheries.

Identification Guide:

The red swamp crayfish *Procambarus clarkii* is a large, red crayfish with long, narrow pincers (chelae), bumps (tubercles) on its chelae, light spotting or mottling over much of its body, and a black wedge pattern on the top (dorsal) side of its tail (abdomen). Juveniles of the species may appear light brown or gray, with chelae that are proportionally smaller relative to the body than in adults (Pflieger 1996). Accurate identification of crayfish is based on morphology of the male reproductive organs (gonopods) and can be challenging for those unfamiliar with crayfish. Any collected crayfish suspected of being introduced, such as *P. clarkii,* should be sent to a taxonomic expert like Dr. Chris Taylor (ctaylor@inhs.uiuc.edu) at the Illinois Natural History Survey or Dr. Jim Fetzner (FetznerJ@CarnegieMNH.org) at the Carnegie Museum of Natural History for confirmation. Keys to the identification of crayfish, such as Hobbs (1976) and guide books like *The Crayfishes of Missouri* (Pflieger 1996), are valuable but may not be available to many resource managers or citizen scientists. Provided below is a brief description of characteristics useful in differentiating *P. clarkii* from crayfishes native to the Pacific Northwest.

Procambarus clarkii belongs to the Family Cambaridae, while crayfishes native to the Pacific Northwest belong to the Family Astacidae (Scholtz 2002). Consequently, *P. clarkii* is reasonably easy to distinguish from crayfishes native to the Pacific Northwest. The most common and widely distributed Pacific Northwest crayfish is the signal crayfish *Pacifastacus leniusculus*, with other Pacific Northwest crayfishes either subspecies of the signal crayfish or species within the *Pacifastacus* genus (Miller 1960; Scholtz 2002). Relative to *P. clarkii,* these crayfish will not have tubercles on their chelae and are unlikely to be red, although crayfish color is variable and red *P. leniusculus* have been observed. *Pacifastacus leniusculus* is often dark brown or blue-gray with a ring of white or light blue coloration at the joint of the two pincers (Figure 2). Gonopods of *P. clarkii* will be distinct from those of crayfishes native to the Pacific Northwest. In male crayfish, gonopods, modified walking legs used for internal fertilization of females, are located mid-body at the intersection of the abdomen and carapace (Figure 3). Only male crayfish are used in crayfish taxonomic keys, so it is important that crayfish collected for identification are males. In *Pacifastacus* sp. crayfishes, gonopods will lack any hooks or extensions, while in *P. clarkii* gonopods end with a curved or tipped hook (Figure 3).

Figure 2. The signal crayfish *Pacifastacus leniusculus* (left), native to the Pacific Northwest, and *P. clarkii* (right), an introduced species.

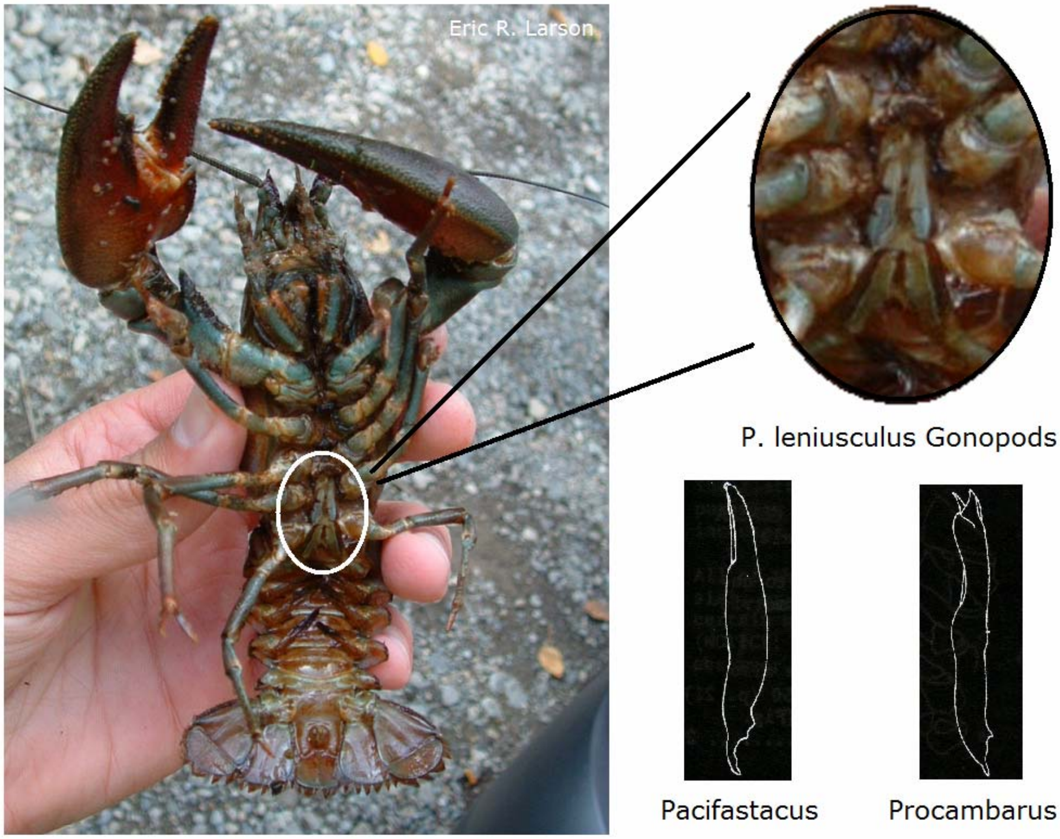

Figure 3. Location of gonopods on male crayfish (left image) and representative sketches of *Pacifastacus* and *Procambarus* gonopods (reproduced from Hobbs 1976).

The web address for a guide to collecting non-native crayfishes in the Pacific Northwest, produced by the Washington Department of Fish and Wildlife, is provided in Section 8. Additionally, web addresses for the purchase of crayfish guides to southeastern U.S. states are also provided. These guides include keys for several potential invasive crayfishes, such as *P. clarkii,* the rusty crayfish *Orconectes rusticus*, and the virile crayfish *O. virilis.* These state guidebooks are generally more affordable and user-friendly than other crayfish taxonomic keys.

2.) Overview

The red swamp crayfish *Procambarus clarkii* is the most economically valuable crayfish in the world as well as the most invasive, an association that is not coincidental. Native to the south central United States and northeastern Mexico, *Procambarus clarkii* is currently an introduced species in at least 20 states and 33 countries (Hobbs et al. 1989; Holdich 1999). As an aquaculture species, *P. clarkii* accounts for over 50,000 metric tons of annual food production for fish farmers in the United States (Huner 1993), but where introduced *P. clarkii* has had severe ecological and economic impacts with few benefits. In many locations where it has been introduced, *P. clarkii* is an agricultural pest consuming crops, damaging water control infrastructure, and directly interfering with fisheries (Lowery and Mendes 1977; Huner 1988; Anastacio et al. 2005). Additionally, *P. clarkii* displaces native crayfishes through disease transmission and competition and alters aquatic food webs through strong foraging effects on aquatic plants, algae, detritus, and other invertebrates (Gherardi 2006). The presence of *P. clarkii* in the Pacific Northwest should be cause for concern among both aquatic resource managers and the general public (Clark and Wroten 1978; Welles 1982; Mueller 2001).

3.) Origin and Distribution

History of Invasiveness

Due to its value as an aquaculture species in the south central United States, *P. clarkii* was deliberately introduced to many of the countries where it has emerged as a nuisance species. In Europe, *P. clarkii* was first introduced to Spain in 1973, and subsequently spread throughout the country and continent as a result of natural and human-assisted dispersal (Gutierrez-Yurrita et al. 1999). Introductions in Europe were intended to supplement declining populations of native European crayfishes, valued for recreational and commercial harvest, but ultimately accelerated native crayfish declines through disease transmission and direct competition (Holdich 1999). As an aquaculture species, *P. clarkii* was introduced in Africa to Uganda in 1964, Sudan in 1975, and Kenya in 1976, and in Central America to Costa Rica in 1966 and Nicaragua around 1976 (Huner 1977). The spread and impact of *P. clarkii* in these countries, which previously lacked native crayfish populations, is poorly documented (but see Lowery and Mendes 1977). *Procambarus clarkii* also was often introduced as forage for other aquaculture species. *Procambarus clarkii* was introduced to the west coast of North America in 1932 to serve as forage at a frog farm and was introduced to Asia through Japan in 1927 as bullfrog forage (Riegel 1959; Kawai and Kobayashi 2006). Subsequent spread of *Procambarus clarkii* in Asia, Africa, North America, and Central and South America likely follows patterns in Europe, with a mix of natural and human-mediated dispersal. Deliberate aquaculture stocking of *P. clarkii* has largely abated due to increased recognition of its impacts as an invasive species, but where established *P. clarkii* seems likely to continue to disperse naturally and through human transport (Hobbs et al. 1989; Lodge et al. 2000).

Many introductions of *P. clarkii* cannot be explained by deliberate aquaculture stocking. In North America, *Procambarus clarkii* has established populations in locations with no known history of *P. clarkii* aquaculture, such as Washington state, Idaho, northern Illinois, Ohio, and the northeastern United States (Clark and Wroten 1978; Norrocky 1983; Mueller 2001; Taylor and Tucker 2004). Like many invasive crayfish species, *Procambarus clarkii* is transported live as part of the bait, aquarium, live seafood, and biological supply trades (Lodge et al. 2000). These vectors are suspected in most *P. clarkii* introductions that cannot be traced to deliberate aquaculture stocking (Norrocky 1983; Mueller 2001; Taylor and Tucker 2004). While some states have banned possession of live crayfish as fishing bait in response to the threat from invasive crayfishes, the transport of live crayfish remains largely unregulated (Lodge et al. 2000; Taylor and Tucker 2004). No live crayfish purchased from a bait dealer, aquarium shop, biological supply company or live seafood supplier should be released into a waterway.

<u>Native and Non-Native Distribution</u>

North American distributional data (native and introduced) for *P. clarkii* presented here (Figure 4) was compiled from museum collection records and state agency or university sampling. These point occurrences are incomplete and represent a work in progress, but may be the most comprehensive *P. clarkii* range data available for North America. Sources of point occurrences include the Academy of Natural Sciences, Alabama Department of Conservation and Natural Resources, Arkansas Game and Fish Commission, Harvard Museum of Natural History, Illinois Natural History Survey, Missouri Department of Conservation, New York State Museum, Oklahoma Biological Survey, Smithsonian Institution, Texas A and M University, U.S. Forest Service, and U.S. Geological Survey, among others.

Global distributional data for *P. clarkii* (Figure 5) was based on Hobbs et al. 1989 and Holdich 1999. Countries with confirmed introduced populations are highlighted, and likely represent a conservative estimate of the species' global distribution.

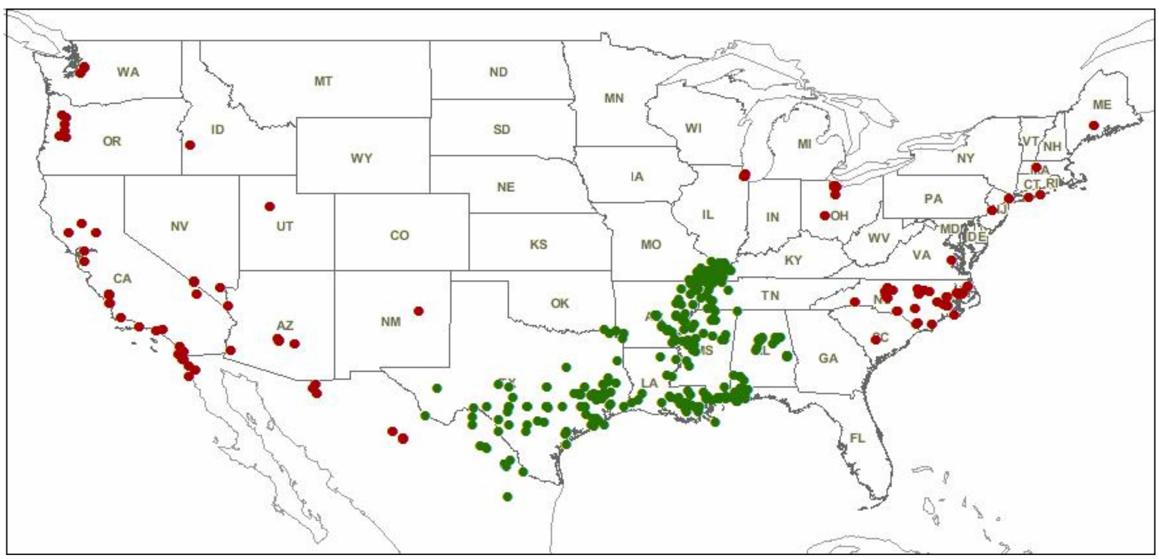

Figure 4. *Procambarus clarkii* native (green) and introduced (red) points occurrences in North America from museum records and agency or university sampling.

Pacific Northwest Distribution

Procambarus clarkii was documented in Idaho in 1978 in an artesian spring in the city of Nampa, Canyon County (Norrocky and Wroten 1978). *Procambarus clarkii* was established in Oregon by the 1980s and is distributed in ponds and streams throughout the Willamette Valley (Welles 1982). *Procambarus clarkii* was first documented in Washington in 2001 and occurs in multiple small lakes in King County (Mueller 2001). Possible pathways of introduction to the Pacific Northwest include the aquarium, bait, live seafood, and biological supply trades, and the species' distribution in the region is likely underestimated here.

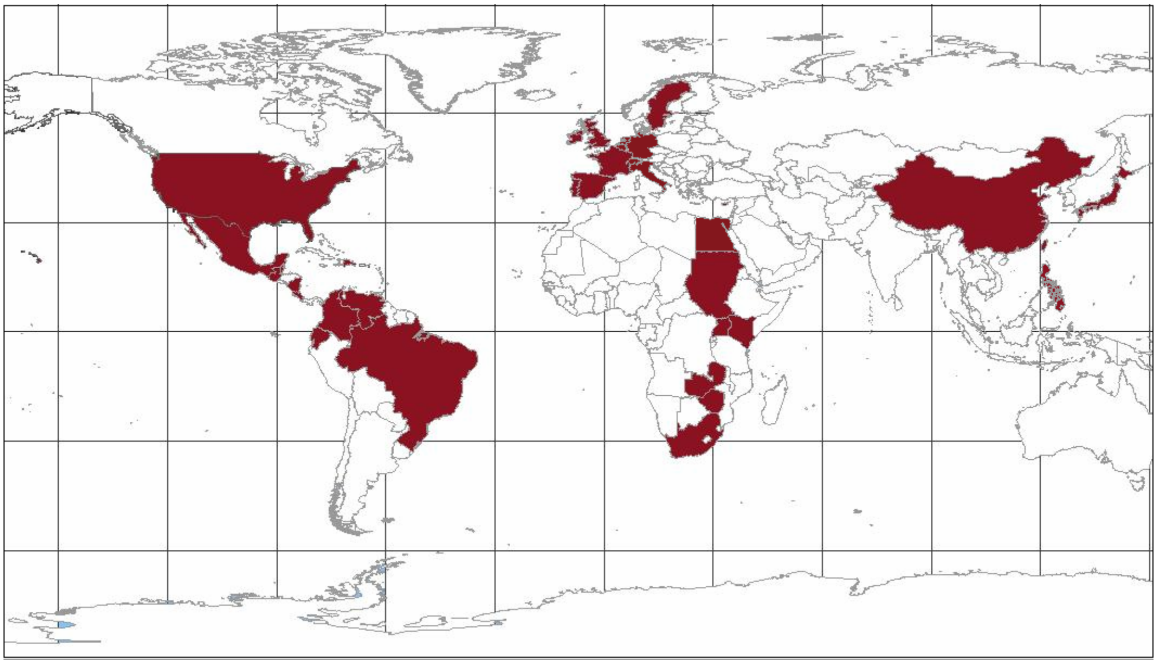

Figure 5. Countries with confirmed *P. clarkii* introductions (red), based on Hobbs et al. 1989 and Holdich 1999.

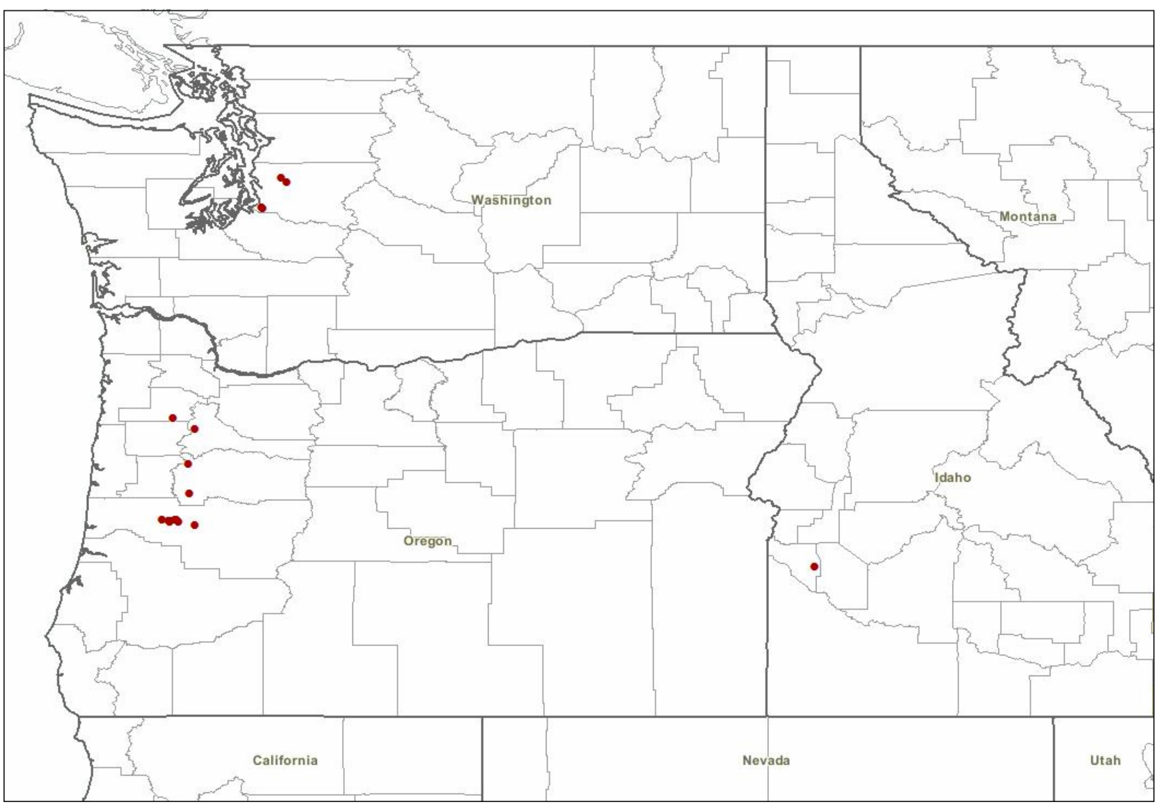

Figure 6. Point occurrences of *P. clarkii* (red) in the Pacific Northwest from museum records and agency or university sampling.

4.) Life History and Ecology

Life Cycle and Reproductive Strategies

Procambarus clarkii was characterized by Momot 1984 as an r-selected crayfish that matures rapidly, reproduces throughout the year, produces many young relative to its size, and is generally short-lived. This is in contrast to *P. leniusculus*, native to the Pacific Northwest, which Momot 1984 identified as a k-selected crayfish that requires several years to achieve maturity, is long-lived, reproduces once a year, and produces fewer young relative to its size than *P. clarkii.* The r-selected life history strategy of *P. clarkii* has been identified as an important trait contributing to the species' success as an invader (Lindqvist and Huner 1999; Gherardi 2006).

Crayfishes of the family Cambaridae, including *P. clarkii,* share the following generalized life cycle, adapted from Reynolds 2002: male crayfish are either reproductively inactive and exhibit Form II gonopods (hard and corneous, or yellow, at the tip) or reproductively active and exhibit Form I gonopods (soft and noncorneous, or white, at the tip), with a molt required to transition between forms. Male crayfish internally fertilize female crayfish, which extrude fertilized eggs that adhere to the underside of the abdomen due to a white sticky substance (glair) excreted from cement glands. Hatchling crayfish stay with the female for several weeks before becoming free living. Crayfish molt as they grow, regenerating their exoskeletons following a molt, and achieve maturity at ages that vary with species. Many crayfish exhibit season-specific reproductive activity and mate once a year (i.e. DiStefano et al. 2002), but *P. clarkii*'s reproductive behavior is more plastic. In its native range, *P. clarkii* is generally ovigerous (or berried; females carrying eggs or hatchlings) in August, September, and October, but in its invaded range in Spain the species was found to be ovigerous in November and December, March and April, or May through October depending on the aquatic system (Gutierrez-Yurrita et al. 1999). The plasticity in *P. clarkii's* life cycle permits the species to adjust to different regimes in water temperature and water availability, and contributes to the species' capacity to colonize and tolerate diverse habitats (Lindqvist and Huner 1999).

Little is known about life history patterns of *P. clarkii* in the Pacific Northwest, although Mueller (2007a) found the majority of male *P. clarkii* in Pine Lake, King County, Washington were Form I (reproductively active) from June through October. Water temperatures in Pine Lake in these months ranged from 22 to 24^{o} C, which have been previously identified as ideal *P. clarkii* breeding conditions (Huner and

Barr 1991). I collected a *P. clarkii* female in North Lake, King County, Washington that was carrying 807 hatchlings on September 18th, 2007 (Figure 1). Differences in life history traits between *P. clarkii* and the Pacific Northwest native *P. leniusculus* are demonstrated in Momot (1984), who uses these two species as examples of r-selected and k-selected life history strategies. To summarize: *P. clarkii* becomes mature at carapace lengths (CL) as small as 25 mm, with average life spans rarely exceeding one or two years and females carrying over 700 eggs. In contrast, *P. leniusculus* becomes mature at 30-40 mm CL, with average life spans of four to eight years and females generally carrying a maximum of 250 eggs. These life history differences have potentially important implications for *P. leniusculus* persistence in the presence of *P. clarkii* and also demonstrate the potential for *P. clarkii* to adapt to and rapidly colonize new habitats.

Feeding Habits

Procambarus clarkii is a generalist omnivore that feeds on detritus, algae, plant matter, aquatic invertebrates, amphibians and fish (Geiger et al. 2005; Renai and Gherardi 2006; Gherardi 2006). *Procambarus clarkii* food consumption is variable, as demonstrated by Gherardi's (2006) finding that *P. clarkii* consumed predominantly detritus, plant matter, or animal matter in different habitats across Spain and Portugal in proportion to resource availability. Correia (2002) similarly found *P. clarkii* to switch prey upon availability, and this plasticity in food use, like plasticity in life history traits, is another *P. clarkii* attribute that has been credited for the species' near-cosmopolitan invasive distribution (Holdich 1999). While *P. clarkii* will feed on any available aquatic resource, studies combining gut content analysis with stable isotopes have found that regardless of stomach contents, crayfish often predominantly assimilate animal matter into their tissue (Whitledge and Rabeni 1997; Parkyn et al. 2001). Animal matter may be particularly important for fast-growing juvenile crayfish. Paglianti and Gherardi (2004) found impaired growth and poor survival of juvenile *P. clarkii* when animal matter was withheld from their diet, and field sampling has shown a greater proportion of animal matter in the diets of juvenile than adult *P. clarkii* (Gutierrez-Yurrita et al. 1998; Geiger et al. 2005) Aquatic invertebrates or other animal matter may be important to *P. clarkii* populations, particularly at the juvenile life history stage.

Environmental Optima and Tolerances

Tolerance to a wide range of environmental conditions was a factor in *P. clarkii's* selection for introduction as an aquaculture organism in many countries, and has contributed to the species' success as an invader (Gutierrez-Yurrita et al. 1999). A warm water species in its native range, the successful establishment of *P. clarkii* in northeastern Illinois, U.S.A.; Zurich, Switzerland; and Hamburg, Germany demonstrates the species' capacity to tolerate cold winter temperatures (Taylor and Tucker 2005). Smart et al. (2002) reported water chemistry requirements of 6.5 - 8.5 pH and <15% salinity necessary for persistence of *P. clarkii* populations in Lake Naivasha, Kenya. Multiple authors have documented water temperatures in the range of 20-25^{o} C as a requirement for *P. clarkii* reproduction, and achieving this temperature range for breeding-length intervals may represent an important limit to the species' distribution (Huner and Barr 1991; Smart et al. 2002; Mueller 2007a). Additionally, calcium ions are necessary for crayfish exoskeleton formation and reformation following molts; however, *P. clarkii* has been found to tolerate low calcium conditions, likely by absorbing calcium ions through the gut with consumption of other invertebrates or mollusks (D'Abramo and Robinson 1989; Gutierrez-Yurrita et al. 1998). Gutierrez-Yurrita et al. (1998) shows that *P. clarkii* shifts to an invertebrate or mollusk diet during low calcium conditions in the Donana freshwater marsh of Spain, and this represents another reason why animal matter may be an important component of *P. clarkii's* diet.

Procambarus clarkii is tolerant of poor water quality and degraded aquatic habitats. *Procambarus clarkii* tolerates anthropogenic disturbance and poor water quality (i.e., agricultural conversion, turbidity, low dissolved oxygen) to a greater extent than native crayfishes it has displaced throughout Europe (Lindqvist and Huner 1999). Riley et al. (2005) found significantly higher occurrences of *P. clarkii* in developed or urban streams than undeveloped streams in southern California, and Brasher et al. (2006) similarly found *P. clarkii* to use urban and agricultural streams in Hawaii. Particularly important in many habitats is *P. clarkii's* capacity to burrow, resist desiccation, and travel overland in the absence of water (Correia and Ferreira 1995; Barbaresi et al. 2004; Cruz and Rebelo 2007). These physiological tolerances and behavioral adaptations make the species well-suited to establish populations in intermittent streams or ephemeral wetlands, such as rice fields, and are a niche that was not occupied by native European crayfishes.

Biotic Associations

Procambarus clarkii occurs in a wide range of aquatic habitats, although it is generally associated with floodplain or ephemeral wetlands with fine substrates suitable for burrowing (Huner and Lundqvist 1995). In warm climates in Europe, *P. clarkii* is most regularly associated with seasonally inundated agricultural fields and ditches, but in cooler European climates *P. clarkii* occurs in ponds and small lakes (Lindqvist and Huner 1999). This is consistent with the species' distribution at northern latitudes in its introduced U.S. range, where it occurs in ponds and small lakes in Oregon, Washington, and New York (Mueller 2001; Chris Pearl U.S.G.S. personal communication; Robert A. Daniels New York State Museum personal communication). *Procambarus clarkii* may also occur in larger permanent lakes and rivers, although Huner and Barr (1991) indicate that the species is poorly adapted to systems with fish predators. Additionally, while *P. clarkii* may occur in both lotic (flowing) and lentic (standing) waters, the species is generally associated with lower current velocities and finer substrates when lotic. Kerby et al. (2005) and Cruz and Rebelo (2007) found stream gradient and current velocity limited *P. clarkii* populations in southern California and Iberian streams, respectively. *Procambarus clarkii* has also been associated with developed as opposed to undeveloped streams (Riley et al. 2005). Finally, like many crayfish species, *P. clarkii* can occur at extremely high densities in aquatic macrophytes. Harper et al. (2002) found *P. clarkii* densities of 500 crayfish per m^2 in vegetation beds of Lake Naivasha, Kenya, where the species was protected from fish and terrestrial predators and supplied with consistent macrophyte and detrital food sources.

Biotic associations of *P. clarkii* likely vary across the species' native and invaded range, although several associations are notable. *Procambarus clarkii* has been identified as a vector for the crayfish plague *Aphanomyes astaci*, a fungus-like disease introduced to Europe from North America that is partially responsible for the collapse of European crayfish stocks (Huang et al. 1994). Additionally, crayfish gills are often infested with symbiotic branchiobdellid worms (Brown et al. 2002), which (due to their high level of endemism and specificity) have been suggested as a tool for determining the source of an invasive crayfish population (Kawai and Kobayashi 2006).

5.) Invasion Process

Vectors and Pathways of Introduction

Historically, the major vector responsible for widespread introductions of *P. clarkii* was deliberate aquaculture stocking. Through this vector, *P. clarkii* was introduced to Africa, Asia, Central America, Europe, and areas in North America (Hobbs et al. 1989; Holdich 1999). The pathway of initial introduction was from the south central United States to invaded countries, although *P. clarkii* was often introduced throughout a country and adjacent regions using invasive stocks (Gutierrez-Yurrita et al. 1999; Kawai and Kobayashi 2006). A genetics study of *P. clarkii* in Europe indicated that the species' populations on the continent could not be traced to any single source, but instead were the product of multiple introductions from the United States, Asia, Africa, and exchanges within European countries (Barbaresi and Gherardi 2000; Gherardi 2006). Similarly, the arrival of *P. clarkii* in Nevada in the 1940's was attributed to introduction from nearby California populations rather than from the species' native range in the southeastern U.S. (Hobbs and Zinn 1948). In this manner, *P. clarkii* introductions may perpetuate themselves once the species is introduced to a region without requiring any additional introductions from the species' native range.

Due to *P. clarkii*'s severe ecological impacts and minimal economic benefits, most deliberate aquaculture stocking of *P. clarkii* ceased by the late 1980's, although illegal movement of *P. clarkii* by aquaculture harvesters remains a threat (Hobbs et al. 1989; Gutierrez-Yurrita et al. 1999; Gherardi 2006). Other vectors for *P. clarkii* introduction have included the bait, aquarium, live seafood, and biological supply trades, although pathways of and vectors for non-deliberate introductions are difficult to identify and quantify (Lodge et al. 2000; Gherardi 2006). *Procambarus clarkii* was also introduced to some areas in Africa for biological control of schistosome-transmitting snails (Hofkin et al. 1991). Continued *P. clarkii* introductions are likely to be non-deliberate and mediated by releases of organisms by a public that is unaware of the threat of invasive crayfishes to native ecosystems. Education of anglers, aquarium hobbyists, and science teachers who use crayfish in their curricula is critical to preventing future *P. clarkii* introductions.

Establishment and Spread

Gutierrez-Yurrita et al. (1999) characterized *P. clarkii* as "the most ecologically plastic of the entire Decapoda," and this plasticity of feeding habits, life cycle, and environmental tolerances likely means that few factors limit *P. clarkii*'s ability to establish in a new habitat. Initial propagule pressure may not be an important factor in *P. clarkii* establishment, as the species' ability to reproduce throughout the year means that even small introductions may contain ovigerous females that can release hundreds of juveniles to the new habitat or may contain individuals that mate immediately upon arrival (Lindqvist and Huner 1999). Only twenty *P. clarkii* were necessary for successful establishment of the species in Japan (Kawai and Kobayashi 2006). Some environmental conditions that may prevent successful establishment of *P. clarkii* include high current velocities or steep stream gradients, water temperatures that fail to achieve the range necessary for *P. clarkii* reproduction (20-25^{o} C), and intense predation pressure from fish (Huner and Barr 1991; Smart et al. 2002; Kerby et al. 2005; Cruz and Rebelo 2007). However, these few known restrictions on *P. clarkii* establishment leave many aquatic habitats at tropical and temperature latitudes vulnerable to colonization by the species, and continued *P. clarkii* range expansion should be anticipated.

Spread of *P. clarkii* may be natural or human mediated. Human-mediated *P. clarkii* introductions are discussed in the previous section. Natural dispersal of *P. clarkii* can occur at a rapid rate. *Procambarus clarkii* has been documented to travel up to three kilometers per day, and the species is capable of traveling over dry land (Gherardi and Barbaresi 2000; Cruz and Rebelo 2007). Because *P. clarkii* has high fecundity, may reproduce several times during a year, and is extremely mobile for a crayfish, the species can disperse rapidly across a landscape. In twenty years, *P. clarkii* went from its site of initial introduction in Spain to being nearly ubiquitous across the entire Iberian peninsula (Gutierrez-Yurrita et al. 1999). Introduced to Japan in low numbers at a bullfrog farm in 1927, *P. clarkii* was widespread across the main island of Honshu by the 1960's through a combination of human-mediated and natural dispersal (Kawai and Kobayashi 2006). These examples demonstrate the capacity for *P. clarkii* to take over a region within several decades of initial introduction, and emphasize the clear need to prevent further introductions and reduce human mediated-dispersal. (see section 6).

<u>Ecological and Economic Impacts</u>

Procambarus clarkii is the most widespread invasive crayfish in the world and produces some of the most severe impacts of any introduced crayfish species. Factors contributing to this species' success as an invader, such as high fecundity, flexible life history strategies, tolerance of a wide spectrum of environmental conditions, and omnivory, also contribute to its capacity to integrate with and impact aquatic ecosystems. I will organize this brief summary of *P. clarkii* ecological and economic impacts by: a.) discussing *P. clarkii* effects on rare and endangered species, b.) discussing *P. clarkii* food web, community and ecosystem effects, c.) discussing *P. clarkii* economic impacts, and d.) discussing instances of *P. clarkii* ecological and economic benefits.

Many rare and endangered species have been negatively affected by *P. clarkii* introductions. In Europe, *P. clarkii* is a vector for the crayfish plague *Aphanomyes astaci*, a fungus-like disease from North America that decimated European crayfish populations (Huang et al. 1994). *Procambarus clarkii* also negatively affects native crayfishes through predation and competition. Crayfish fragments are regularly found in the stomachs of *P. clarkii* (Gutierrez-Yurrita et al. 1998); Mueller (2007b) found a high rate of *P. clarkii* cannibalism on small individuals of the native crayfish *P. leniusculus* in a Washington lake. *Procambarus clarkii* is dominant over many native crayfishes due to the species' large chelae and overall size. Gherardi and Daniels (2004) and Gherardi and Cioni (2004) found *P. clarkii* to competitively exclude native crayfishes from shelter, which can increase susceptibility to predation under natural conditions. Paglianti and Gherardi (2006) found *P. clarkii* juveniles to grow faster on the same diet than native European crayfish, providing a size advantage that may produce competitive asymmetries between these species. While much of *P. clarkii's* invaded range does not contain native crayfishes, the leading threat to native crayfish conservation is invasive species and consequently *P. clarkii* is a challenge for European and North American crayfish persistence (Lodge et al. 2000).

Procambarus clarkii has also been shown to impact native amphibians and fish. Amphibians are especially vulnerable to *P. clarkii* predation. Many amphibians are naïve to introduced predators and lack adequate chemical or behavioral defenses for *P. clarkii* (Pearl et al. 2003; Renai and Gherardi 2004). Cruz and Rebelo (2005) found *P. clarkii* to reduce survival of 13 amphibian species native to the Iberian peninsula. Similarly, Gamradt and Katz (1996) reported reductions in California newt *Taricha tarosa* survival due to *P. clarkii* predation. Predation by introduced species has been identified as one factor in global amphibian declines, and *P. clarkii's* use of ephemeral wetlands and other amphibian habitats will remain a conservation concern for these species (Alford and Richards 1999). Few investigators have examined *P. clarkii* impacts on native fish, but Mueller et al. (2006) documented predation by *P. clarkii* on the endangered razorback sucker *Xyrauchen texanus* in the Colorado River of the southwestern United States. *Procambarus clarkii* is a large, aggressive crayfish that can occur in high densities in many habitats and will consume animal matter, and consequently represents a serious threat to the conservation of aquatic invertebrates and vertebrates where introduced.

Procambarus clarkii has the ability to alter the structure and function of aquatic ecosystems through its high densities and foraging and burrowing behavior. Ecosystem impacts of *P. clarkii* have been best documented in the Mediterranean wetlands of Europe, and may be summarized as follows: *P. clarkii* decreases the abundance and diversity of aquatic macrophytes, aquatic invertebrates (particularly snails), amphibians, plant-eating birds, and increases turbidity and nutrient loading of the water (Angeler et al. 2001; Geiger et al. 2005; Rodriguez et al. 2005; Gherardi and Acquistapace 2007). Rodriguez et al. (2005) found a 99% loss of macrophyte cover, a 71% loss in macroinvertebrate genera, and an 83% loss of amphibian species present in a shallow lake in northwest Spain following *P. clarkii* invasion. This loss of community diversity and simplification of aquatic habitats reduces the complexity of food webs (Geiger et al. 2005). Crayfish become extremely important in these systems, and Mediterranean wetlands invaded by *P. clarkii* transition to communities dominated by fish and birds that prey on crayfish (Rodriguez et al. 2005). Ecosystem effects similar to those observed for *P. clarkii* in European wetlands have also been documented for lakes and wetlands in California and Africa; in particular, *P. clarkii* may be anticipated to reduce macrohpyte and macroinvertebrate abundance and diversity (Feminella and Resh 1989; Harper et al. 2002). Little work has been done investigating *P. clarkii* community and ecosystem effects where present in higher latitude streams, ponds, or lakes, and such research would be a valuable contribution to the understanding of *P. clarkii*'s invasive role in the Pacific Northwest.

Crayfish are often characterized as “ecosystem engineers” due to the effect of their foraging and burrowing on sediment transport and nutrient cycling (Creed and Reed 2004). Heavy metals and toxins accumulate in *P. clarkii* due to its benthic foraging, and as a result crayfish serve as a mechanism for direct transport of toxins up the food chain to fish, birds, and mammals (Gutierriez-Yurrita et al. 1999). Additionally, *P. clarkii*'s burrowing and foraging behavior disturbs sediments and transports nutrients into the water column, reducing both water quality and nutrient content in the substrate (Angeler et al. 2001). The burrowing behavior of *P. clarkii* has implications beyond ecosystem engineering: dense aggregations of *P. clarkii* burrows have also damaged water control infrastructure like levees and ditches and affected the capacity of farmers to irrigate their fields (Huner 1988; Kawai and Kobayashi 2006).

Further direct economic impacts of *P. clarkii* include the species' interference with agriculture and fisheries. While *P. clarkii* is cultured and harvested from inundated rice fields in much of its native range, balancing crayfish and rice production is challenging and the species' damage to crops in its invaded range has often outweighed benefits of harvest (Anastacio et al. 2005). Rice growing areas of California, Japan, Portugal, and Spain have all suffered economic losses associated with *P. clarkii* foraging on rice (Somner 1984; Anastacio et al. 2005 Kawai and Kobayashi 2006). Even in areas with successful *P. clarkii* harvests, farmers may not benefit from crayfish. In Spain, fishermen harvesting crayfish may be independent of rice farmers and damage crops and property in the process of fishing without reimbursement to the farmers (Gutierrez-Yurrita et al. 1999). Additionally, crayfish harvesters in Spain and Portugal use nets and traps that may kill fish, amphibians, and birds; Gutierrez-Yurrita et al. (1999) report that 42,000 birds died in 1989 in crayfish traps in a Spanish national park. In Africa, where *P. clarkii* was introduced to supplement fisheries, the species is harvested at low levels but interferes with existing gill net fisheries by feeding on caught fish (Lowery and Mendes 1977). Hobbs et al. (1989) reported few sites where *P. clarkii* was introduced and produced positive economic impacts, and the failure of *P. clarkii* to replicate its native range aquaculture production in its invaded range has likely discouraged further introductions of the species.

Some economic and ecological benefits are associated with *P. clarkii* introductions. The species has produced successful harvests in some areas; *P. clarkii* is harvested in Africa and the Iberian peninsula, and is an emerging aquaculture species in China (Hobbs et al. 1989). Gutierrez-Yurrita et al. (1999) report that *P. clarkii* fisheries have complemented the incomes and improved the standard of living of many families near marshes where the species has been introduced, although the market for *P. clarkii* is seasonal, volatile, and will likely remain a marginal fishery. Spain harvests 3,000 tons of *P. clarkii* annually, which is used within the country and exported to France, Belgium, Denmark and Sweden (Gutierrez-Yurrita et al. 1999). *Procambarus clarkii* is harvested at even lower numbers in Kenya and exported elsewhere in Africa and to Europe (Hobbs et al. 1989). Some documented ecological benefits of *P. clarkii* include the recovery of wading birds and otters in Mediterranean wetlands where *P. clarkii* has become established, although these benefits come with the previously documented ecological and economic costs (Delibes and Adrian 1987; Rodriguez et al. 2005).

6.) Management Strategies and Control

As with most invasive species, the best management strategy for controlling *P. clarkii* invasions is prevention. Once established, crayfish integrate strongly with native ecosystems, producing major impacts (see section 5), and are extremely difficult to remove. Government agencies should be discouraged from introducing *P. clarkii* for aquaculture or other purposes due to the species' well-documented negative impacts and limited benefits. Education efforts should be directed at the general public to discourage release of any non-native aquatic organisms, and regulatory efforts should be directed at the bait, aquarium, live seafood and biological supply industries to discourage the transport of known invasive species (although the cessation of such practices for a commercially valuable species like *P. clarkii* seems unlikely). Invasive crayfish have received increasing attention over the past several decades from the scientific community, but to effectively prevent further *P. clarkii* introductions this awareness needs to spread to governments and the general public (Hobbs et al. 1989; Holdich 1999; Lodge et al. 2000; Gherardi 2006).

There has been little success in controlling *P. clarkii* once the crayfish is established. Pesticides have been applied to control the species in agricultural fields, but this produced severe impacts on bird populations and consequently this approach is discouraged (MacKenzie 1986). Distributions of *P. clarkii* may be restricted by stream barriers like culverts and dams, as well as high stream flows, and Kerby et al. (2005) encouraged using this information to manage the spread of *P. clarkii* populations. Additionally, a lake population of the invasive rusty crayfish *O. rusticus* has recently been nearly eradicated through a combination of trapping and fish predator management (Hein et al. 2007). Due to *P. clarkii*'s vulnerability to fish predation (Huner and Barr 1991), a similar approach may work for this species, although such an effort by Frutiger and Muller (2002) was unsuccessful and complete eradication of *P. clarkii* from a large aquatic ecosystem or landscape is probably not practical. Removal of *P. clarkii* will be labor intensive, costly, and may carry repercussions for other members of aquatic ecosystems, and consequently prevention of introductions and spread of this species should be a management priority for government agencies and the general public alike.

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8.) Other Resources

Washington Guide to Collecting Nonnative Crayfish:

http://wdfw.wa.gov/fish/ans/identify/html/orconectes_rusticus/IdentifyingCollecting NonnativeCrayfishWashington.pdf

The Crayfishes of Missouri:

http://www.mdcnatureshop.com/mdc.cgi/01-0250.html

The Crayfishes of Kentucky:

http://www.inhs.uiuc.edu/chf/pub/recentpub.html#L

America's Crayfish Educational Video:

http://www.uwtv.org/programs/displayevent.aspx?rID=3722&fID=572

9.) Experts in the Pacific Northwest

Craig Busack   Washington Department of Fish and Wildlife

busaccsb@DFW.WA.GOV

Initiating studies of invasive crayfish in Washington for the state, particular emphasis on Snake and Columbia rivers and reservoirs.

Karl Mueller ENVIRON International (Consulting)
kmueleer@environcorp.com 206-336-1651
First documented *P. clarkii* in Washington state while a Washington Department of Fish and Wildlife employee, maintains an active interest in crayfish in Washington. Volunteers with the Washington Lake Protection Association.

Julian Olden University of Washington Fisheries School
olden@u.washington.edu 206-616-3112
University of Washington faculty with expertise in aquatic invasive species; initiating studies on *P. clarkii* in western Washington.

Chris Pearl U.S. Geological Survey
Christopher_pearl@usgs.gov 541-650-1011
Amphibian ecologist who has conducted studies on *P. clarkii* in Willamette Valley, Oregon. Has published on *P. clarkii* interactions with native Northwest amphibians.