

The State of Crayfish in the Pacific Northwest



Eric R. Larson and Julian D. Olden

Larson is a graduate student at the University of Washington, Seattle, and can be contacted at School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195. E-mail: lars9570@uw.edu. Olden is an assistant professor in the School of Aquatic and Fishery Sciences at the University of Washington, and can be contacted at the same address. His E-mail is: olden@uw.edu .

ABSTRACT: We summarize the state of knowledge on crayfish in the Pacific Northwest region of the United States and Canada, emphasizing distributions and conservation status of native species, as well as known introductions and distributions of alien crayfishes, and reviewing fishing regulations relevant to crayfish across five states and provinces. We found the present distribution and ecology of native crayfishes in this region to be poorly known, inhibiting accurate conservation assessments and management. The number of alien crayfishes established in the region, ranging in distribution from localized to widespread and including several major invasive species, now exceeds the diversity of native crayfishes. The treatment of crayfish by fishing regulations and laws varies among states and provinces, potentially impairing successful management and conservation of these species in shared ecosystems such as the Snake and Columbia rivers. We conclude with recommendations for crayfish management and regulation, and a call for more research on the ecology of crayfish in the Pacific Northwest.

El Estado Del Langostino En El Pacífico Noroeste

Se presenta un resumen del estado de conocimiento acerca del langostino en la región del Pacífico noroeste de los Estados Unidos de Norteamérica y Canadá, haciendo énfasis en la distribución y estado de conservación de las especies nativas así como también en introducciones conocidas y distribución de especies foráneas de langostinos; también se hace una revisión de las regulaciones pesqueras relevantes para los langostinos a lo largo de cinco estados y provincias. Se encontró que la distribución actual y ecología de los langostinos nativos de esta región son poco conocidas, lo que impide realizar evaluaciones precisas de conservación y manejo. El número de langostinos foráneos establecidos en la región, cuya distribución va desde los altamente localizados a los ampliamente distribuidos incluyendo varias de las especies invasivas más importantes, excede la diversidad de langostinos nativos. El manejo de los langostinos a través de leyes y medidas regulatorias de pesca varía entre estados y provincias, lo que potencialmente puede reducir el éxito de la conservación y manejo de estas especies en ecosistemas compartidos como los ríos Snake y Columbia. Se concluye con recomendaciones para el manejo y regulación del langostino y se hace un llamado para incrementar los esfuerzos de investigación en la ecología del langostino del Pacífico noroeste.

INTRODUCTION

Crayfishes of North America have received increased attention from fisheries biologists over recent decades in response to several factors. First, crayfish often fill a keystone role in aquatic food webs as omnivorous consumers of plant matter, animal matter, and detritus, and serve as an important link between these energy sources and aquatic and terrestrial predators (Rabeni 1992; Creed 1994; Usio and Townsend 2004; Tablado et al. 2010). Consequently, the addition (invasion) or subtraction (extirpation) of a crayfish species can have far-reaching consequences for communities and ecosystems (e.g., Nyström et al. 1996; Dorn and Mittelbach 1999). Invasive crayfish species introduced to new regions have had severe impacts on aquatic communities and valuable recreational and commercial fisheries (e.g., Wilson et al. 2004; McCarthy et al. 2006). Invasive crayfishes have also contributed to population declines, extirpations, and extinctions of native crayfishes (e.g., Bouchard 1977a; Light et al. 1995), combining with other stressors such as habitat loss and degradation to make crayfish one of North America's most imperiled taxonomic groups (Strayer and Dudgeon 2010). Finally,

the value of crayfish in recreational and commercial fisheries also requires attention and regulation from fisheries biologists (Miller and Van Hyning 1970; Roell and Orth 1998).

Recognition of the importance of crayfish has resulted in heightened research and management attention dedicated to this taxonomic group, ranging from evaluations of species conservation status (Taylor et al. 2007) to policy recommendations for the prevention of crayfish invasions (DiStefano et al. 2009). However, we perceive a striking regional disparity in the attention given crayfishes by fisheries biologists. Researchers in the southeastern United States (US) are increasing efforts to document and conserve the region's endemic crayfish diversity (e.g., Larson and Olden 2010; Welsh et al. 2010), while researchers in the Great Lakes region and California have made important contributions quantifying the economic and ecological costs associated with crayfish invasions (e.g., Gamradt and Kats 1996; Keller et al. 2008). By contrast, few recent studies on distributions, ecology, or management of crayfish have been conducted in the Pacific Northwest region of the US and Canada (but see Lewis 1997; Bondar et al. 2005a; Mueller and Bodensteiner 2009).



Native crayfishes of the Pacific Northwest: A. Snake River pilose crayfish (*Pacifastacus connectens*); B. pilose crayfish (*Pacifastacus gambelii*); C. signal crayfish (*Pacifastacus leniusculus klamathensis*); D. signal crayfish (*Pacifastacus leniusculus leniusculus*). Photos by N. Usio (A), T. Woolf (B), D. VanSlyke (C), and J. Benca (D).

This oversight is somewhat surprising given the unfortunate history of crayfish invasions and conservation in adjacent California, where the native sooty crayfish (*Pacifastacus nigrescens*) was declared extinct in 1977, and the native Shasta crayfish (*Pacifastacus fortis*) is listed under the US Endangered Species Act. Both declines have been attributed to the combined effects of habitat loss and invasive crayfishes (Bouchard 1977a; Light et al. 1995). These Californian crayfishes represented 40% of the native crayfish diversity west of the Continental Divide in North America. The remaining three western crayfishes are native to the Pacific Northwest, from coastal British Columbia, Oregon, and Washington, inland to the Columbia and Snake River headwaters of Montana, Nevada, Wyoming, and Utah (Miller 1960). These species have almost no contemporary published records on their distribution and ecology to justify their present “stable” conservation status (Taylor et al. 2007). Furthermore, the perception of the Pacific Northwest as uninvaded by aquatic nuisance species relative to eastern North America is no longer justifiable (Sanderson et al. 2009), and the increasingly invaded status of the region includes multiple newly discovered populations of invasive crayfishes from eastern North America (Mueller 2001; Olden et al. 2009a; Larson et al. 2010).

Crayfish management in the Pacific Northwest may also be complicated by the common asynchrony between political boundaries and natural populations, communities, and ecosystems that cross them (Powell 1890; Giordano and Wolf 2003). For example, inconsistent alien species regulations between nations or states sharing aquatic ecosystems can leave entire regions vulnerable to invasion because of “weak links” (Peters and Lodge 2009). Similarly, activities such as wild fish harvest can be mismanaged or promote conflict when adjacent jurisdictions pursue differing agendas (Mitchell 1997; Brown 1999). Such transboundary resource management issues are certainly relevant in the Pacific Northwest, where most major aquatic ecosystems such as the Columbia and Snake rivers cross the borders of multiple US states and the Canadian province of British Columbia. Relevant to crayfish, this means that how one state or province regulates alien species, the use of live bait, or the harvest of wild populations can affect neighboring jurisdictions and their aquatic resources (DiStefano et al. 2009; Peters and Lodge 2009).

Here we summarize the state of knowledge on crayfish in the Pacific Northwest, with the intent of providing an introduction for fisheries biologists in the region and a contemporary update to past work on this subject (Miller 1960; Bouchard 1977a). We first present historic point occurrences of native crayfishes in the region from the diligent summary of Miller (1960), crustacean collections of the Smithsonian Institution and Carnegie Museum of Natural History, and more recent published accounts (e.g., Johnson 1986; Hubert 1988; Bondar et al. 2005a). Relevant issues in taxonomy, identification, and ecology of these species are briefly discussed, but we focus primarily on providing known distributions for use as a historic benchmark in evaluating current conservation status. We next summarize known

alien crayfish occurrences from museum records, published accounts, and recent surveys (e.g., Sheldon 1989; Clark and Lester 2005), with the aim of synthesizing knowledge on the accumulating crayfish invasions of the Pacific Northwest. For both native and alien species, our reliance on point occurrences from museum records and published accounts likely leads to underestimates in ranges, although the inverse may be true for native crayfishes that could be suffering population declines.

We also review crayfish-relevant fishing regulations and laws for states and provinces of the Pacific Northwest, focusing on prohibited species, live bait, and recreational and commercial harvest. We chose to summarize these policies for British Columbia, Idaho, Montana, Oregon, and Washington, as these states and province dominate the region’s surface area. We exclude California, Nevada, Utah, and Wyoming for brevity, but do report on native and alien crayfish distributions for these states where they border the Pacific Northwest. Fishing regulations and laws were reviewed by state or provincial managers for accuracy (see acknowledgements). The intent of this policy review was to evaluate cross-jurisdictional consistency in regulations and laws relevant to minimizing the risk of crayfish invasions and to compare how the recreational and commercial harvest of crayfish is managed. We conclude with suggested research priorities and management recommendations for crayfish in the Pacific Northwest.

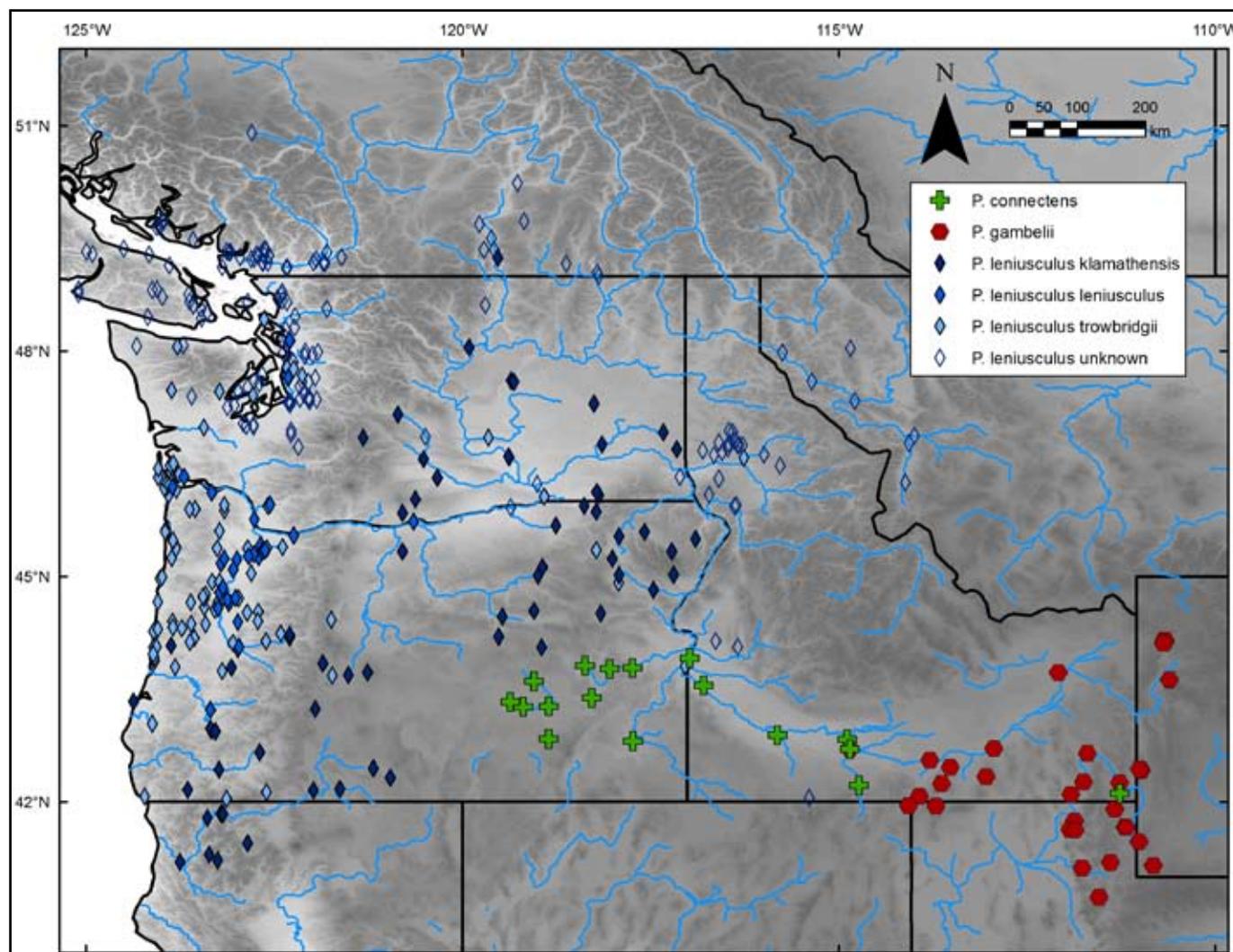
NATIVE CRAYFISHES

Snake River pilose crayfish (*Pacifastacus connectens*)

The Snake River pilose crayfish (*Pacifastacus connectens*) was described by Faxon (1914) and considered a subspecies of the pilose crayfish (*Pacifastacus gambelii*) until reclassified as a distinct species by Hobbs (1972) and Bouchard (1977b), who grouped *P. connectens* in the subgenus *Hobbsastacus* with *P. gambelii*, *P. fortis*, and the extinct *P. nigrescens* on the basis of mandible morphology. *Pacifastacus connectens* may be most easily distinguished from the signal crayfish (*Pacifastacus leniusculus*) by the presence of clusters of setae (hairs) on the chelae (claws), and from *P. gambelii* by the presence of spines or tubercles (bumps) on a carapace ridge located just behind the eye (postorbital ridge).

The range of *P. connectens* historically extended from the desert lake basins of southeastern Oregon across the Snake River and tributaries of southern Idaho (Figure 1), and presumably these same streams in northern Nevada. Our literature review revealed no studies on the ecology or life history of this species and no contemporary survey of its distribution or conservation status. The American Fisheries Society recognizes its conservation status as currently stable (Taylor et al. 2007), although the states of Idaho and Oregon consider the species vulnerable. Threats to *P. connectens* might include land use change and resultant habitat loss or degradation, as well as the introduction of invasive species to

Figure 1. Point occurrences from literature and museum records for crayfish species and subspecies native to the Pacific Northwest.



the region. In particular, several invasive crayfishes have been documented from southern Idaho (Clark and Wroten 1978; Clark and Lester 2005).

Pilose crayfish (*Pacifastacus gambelii*)

The pilose crayfish *Pacifastacus gambelii* has had an unclear taxonomic and distributional history (Riegel 1959), including a type description from California (Girard 1852) that was later disputed as a specimen instead collected while in transit to California (Faxon 1885). The species is presumed native to the states of Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming (Hobbs 1972; Taylor et al. 2007). As of Miller (1960), historic records that could be reliably identified as *P. gambelii* were known only from the Snake River and its tributaries of Idaho, Nevada, Utah, and Wyoming, as well as Great Salt Lake tributaries like the Bear and Weber rivers of Utah and Wyoming (Figure 1). We are inclined to conclude that the historic attribution of this species to Oregon was instead *P. connectens*, and we found no records of either species

in Washington. Faxon (1885) reported *P. gambelii* to occur widely east of the Continental Divide in the upper Missouri River and other drainages, a claim met with some skepticism by Bouchard (1978) and an absence of known museum records. Sheldon (1989) did not report *P. gambelii* from Pacific drainages of western Montana. Knowledge of the distribution of *P. gambelii* and relationship to *P. connectens* would benefit from further investigation.

The American Fisheries Society recognizes *P. gambelii* as currently stable (Taylor et al. 2007), while state assignments range from critically imperiled in Montana to apparently secure in Idaho. Like *P. connectens*, the ecology and life history of *P. gambelii* is minimally known, although Koslucher and Minshall (1973) reported omnivorous feeding habitats, typical of crayfishes, for *P. gambelii* in a desert stream of Idaho and Utah. Conservation threats to *P. gambelii* might include land use change, habitat loss or degradation, and invasive species. Alarmingly, Hubert (2010) recently revisited sites sampled for crayfishes in Wyoming from 1986 to 1988 (Hubert 1988) and found *P. gambelii* absent from all sites previously occupied in the Bear River drainage, replaced by the invasive virile crayfish (*Orconectes virilis*).

Signal crayfish (*Pacifastacus leniusculus*)

The signal crayfish *Pacifastacus leniusculus* is the most widely distributed and best known of the crayfishes native to the Pacific Northwest, although it has been better studied as an invasive species in California, Europe, and Japan (e.g., Abrahamsson and Goldman 1970; Nyström et al. 1996; Usio et al. 2009). *Pacifastacus leniusculus* was initially described as three species: *P. klamathensis* (Stimpson 1857), *P. leniusculus* (Dana 1852), and *P. trowbridgii* (Stimpson 1857). Riegel (1959) considered *P. leniusculus* and *P. trowbridgii* to be synonymous but *P. klamathensis* a unique species, while Miller (1960) considered all three to be subspecies of *P. leniusculus* due to observed intergrade forms. This view was adopted by later taxonomic guides (Hobbs 1972; Bouchard et al. 1977b). Genetic work to date has found *P. l. leniusculus* and *P. l. trowbridgii* to be the most similar and *P. l. klamathensis* the most distinct subspecies (Agerberg and Jansson 1995).

Where possible, we report distributions by subspecies for *P. leniusculus* (Figure 1), although many distributional records neglect to include a subspecies designation. Some morphological features useful in differentiating *P. l. leniusculus* from *P. l. trowbridgii* include a narrow or fusiform rather than broad or robust carapace, and the presence of sharp spines rather than rounded tubercles on the postorbital ridge (Riegel 1959; Miller 1960). The subspecies *P. l. klamathensis* lacks either spines or tubercles on the postorbital ridge, and has also been noted to lack the white or blue-green coloration across the joint of the chelae commonly found in the other two subspecies (Riegel 1959; Miller 1960). While often brown or tan, the life colors of *P. leniusculus* are highly variable, and can range from bright red to blue.

The native distribution of *P. leniusculus* extends from the Klamath River of northern California to southern British Columbia, and inland to Columbia River tributaries of western Montana (Figure 1). Bouchard (1978) notes that the biogeography of *P. leniusculus* subspecies is likely confounded by translocation of this species within its native range, as either bait or through the stocking of ponds and lakes. The most apparent pattern in subspecies distributions emerges from *P. l. klamathensis*, which occupies coastal rivers of northern California and southwestern Oregon in the southern portion of its range, but then transitions to drainages east of the Cascade Mountains of Oregon and Washington in its northern range. *Pacifastacus l. leniusculus* and *P. l. trowbridgii* are common in northwest Oregon, coastal Washington, and the lower Columbia River (Figure 1). Subspecies designations are rare for British Columbia, Idaho, and Montana. A number of studies on the basic ecology and life history of *P. leniusculus* are available from the Pacific Northwest. Many of these are in the form of graduate theses or agency reports that were unfortunately never published in the peer-reviewed literature. Some notable works include physiological and life history investigations into the viability of the species for aquaculture (e.g., Coykendall 1973; Mason 1974), recent studies from British

Columbia on ecological function in small streams (e.g., Bondar et al. 2005b; Bondar and Richardson 2009), and exhaustive mark-recapture estimates of lake populations (e.g., Johnson 1971; Lewis 1997).

All subspecies of *P. leniusculus* are recognized as currently stable by the American Fisheries Society (Taylor et al. 2007), although state and province designations vary and conservation concern is expressed for the species in British Columbia (Bondar et al. 2005a). *Pacifastacus leniusculus* may be affected by invasive crayfishes in some portions of its range. Bouchard (1977a) and Sheldon (1989) report apparent losses of *P. leniusculus* habitat to invasive crayfishes of the genus *Orconectes*, and both authors describe a pattern of habitat partitioning in which *P. leniusculus* persists in fast flowing waters while *Orconectes* dominates slow or impounded waters. Other records have also observed an absence of *P. leniusculus* from sites presently dominated by invasive crayfishes (Olden et al. 2009a; Larson et al. 2010). Although resistant to extinction due to its large range size and wide success as an invasive species, subspecies and populations of *P. leniusculus* in its native range may still be threatened by invasive species or other factors like habitat loss and degradation.

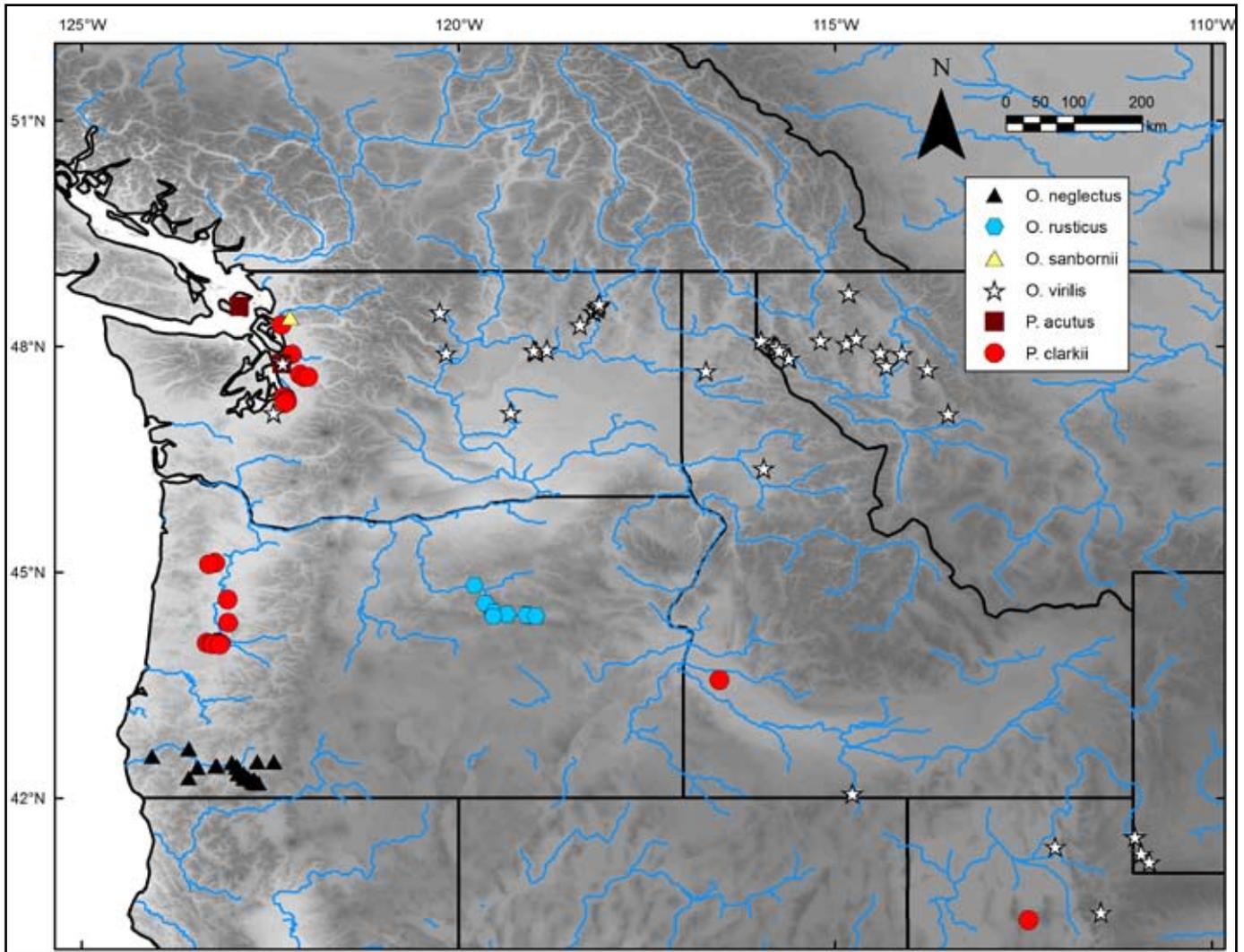
ALIEN CRAYFISHES

All known alien crayfishes in the Pacific Northwest belong to the family Cambaridae of eastern North America. These crayfishes differ from native *Pacifastacus*, which belong to the family Astacidae, by the presence of ventral hooks on upper segments of walking legs in mature males (Hobbs 1972). The large tubercles on the chelae or carapace of many Cambarid adults, absent in *Pacifastacus*, may be a more conspicuous trait to biologists unfamiliar with crayfishes. Identification to species of

Table 1. Alien crayfishes in the Pacific Northwest (including upper Snake River and tributaries and the Great Salt Lake basin in Utah and Wyoming) by species and state with year discovered and reporting sources.

Species	State	Year	Sources
<i>Orconectes neglectus</i>	Oregon	1966	Bouchard (1977a)
<i>Orconectes rusticus</i>	Oregon	2005	Olden et al. (2009a)
<i>Orconectes sanbornii</i>	Washington	1987	Larson and Olden (2008) Larson et al. (2010)
<i>Orconectes virilis</i>	Utah	1981	Johnson (1986)
	Montana	1988	Sheldon (1989)
	Idaho	1999	Clark and Lester (2005)
	Washington	2006	Larson and Olden (2008) Larson et al. (2010)
	Wyoming	2007-2009	Hubert (2010)
<i>Procambarus acutus</i>	Washington	2009	Larson and Olden (unpub.)
<i>Procambarus clarkii</i>	Idaho	1975	Clark and Wroten (1978)
	Utah	1978	Johnson (1986)
	Washington	2000	Mueller (2001) Larson and Olden (2008)
	Oregon	1999-2001	Pearl et al. (2005)

Figure 2. Point occurrences from literature and museum records for alien crayfish species in the Pacific Northwest.



Cambarid crayfishes requires keys based on mature (Form I) male reproductive organs (gonopods), and consultation with an expert is recommended. Information on typical life colors is provided for alien crayfishes found in the Pacific Northwest, with the caveat that this trait can vary across populations.

Ringed crayfish (*Orconectes neglectus*)

The ringed crayfish (*Orconectes neglectus*), native to the Great Plains and Ozark Plateaus of the central US, was the first crayfish from eastern North America documented in the Pacific Northwest (Table 1). Bouchard (1977a) provides a summary of its discovery and basic ecology in Oregon, the only state in the region from which it is known (Figure 2). Widespread by 1977 in the Rogue River and tributaries, little subsequent work on the species has been pursued, and its present distribution in that drainage, or potentially in adjacent systems, has not been assessed. Bouchard (1977a) speculated that *O. neglectus* was introduced to the Rogue River either incidentally with stocking of warmwater fish, or through the use of crayfish as bait. *Orconectes neglectus* has

prominent orange and black rings at the tips of the chelae, and a dark u-shaped saddle mark on the dorsal surface of the carapace that is pronounced relative to other *Orconectes* species in the region.

Rusty crayfish (*Orconectes rusticus*)

The rusty crayfish (*Orconectes rusticus*), native to the Ohio River drainage, is a highly invasive crayfish that has had well-documented impacts in aquatic ecosystems of the Great Lakes region and elsewhere (McCarthy et al. 2006; Keller et al. 2008). It was not known to occur west of the Continental Divide until found in the John Day River of central Oregon in 2005 (Figure 2; Table 1). Olden et al. (2009a) speculated that *O. rusticus* may have been introduced to the John Day River as bait for popular warmwater fisheries, or through its use in schools and biological supply in the region (Larson and Olden 2008). *Orconectes rusticus* has not yet been found elsewhere in the Pacific Northwest. Its status and spread in the John Day River demands monitoring and, if feasible, management intervention. *Orconectes rusticus*

possesses distinctive rust-colored spots on both lateral surfaces of the carapace, and often black or orange tips of the chelae. Rapid identification of newly established *O. rusticus* populations is necessary for control or eradication (Hein et al. 2006).

Sanborn's crayfish (*Orconectes sanbornii*)

Sanborn's crayfish (*Orconectes sanbornii*), native to the Ohio River drainage, represents an unusual crayfish introduction to the Pacific Northwest. The species has not been found introduced elsewhere in the world. Larson and Olden (2008) found *O. sanbornii* in Big Lake, Washington, in the summer of 2008 (Figure 2), although this species was incorrectly identified as *O. virilis* (corrected in Larson et al. 2010). Consultation with crayfish taxonomist Christopher Taylor, Illinois Natural History Survey, revealed a Smithsonian Institution record for *O. sanbornii* from this lake and adjacent streams from 1987 (Table 1). Origins of the *O. sanbornii* population in northwest Washington are unknown. *Orconectes sanbornii* appears brown or tan with less distinctive life colors than either *O. neglectus* or *O. rusticus*.

Virile crayfish (*Orconectes virilis*)

The virile (or northern) crayfish *Orconectes virilis* may be the most widely invasive crayfish in the Pacific Northwest, known from Idaho, Montana, and Washington, as well as adjacent states like Utah and Wyoming (Figure 2; Table 1). Native over a large area of North America east of the Continental Divide, *O. virilis* is now widespread in the west, with populations documented in California and the Colorado River drainage (Riegel 1959; Johnson 1986). The species may have been introduced to the Pacific Northwest through multiple pathways. In California, *O. virilis* was first established in the Central Valley after escapes from laboratory ponds at Chico State University (Riegel 1959). By contrast, both Johnson (1986) and Sheldon (1989) report that *O. virilis* was deliberately stocked by the states of Utah and Montana, respectively, to serve as forage for warmwater fishes. *Orconectes virilis* was first detected in the Columbia River in Washington State in 2006, and this occurrence could represent time-lagged downstream dispersal from stocked populations in western Montana. Alternatively, the species is commonly used as fishing bait and occurs in biological supply (Larson and Olden 2008; DiStefano et al. 2009). We suspect the species is present in British Columbia in the Columbia River due to occurrences in the Montana headwaters and the northern Washington mainstem of this river.

Although not as well studied as some invasive crayfishes, *O. virilis* has been found to compete with fishes endemic to the west for food (Carpenter 2005; Rogowski and Stockwell 2006), and to prey on fish eggs in its native range (Dorn and Mittelbach 2004). Sheldon (1989) suspected *O. virilis* competed with and displaced native *P. leniusculus* in rivers and reservoirs of western Montana. *Orconectes virilis* has apparently replaced *P. gambelii* from multiple sites where this native species historically occurred in

the Bear River drainage of southwestern Wyoming (Hubert 2010). *Orconectes virilis* has also been implicated in declines of the crayfish *P. fortis* in northern California (Bouchard 1977a; Light et al. 1995). Owing to its large native range and substantial genetic diversity (Filipova et al. 2010), the appearance of *O. virilis* can be quite variable. Body color may be brown, green, or tan. Chelae are typically green or blue-green, with pronounced yellow tubercles.

White river crawfish (*Procambarus acutus*)

The white river crawfish (*Procambarus acutus*), native over a large and disjunct range in eastern North America, has recently been documented in the Pacific Northwest. Historically, *P. acutus* was only known west of the Continental Divide from a single stream in California, where its invasion in the 1920s was attributed to the release of laboratory animals by local schools (Bouchard 1977a). Bouchard (1977a) revisited this stream a half century later and found only the red swamp crawfish (*Procambarus clarkii*), suggesting either an initial misidentification, or perhaps the subsequent replacement of *P. acutus* by *P. clarkii*. As a result, the late 2009 discovery of *P. acutus* in Echo Lake, Seattle, Washington, and the early 2010 discovery of the species from a wetland on Lopez Island, Washington, may represent the only known populations of this species in the western US (Figure 2). *Procambarus acutus* specimens from both sites were verified by Christopher Taylor and deposited at the Illinois Natural History Survey. Origins of these populations remain unknown. *Procambarus acutus* is often dark burgundy with pronounced tubercles on the chelae and carapace. *Procambarus acutus* may be distinguished from the widely invasive *P. clarkii* in the west by an open rather than closed or absent areola (hourglass-shaped area on the dorsal surface of the carapace).

Red swamp crawfish (*Procambarus clarkii*)

The red swamp crawfish *Procambarus clarkii*, native to the southern US and northeastern Mexico, is the most invasive crayfish in the world. It has been introduced to Africa, Asia, Europe, and within North America through a variety of pathways, although primarily via stocking for aquaculture or wild harvest (Hobbs et al. 1989). It is also a common species in the biological supply trade (Larson and Olden 2008). In western North America, *P. clarkii* was first brought to California in the 1930s as forage for frog farms, and was widespread from southern California to the Central Valley by the 1950s (Riegel 1959). The species was first found in the Pacific Northwest from a spring in southwestern Idaho in 1975, and then northern Utah in 1978 (Table 1; Clark and Wroten 1978; Johnson 1986). *Procambarus clarkii* was documented in wetlands of the Willamette Valley, Oregon by 1999 (Pearl et al. 2005), and from an urban lake in western Washington by 2000 (Mueller 2001). *Procambarus clarkii* has since been found in nearly a dozen lakes and wetlands of western Washington (Figure 2; Larson and Olden 2008).

Some of the many impacts of invasive *P. clarkii* populations

have included predation on amphibians (Gamradt and Kats 1996), and transformation of lakes and wetlands from clear to turbid water states through consumption of macrophyte beds and bioturbation by burrowing (Matsuzaki et al. 2009). A few studies have begun to investigate the ecology and potential impacts of *P. clarkii* in the Pacific Northwest. Mueller and Bodensteiner (2009) did not find competitive dominance of *P. clarkii* over native *P. leniusculus* under field conditions in a Washington lake. Olden et al. (2009b) observed that *P. clarkii* was less predatory on an invasive snail common to Washington than *P. leniusculus*. More work on the distribution and impacts of this invader in the Pacific Northwest is needed. *Procambarus clarkii* adults generally range from bright red to black with tubercles on the carapace and chelae, although juveniles may be lighter in color.

CRAYFISH MANAGEMENT AND REGULATIONS

Prohibited Species

Prevention is the preferred management strategy for aquatic invasive species (Vander Zanden and Olden 2008), and the complete prohibition of alien species anticipated to become invasive may be an effective and proactive first line of defense. For crayfish, this means restricting the species permitted in a region via dominant pathways of introduction, such as the aquarium, biological supply, live bait, and live seafood trades (Lodge et al. 2000; DiStefano et al. 2009; Peters and Lodge 2009). We found that the crayfish species explicitly prohibited by states and provinces of the Pacific Northwest were extremely variable as of the summer of 2010. We found no evidence that British Columbia prohibits any crayfish species. Montana explicitly prohibits only *O. rusticus*, but recognizes non-classified species alien to the state as prohibited for private possession. Idaho prohibits *O. rusticus*, the parthenogenic marbled crayfish *Procambarus* sp., and three southern hemisphere species in the genus *Cherax*. Oregon prohibits all eastern North American crayfishes in the family Cambaridae. Washington has the most restrictive regulations, prohibiting not only all crayfishes in the family Cambaridae but also all species in the southern hemisphere family Parastacidae, with exceptions for three species in the genus *Cherax* and the entire genus *Engaeus*. Characteristic of a “weak links” problem (Peter and Lodge 2009), two of these southern hemisphere species allowed in Washington — the redclaw crayfish (*Cherax quadricarinatus*) and the marron (*Cherax tenuimanus*) — are prohibited in neighboring Idaho.

Our inquiries related to prohibited species lists were often answered with the caveat that states and provinces have laws against the stocking or release of organisms into natural waters. For example, Idaho fishing regulations are typical in specifying: “It is unlawful to release or allow the release of any species of live fish (including crayfish), or fish eggs, in the state of Idaho without a permit from the director of Idaho Department of Fish and Game, except at the same time and place where caught.” We respond that such laws are important but also limited; they probably do little to deter introductions, are difficult to enforce

because violators are infrequently apprehended, and they are reactive because they apply punishments after an alien species is already introduced (Johnson et al. 2009). These laws are also predominantly published in fishing regulations and fail to address common pathways of crayfish introduction such as the aquarium or biological supply trades. Standardizing a uniform list of crayfishes prohibited (or permitted in a “white list”; Lodge et al. 2000) across states and provinces of the Pacific Northwest, and implementing their enforcement across diverse introduction pathways, is both advisable and urgently needed. Outreach and education efforts are also critical for informing the public about the existence of these laws and regulations, and the ecological and economic consequences of species invasions.

Live Bait

Crayfish invasions are often attributed to the historically common use of crayfish as live fishing bait (Lodge et al. 2000; DiStefano et al. 2009). Like regulations on prohibited species, live bait regulations vary between states and provinces of the Pacific Northwest. The most common practice, implemented by Idaho, Oregon, and Washington, is to permit the use of live crayfish only in the water body where the organism was captured. British Columbia allows live crayfish as bait in streams but not lakes, while Montana allows the use of live crayfish on all waters not restricted to artificial lures. We recommend allowing live bait only in the water where the organism was directly captured as a precautionary means of reducing risk of introductions, but others have strongly recommended complete bans on use of live crayfish as bait (Lodge et al. 2000).

Recreational Harvest

All states and provinces in the Pacific Northwest allow the recreational harvest of crayfish for personal consumption. British Columbia, Idaho, and Montana require a fishing license for recreational crayfish harvest, whereas Oregon and Washington do not. Recreational harvest is open year round in Oregon, defined by the game fish season of the water body in Idaho, and open only from the first Monday in May to October 31st in Washington. British Columbia and Montana do not specify crayfish harvest seasons in their fishing regulations. Idaho and Montana have no limits on recreational crayfish catch. British Columbia allows 25 crayfish in possession, Oregon allows 100 crayfish harvested per day with two limits in possession, and Washington allows 10 lbs. in shell per day. Only British Columbia (9 cm) and Washington (3 ¼ in or 8.3 cm) publish minimum total lengths for harvestable crayfish in the recreational fishery. Gear allowed ranges from any number or size of traps in British Columbia to a limit of five units of gear (traps or pots) per person in both Idaho and Washington. Idaho and Montana set limits for maximum trap sizes, and Idaho and Oregon allow other techniques like hand nets, baited lines, or seines. All states and provinces require the release of female crayfish with eggs in both recreational and commercial fisheries, although Washington excludes invasive crayfishes from this regulation.

The increasingly widespread presence of alien crayfishes

Figure 3. An excerpt from the 2010 Washington Department of Fish and Wildlife fishing regulations addressing the harvest of native and alien crayfish and their identification.

CRAYFISH (Crawfish)			
ALL WATERS	NATIVE SPECIES	1 st Mon. in May-Oct. 31	Min. size 3/4" from tip of rostrum (nose) to tip of tail. Daily limit 10 lbs in shell. All females with eggs or young attached must be immediately returned to the water unharmed. No Shellfish/Seaweed license is required. See gear rules on page 139.
	NONNATIVE SPECIES	1 st Mon. in May-Oct. 31	Must be kept in a separate container. Must be dead before being removed from riparian area (immediate vicinity of water body). No daily limit, size, or sex restrictions. No Shellfish/Seaweed license is required. See gear rules page 139.

There is only one native crayfish species in Washington – the signal crayfish (*Pacifastacus leniusculus*). This species can be identified by its uniform brownish coloration, white or light coloration of the claw joint, and the smooth surface of its carapace and claws compared to that of nonnative species. **Native crayfish are the only crayfish that may be removed from the vicinity of the waterbody alive.** If you cannot positively identify your catch as a nonnative species, the daily limit and other restrictions listed above for native crayfish apply.

Native Signal Crayfish
(*Pacifastacus leniusculus*)

White or light-colored claw joints

No pronounced bumps or distinct dark tips on claws

Claws can range in color from blue or green with red underneath

Photo - Eric Larson UW

Nonnative Rusty Crayfish

Dark patch

Dark spot

Illustration - Jeff Gunderson MN SeaGrant

Nonnative Red Swamp Crayfish claw

Pronounced bumps on claws

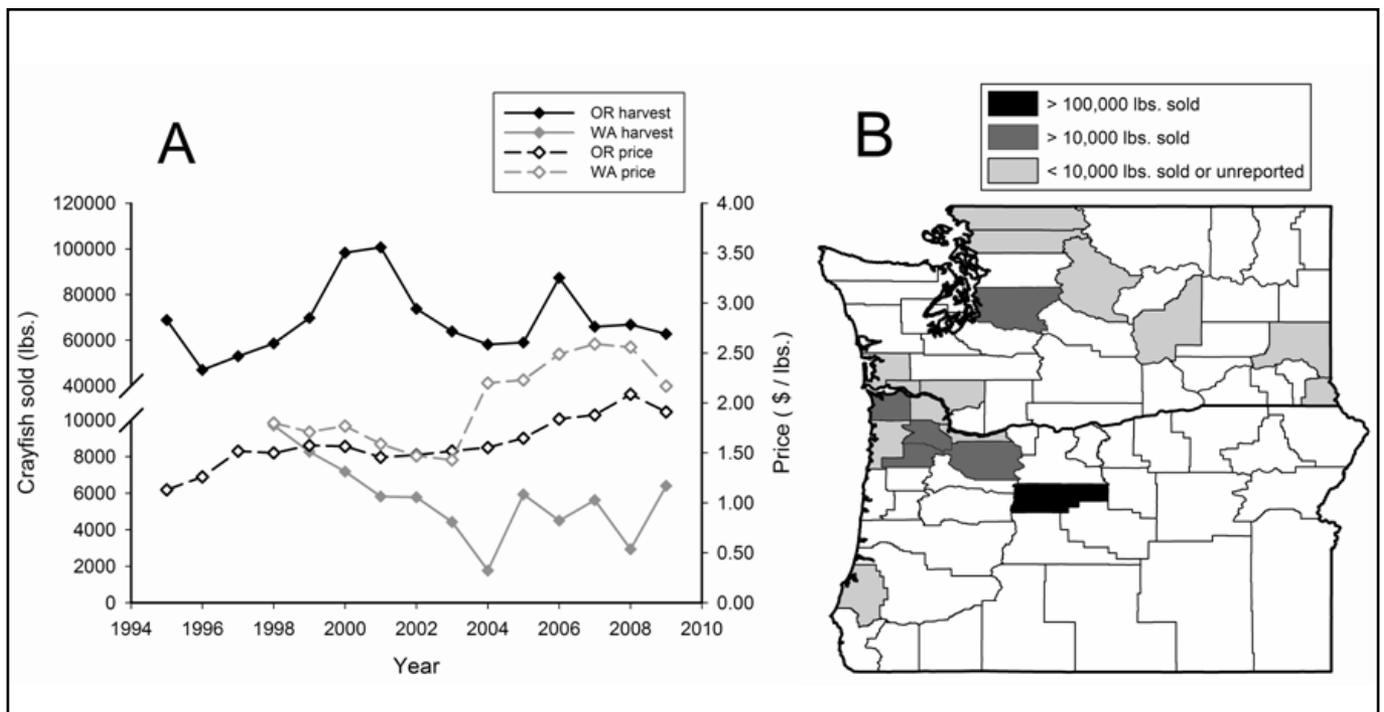
Nonnative Northern Crayfish claw

Claw Photos - Julian Olden

How to humanely kill and preserve crayfish

There are two important steps to killing a crayfish quickly and humanely. The first is to chill them in ice or ice slurry for 20-30 minutes, and the second is to pierce their head with a knife.

Figure 4. Commercial crayfish harvest in Oregon and Washington as A. lbs. sold and price per lb. by year; B. cumulative lbs. sold by county between 2004 and 2009.



in the Pacific Northwest raises challenges for both recreational and commercial harvest (see below). While it seems reasonable to allow the harvest of alien crayfishes that are now well-established in the region, valid concern exists over the potential for harvest to encourage subsequent illegal introductions by the public (Johnson et al. 2009). In 2010, Washington revised their fishing regulations to address this concern, allowing the harvest of invasive crayfishes such as *O. virilis* or *P. clarkii* but specifying that these species cannot be transported live (Figure 3). Implementation of this regulation may be challenged by the preference of most harvesters to transport or store crayfish live in shell until the time of consumption (Momot 1991). Washington fishing regulations provide an identification guide for native and alien crayfishes and recommendations for humane euthanasia of crayfish (Figure 3). The presence of alien crayfishes in the Pacific Northwest complicates the management of both recreational and commercial fisheries. The popularity and spatial distribution of recreational crayfish harvest in the region is worth quantifying, perhaps through a mail survey of fishing license holders or a no-cost crayfish recreational license.

Commercial Harvest

The legality and popularity of commercial harvest of crayfish varies across the Pacific Northwest. British Columbia provides little information on the status of commercial harvest in the province. Montana prohibits commercial harvest of crayfish, resulting from public concerns that crayfish might be over-harvested or that commercial harvest might negatively affect sport fish dependent on crayfish (Sheldon 1989). Idaho allows commercial harvest in select rivers and lakes from April 1st to October 31st, defines a minimum harvestable size for crayfish (3 5/8 in or 9.2 cm total length), allows only the harvest of *Pacifastacus* species, and reports no catch statistics.

Relative to their Pacific Northwest neighbors, Oregon and Washington harvest a large volume of crayfish commercially. Washington issued between 3 and 13 commercial crayfish permits annually between 1998 and 2009, with a mean of 5,697 lbs. and maximum of 9,710 lbs. sold (Figure 4). The majority of Washington's commercial crayfish harvest occurs in large lakes of King County in proximity to Seattle, although some harvest is reported from the Columbia and Snake rivers (Figure



Common invasive crayfishes in the Pacific Northwest: A. ringed crayfish (*Orconectes neglectus*); B. rusty crayfish (*Orconectes rusticus*); C. virile crayfish (*Orconectes virilis*); D. red swamp crawfish (*Procambarus clarkii*). Photos by J. Ludlam (A), the authors (B, C), and F. Tomasinelli (D).

4). Crayfish have recently sold for between \$1.50 and \$2.50 per lb. in Washington (Figure 4). The season and minimum size of harvestable crayfish is the same as for the recreational fishery. Commercial harvesters are restricted to a total of 400 traps or pots on a license, smaller lakes with large public parks or extensive residential development are prohibited for harvest, and the number of traps allowed on a lake is scaled to the lake's surface area. Washington requires traps to have individual lines and buoys labeled with the harvester's name and address, and it also requires that traps have a biodegradable release device to disable the trap if lost or not recovered.

The commercial crayfish harvest in Oregon is a degree of magnitude larger than in Washington, and has an interesting history recounted in Miller and Van Hyning (1970) and Lewis (1997). Miller and Van Hyning (1970) summarize the history of commercial crayfish harvest in Oregon from its inception in the 1890s, documenting fluctuations in popularity with the Great Depression and both World Wars, and report a maximum historic crayfish harvest of 176,000 lbs. sold in 1930. Historic uses of harvested crayfish ranged from fishing bait, to free food at depression-era lunch counters, to export in the seafood trade to Europe (Momot 1991). More recently, a mean of 72,081 lbs. has been sold per year with a maximum of 100,698 lbs. sold (Figure 4). The lower Columbia River and adjacent areas in western Oregon are popular sites for commercial crayfish harvest (Figure 4; Miller and Van Hyning 1970), but Jefferson County, Oregon dominates the commercial harvest with a sum of 189,769 lbs. of crayfish sold between 2004 and 2009 (Figure 4). This may be attributable to a popular fishery in Lake Billy Chinook, including a tribal fishery by the Confederated Tribes of Warm Springs (Lewis 1997). Oregon no longer issues and enumerates permits exclusively for commercial crayfish harvest, but rather crayfish can be harvested under a general commercial fishing permit. Commercial crayfish regulations resemble those of Washington, but with an April 1st to October 31st open season, and a larger minimum size of 3⁵/₈ in or 9.2 cm total length.

DISCUSSION

The conservation status of native species is often uncritically assumed secure for too long. The bull trout (*Salvelinus confluentus*) is a representative example from the Pacific Northwest, in which a species progressed over the course of a century from long-neglected to belatedly protected under the US Endangered Species Act (Rieman et al. 1997). We have summarized here the state of knowledge on native crayfishes in the Pacific Northwest to prevent a similar such progression, which has already occurred in adjacent California (Bouchard 1977a; Light et al. 1995). We recommend the following as the most urgent needs for native crayfish research and conservation in the Pacific Northwest: documenting the present distributions of native crayfishes and comparing them to the best available historic benchmarks (Figure 1); evaluating conservation statuses relative to threats like land use change and prevalence of invasive species; and quantifying the life history and ecological attributes of these species, particularly in contrast to the invasive crayfishes that are increasingly common in the region (Figure 2).

It is now well-established that the ecological function of one crayfish species does not equal that of another (e.g., McCarthy et al. 2006; Olsson et al. 2009). Invasive crayfishes in the Pacific Northwest should be anticipated to interact with native communities, ecosystems, or valuable fisheries in ways that differ from native *Pacifastacus* species, particularly owing to the wide evolutionary separation between the Cambarid crayfishes of eastern North America and Astacid crayfishes of western North America. Research should be directed at evaluating these differences as well as developing management and control options for invasive crayfishes (Freeman et al. 2010). Ample experience from other regions of the world suggests that invasive crayfishes will have unwanted impacts in the Pacific Northwest (McCarthy et al. 2006; Matsuzaki et al. 2009), and consequently immediate precautionary measures should be taken to prevent additional introductions. States and provinces in the Pacific Northwest need to agree on a region-wide black list of prohibited, or white list of permitted, crayfishes and pursue its enforcement, including oft-neglected pathways, such as the aquarium and biological supply trades (Lodge et al. 2000; Keller and Lodge 2007). The use of crayfish as live bait cannot be unrestricted; at a minimum, crayfish should only be permitted as bait in the water where directly collected by the angler. The management of recreational and commercial crayfish harvest must adjust to the increasingly common occurrence of invasive crayfishes in the region and take measures to discourage the illegal stocking of these crayfishes for harvest (Johnson et al. 2009).

The recreational and commercial harvest of crayfish has a long and interesting history in the Pacific Northwest (Miller and Van Hyning 1970), and represents a significant economic commodity (Figure 4). Evaluations of the efficacy of fishing regulations for crayfish are rare (but see Lewis 1997), and some evidence indicates that the harvest of crayfish can affect broader aquatic communities (Roell and Orth 1988). Quantifying the extent and popularity of recreational harvest of crayfishes in the Pacific Northwest would be valuable, and could be used to target outreach materials for discouraging illegal stocking of invasive crayfishes. Lakes and rivers with active commercial crayfish harvest would benefit from evaluation of the effectiveness of regulations in protecting both crayfish populations and other members of the aquatic community.

Over the journal's history, *Fisheries* has published multiple reviews on the state of crayfish management and conservation in North America (Bouchard 1978; Momot 1991; Lodge et al. 2000; Taylor et al. 2007). Many of these papers have made reasonable and legitimately urgent management recommendations that have yet to see wide implementation (DiStefano et al. 2009; Peters and Lodge 2009). We have added to this literature by summarizing the state of crayfish in the Pacific Northwest, and found the conservation status of native crayfishes to be poorly known, invasive crayfishes to be increasingly widespread, and adjacent states and provinces to be pursuing inconsistent regulations related to crayfish management. Basic research by fisheries biologists and coordination among state, provincial, and federal managers is needed to safeguard populations of native crayfishes and minimize the threat of invasive crayfishes in the Pacific Northwest, and we hope that our review provides an impetus for such a response.

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