# Feature:
## CONSERVATION MANAGEMENT

# Conservation and Management of Crayfishes: Lessons from Pennsylvania

**David A. Lieb**
**Invertebrate zoologist/non-game biologist, Pennsylvania Fish and Boat Commission and Western Pennsylvania Conservancy, Bellefonte, Pennsylvania, c-dlieb@state.pa.us. (Note: During this project, Lieb was a Ph.D. student and graduate research assistant at The Pennsylvania State University, University Park, Pennsylvania.)**

**Raymond W. Bouchard**
**Academy Fellow, Patrick Center for Environmental Research, The Academy of Natural Sciences, Philadelphia, Pennsylvania**

**Robert F. Carline**
**Fisheries biologist, U.S. Geological Survey (retired)**

**Ted R. Nuttall**
**Professor of Biology, Department of Biology, Lock Haven University, Lock Haven, Pennsylvania**

**John R. Wallace**
**Professor of Biology, Department of Biology, Millersville University, Millersville, Pennsylvania**

**Carrie L. Burkholder**
**CET Engineering Services, Harrisburg, Pennsylvania**



ABSTRACT: *North America's crayfish fauna is diverse, ecologically important, and highly threatened. Unfortunately, up-to-date information is scarce, hindering conservation and management efforts. In Pennsylvania and nearby states, recent efforts allowed us to determine the conservation status of several native crayfishes and develop management strategies for those species. Due to rarity and proximity to urban centers and introduced (exotic) crayfishes,* Cambarus (Puncticambarus) *sp., an undescribed member of the* Cambarus acuminatus *complex, is critically imperiled in Pennsylvania and possibly range-wide.* Orconectes limosus *is more widespread; however, recent population losses have been substantial, especially in Pennsylvania and northern Maryland, where its range has declined (retreated eastward) by greater than 200 km. Introduced congeners likely played a major role in those losses. Although extirpated from some areas,* Cambarus bartonii bartonii *remains widespread and is not an immediate conservation concern. In light of these findings, the role of barriers (e.g., dams), environmental protection, educational programs, and regulations in preventing crayfish invasions and conserving native crayfishes is discussed, and management initiatives centered on those factors are presented. The need for methods to eliminate exotics and monitor natives is highlighted. Although tailored to a specific regional fauna, these ideas have broad applicability and would benefit many North American crayfishes.*

## Conservación y Manejo de Langostillas: Lecciones de Pennsylvania

RESUMEN: las langostillas de Norteamérica son diversas, ecológicamente relevantes y considerablemente amenazadas. Infortunadamente, a la fecha la información es escasa lo cual dificulta su conservación y manejo. En Pennsylvania y estados aledaños, esfuerzos recientes han permitido determinar el estado de conservación de varias langostillas autóctonas y desarrollar estrategias de manejo para las mismas. Debido a su rareza, proximidad a centros urbanizados e introducción de las langostillas (foráneas), la especie *Cambarus* (*Puncticambarus*) sp., miembro desconocido del complejo *Cambarus acuminatus*, se encuentra en peligro crítico en Pennsylvania y posiblemente también en el resto de su distribución. *Orconectes limosus* presenta una distribución más amplia; sin embargo recientemente ha habido una pérdida importante de sus poblaciones, particularmente en Pennsylvania y al norte de Maryland, lugar donde su distribución se ha reducido (retrocediendo hacia el este) en unos unos 200 km. Es muy posible que los congéneres introducidos hayan jugando un papel predominante en estas pérdidas. *Cambarus bartonii bartonii*, aunque extirpada de algunas zonas, continúa siendo de amplia distribución y no se encuentra en peligro inmediato en términos de conservación. A la luz de estos resultados, se discute la importancia relativa que las barreras (presas), protección ambiental, programas educativos y regulaciones han tenido en cuanto a la prevención de invasiones y conservación de langostillas nativas. Así mismo se presentan iniciativas de manejo centradas en dichos factores. Se resalta la necesidad de métodos para eliminar especies exóticas y monitorear las nativas. Estas ideas, aunque diseñadas para una fauna regional particular, entrañan una aplicabilidad más amplia y beneficiarían diversas langostillas Norteamericanas.

## Introduction

North America is home to a diverse, ecologically important crayfish fauna that is threatened by human activities (Master et al. 1998; Wilcove et al. 1998; Lodge et al. 2000a; Taylor et al. 2007). Until recently, the conservation and management of those species has been a low priority for most state, federal, and academic institutions. The recent publication of several large-scale conservation assessments, which suggest that about half of North America's crayfishes are imperiled across all or parts of their range (Taylor et al. 1996, 2007; Master et al. 1998, 2000), greatly increased awareness and interest in the group.

Although more focused efforts in particular regions followed, the accurate classification (e.g., vulnerable, secure) of many species remains hampered by a lack of up-to-date distributional and ecological information (Taylor et al. 2007; Simmons and Fraley 2010). This is problematic because such classifications often provide the basis for assigning conservation priorities at the local and national levels (Possingham et al. 2002). Thus, incorrect classifications may be costly, resulting in biodiversity losses and wasted resources.

In Pennsylvania and nearby states, recent efforts combined with historical data (Table 1) allowed us to accurately classify most of eastern Pennsylvania's native, surface-dwelling crayfish species: (1) *Cambarus bartonii bartonii*; (2) *Cambarus* (*Puncticambarus*) sp., an undescribed member of the *Cambarus acuminatus* complex; and (3) *Orconectes limosus*. Our ability to assess changes in the crayfish fauna at individual sites and across the landscape was a key element in this process. We also developed a number of management strategies that should aid in the conservation of those species.

Because *Procambarus clarkii*, *Cambarus robustus*, *Orconectes obscurus*, *Orconectes rusticus*, and *Orconectes virilis* have been introduced to eastern Pennsylvania and *Procambarus acutus* has greatly expanded its range in the region as a result of human activities (Bouchard et al. 2007; Lieb et al. 2007a, 2011), the aim of many of these management strategies is to prevent additional crayfish introductions. Successful prevention is of vital importance because introduced (exotic) crayfishes are one of the biggest threats to native crayfishes in North America and elsewhere (Lodge et al. 2000a; Taylor 2002; Taylor et al. 2007). Although stopping the spread of exotic crayfish is difficult once they become widespread (Peters and Lodge 2009), the distributions of most introduced crayfishes in eastern Pennsylvania are still limited (Bouchard et al. 2007; Lieb et al. 2007a, 2011). Thus, in eastern Pennsylvania, as in much of North America, there is still time to stop the spread of introduced crayfishes and preserve the native stocks that remain. Although tailored to a specific fauna, the management strategies presented herein have broad applicability and would likely benefit many of North America's crayfishes, as well as other aquatic invertebrate species of concern.

TABLE 1. Historical and contemporary crayfish studies that aided in the development of the conservation classifications (e.g., vulnerable, secure) and management strategies provided herein. Studies are listed by state (United States) or province (Canada). "Statewide" refers to studies that include most of the state; NPS=National Park Service, PA=Pennsylvania.

| State/province | Coverage | Source |
|---|---|---|
| Historical | | |
| Maryland | Statewide<br>Patapsco River drainage | Meredith and Schwartz 1960<br>Schwartz et al. 1963 |
| New York | Statewide | Crocker 1957 |
| Pennsylvania | Statewide<br>Statewide | Ortmann 1906<br>Bouchard et al. 2007[a] |
| West Virginia | Northern part of the state | Ortmann 1906 |
| Contemporary | | |
| Maryland | Statewide | Kilian et al. 2010 |
| New York | Upper Susquehanna River drainage<br>Schoharie Creek drainage | Kuhlmann and Hazelton 2007<br>Daniels 1998 |
| North Carolina | Western part of the state | Simmons and Fraley 2010 |
| Pennsylvania | Statewide with emphasis on eastern PA<br>NPS properties across the state<br>Valley Creek<br>Valley Creek<br>Southeastern part of the state<br>Southeastern part of the state | Bouchard et al. 2007<br>Lieb et al. 2007a<br>Lieb et al. 2007b<br>Lieb et al. 2008<br>Lieb and Bhattarai 2009<br>Lieb et al. 2011 |
| West Virginia | Statewide<br>Statewide<br>Statewide<br>Eastern Potomac River drainage | Jezerinac et al. 1995<br>Loughman et al. 2009<br>Loughman and Welsh 2010<br>Swecker et al. 2010 |
| Ontario | South-central part of the province | Edwards et al. 2009 |

[a]Includes historical museum records.

# Methods

## Assessing Changes at Individual Sites and across the Landscape

Eleven sites in the Potomac and Susquehanna drainages of Pennsylvania that historically supported *O. limosus* and/or *C. b. bartonii* were resurveyed (Table 2). Nine were from Ortmann (1906); two were from the United States National Museum, Smithsonian Institution (USNM 46320 and 48413 [Conoy Creek]; USNM 310622 [Penns Creek tributary]). USNM data included catch numbers for each species; Ortmann's data were presence/absence. In most cases, historical site descriptions were limited to stream and town names, and contemporary collections were made as close to those towns as possible. The exception was a site whose historical description was "tributary of Penns Creek, two miles west of New Berlin." Because the name of the stream was unknown, we surveyed Sweitzers Run and Tuscarora Creek, the only major Penns Creek tributaries located less than 4.8 km (3 miles) west of New Berlin.

Contemporary collections included a thorough search of multiple riffle-pool sequences and all available habitat types, which is an effective method for determining community composition and compiling species lists for individual sites (see Bouchard et al. 2007; Lieb et al. 2007a, 2011 for additional details). Historical collection methods are available from Ortmann (1906) or are unknown (USNM data). Resampling efforts at *O. limosus* and/or *C. b. bartonii* sites in the Delaware basin of Pennsylvania and nearby states are described elsewhere (Schwartz et al. 1963; Daniels 1998; Kuhlmann and Hazelton 2007; Loughman et al. 2009; Kilian et al. 2010; Loughman and Welsh 2010; Swecker et al. 2010; Lieb et al. 2011).

TABLE 2. Historical and contemporary crayfish collections from resampled sites in the Susquehanna (S) and Potomac (P) River drainages of Pennsylvania. Historical data were collected in 1912 (Conoy Creek), 1956 (Penns Creek tributary), or were taken from Ortmann (1906), who did not provide collection dates for individual sites. Contemporary data were collected in 2006 and 2007. R=Raystown, Br=Branch, Cr=Creek, R=River, Trib=Tributary, NA=Not available, *bartonii=Cambarus bartonii bartonii, limosus=Orconectes limosus, obscurus=Orconectes obscurus, rusticus=Orconectes rusticus, virilis=Orconectes virilis.*

| Stream (drainage) | County | Nearby town | Lat, Long (decimal°) | Historical | | Contemporary | |
|---|---|---|---|---|---|---|---|
| | | | | Species | *n* | Species | *n* |
| Back Cr (P) | Franklin | Williamson | 39.85422, −77.79622 | *limosus* | NA | *virilis* | 18 |
| Conococheague Cr (P) | Franklin | Chambersburg | 39.96102, −77.64832 | *bartonii*<br>*limosus* | NA<br>NA | *bartonii*<br>*obscurus*<br>*virilis* | 1<br>8<br>11 |
| Conococheague Cr (P) | Franklin | Williamson | 39.84675, −77.79425 | *limosus* | NA | *bartonii*<br>*obscurus*<br>*virilis* | 1<br>10<br>37 |
| Bald Eagle Cr (S) | Centre | Milesburg | 40.94309, −77.78700 | *bartonii*<br>*limosus* | NA<br>NA | *obscurus* | 25 |
| Conoy Cr (S) | Lancaster | Bainbridge | 40.08473, −76.66097 | *bartonii* | 20 | *rusticus* | 82 |
| Conodoquinet Cr (S) | Cumberland | West Fairview | 40.25543, −76.92745 | *limosus* | NA | *rusticus* | 22 |
| Fishing Cr (S) | Columbia | Bloomsburg | 40.99537, −76.47353 | *limosus* | NA | *obscurus* | 26 |
| Montour Cr (S) | Perry | Green Park | 40.35842, −77.31798 | *bartonii*<br>*limosus* | NA<br>NA | *obscurus*<br>*rusticus* | 3<br>55 |
| R Br Juniata R (S) | Bedford | Bedford | 40.02013, −78.50278 | *limosus* | NA | *obscurus* | 7 |
| Trib of Penns Cr (S) | Union/Snyder | New Berlin | Two possibilities[a] | *limosus* | 1 | *bartonii*<br>*obscurus*<br>*rusticus* | 10[b]<br>17[b]<br>56[b] |
| Yellow Breeches Cr (S) | Cumberland/York | New Cumberland | 40.22395, −76.86070 | *limosus* | NA | *rusticus* | 39 |

[a]40.87208, -77.01345 (Sweitzers Run) or 40.86767, -77.00650 (Tuscarora Creek); see methods for further explanation.
[b]Total for Sweitzers Run and Tuscarora Creek.



Assessments of change at larger scales were possible because of the availability of contemporary and historical crayfish data from a substantial part of the native ranges of *C. b. bartonii*, *C.* (*P.*) sp., and *O. limosus* (see Table 1 and range information in Hobbs 1989; Jezerinac et al. 1995; Lieb et al. 2011). Coverage of Pennsylvania, Maryland, and West Virginia was especially complete, allowing a particularly clear picture of change in those areas.

To illustrate change in Pennsylvania, maps showing historical and contemporary crayfish distributions were created (Figures 1–5). For *O. limosus*, historical data were collected prior to 1957 and contemporary data were collected from 1984 to 2007 (no data available from 1957 to 1983). For *O. obscurus*, historical data were collected prior to 1912 and contemporary data were collected from 1965 to 2007 (no data available from 1912 to 1964). For *C. b. bartonii*, the data were split approximately in half: historical data were collected prior to 1960 and contemporary data were collected from 1964 to 2006 (no data available from 1960 to 1963). For recent invaders, only contemporary data were available (*O. rusticus:* 1976 to 2006, *O. virilis*: 1986 to 2007). Some data could not be mapped because of incomplete site descriptions (e.g., only a county name provided). Similar maps for Maryland were published by Kilian et al. (2010).

## Conservation Classifications

Conservation classifications from published sources and updated classifications developed for this study are provided in Table 3. Published classifications are from the American Fisheries Society (AFS) Endangered Species Committee (Taylor et al. 2007) and the National Heritage Network (NHN; NatureServe 2010). Updated classifications relied heavily on range extent, number of populations, changes at individual sites and across landscapes, and threats to existing populations and were based on criteria and classification definitions provided by

TABLE 3. Conservation classifications for several of eastern Pennsylvania's native crayfishes. Abbreviations used: CS=Currently stable; G5, S5 (species classification) and T5 (subspecies classification)=Secure; S4=Apparently secure; S3=Vulnerable; S1=Critically imperiled; NL=Not listed; AFS=American Fisheries Society; NHN=National Heritage Network; *C.=Cambarus*; *O.=Orconectes*; *b.=bartonii*; *P.=Puncticambarus*. Updated classifications were developed for this study. An asterisk (*) indicates that more information is needed to update the classification. See methods for further explanation of classification procedures and sources.

| | Global | | | Pennsylvania | |
|---|---|---|---|---|---|
| Species | AFS | NHN | Updated | NHN | Updated |
| *C. b. bartonii* | CS | G5T5 | G5T5 | S5 | S5 |
| *C.* (*P.*) sp. | NL | NL | * | NL | S1 |
| *O. limosus* | CS | G5 | * | S4 | S3 |

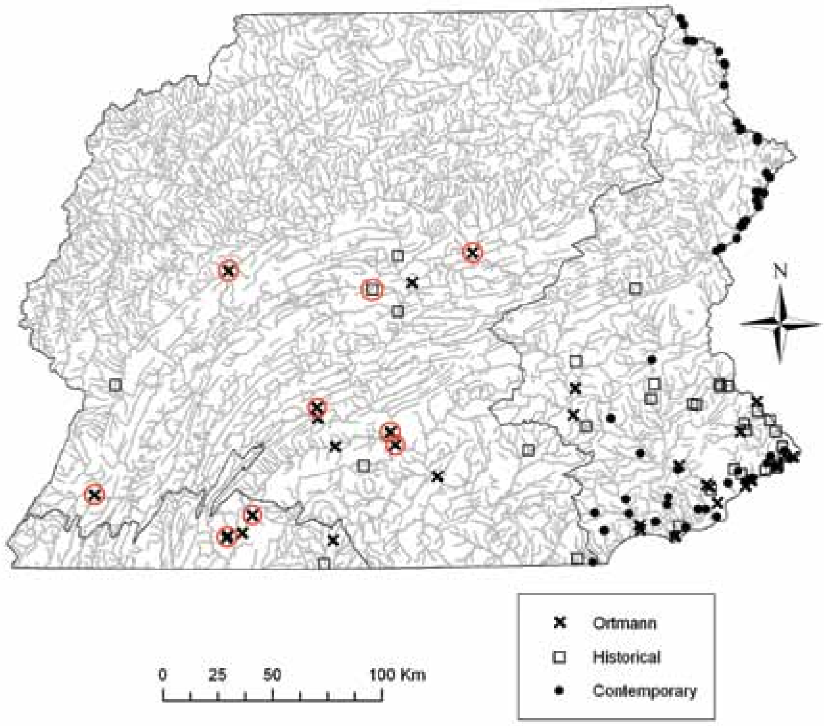


**Figure 1.** Map of eastern Pennsylvania with historical and contemporary *Orconectes limosus* collection sites. Sites from Ortmann (1906) are plotted separately from the remaining historical data. From east to west, the Delaware, Susquehanna, and Potomac River drainages are delineated. For simplicity, streams that flow directly into the Chesapeake Bay are included in the Susquehanna drainage. Historical *O. limosus* sites in the Susquehanna and Potomac drainages that were resurveyed for crayfishes are circled; *O. limosus* was not found at any of them. Because the Back and Conococheague Creek sites near the town of Williamson (Potomac drainage) are close together, their site markers overlap. See Table 2 and Methods for additional details. Modified from Bouchard et al. (2007).

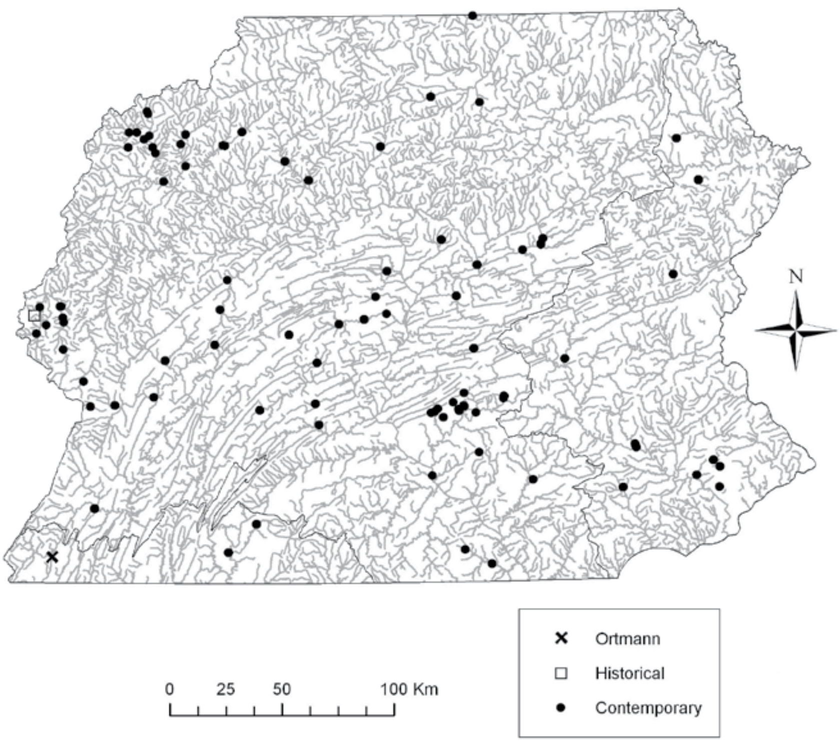


**Figure 2.** Map of eastern Pennsylvania with historical and contemporary *Orconectes obscurus* collection sites. The Ortmann (1906) site is plotted separately from the other historical site. From east to west, the Delaware, Susquehanna, and Potomac River drainages are delineated. For simplicity, streams that flow directly into the Chesapeake Bay are included in the Susquehanna drainage. See Table 2 and Methods for additional details. Modified from Bouchard et al. (2007).

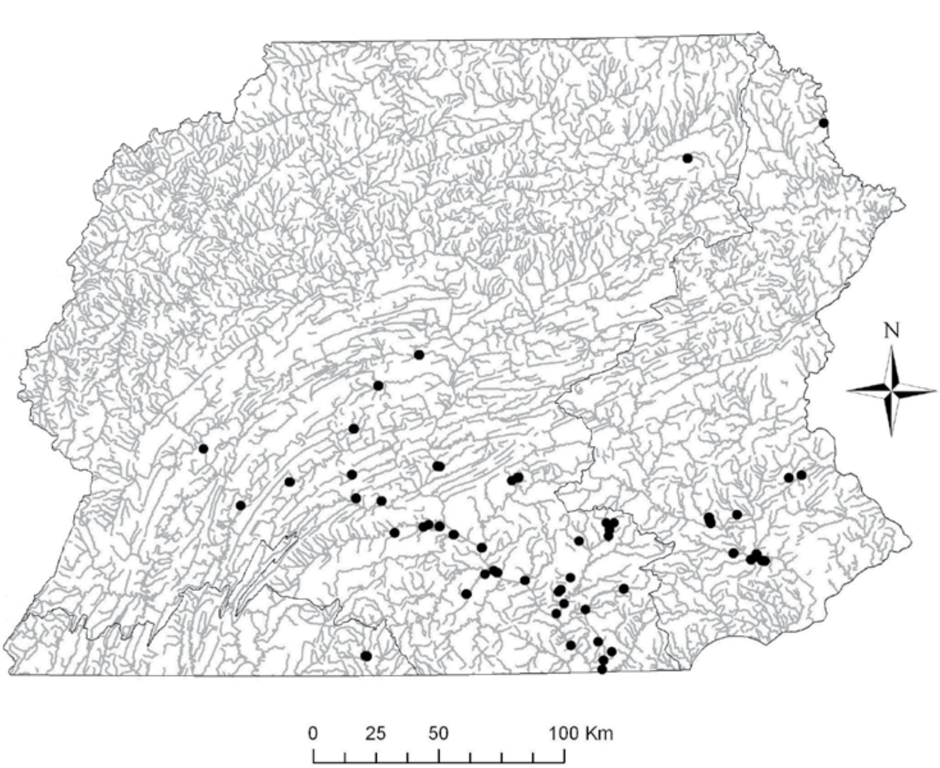


Figure 3. Map of eastern Pennsylvania with *Orconectes rusticus* collection sites. From east to west, the Delaware, Susquehanna, and Potomac River drainages are delineated. For simplicity, streams that flow directly into the Chesapeake Bay are included in the Susquehanna drainage. See Table 2 and Methods for additional details. Modified from Bouchard et al. (2007).

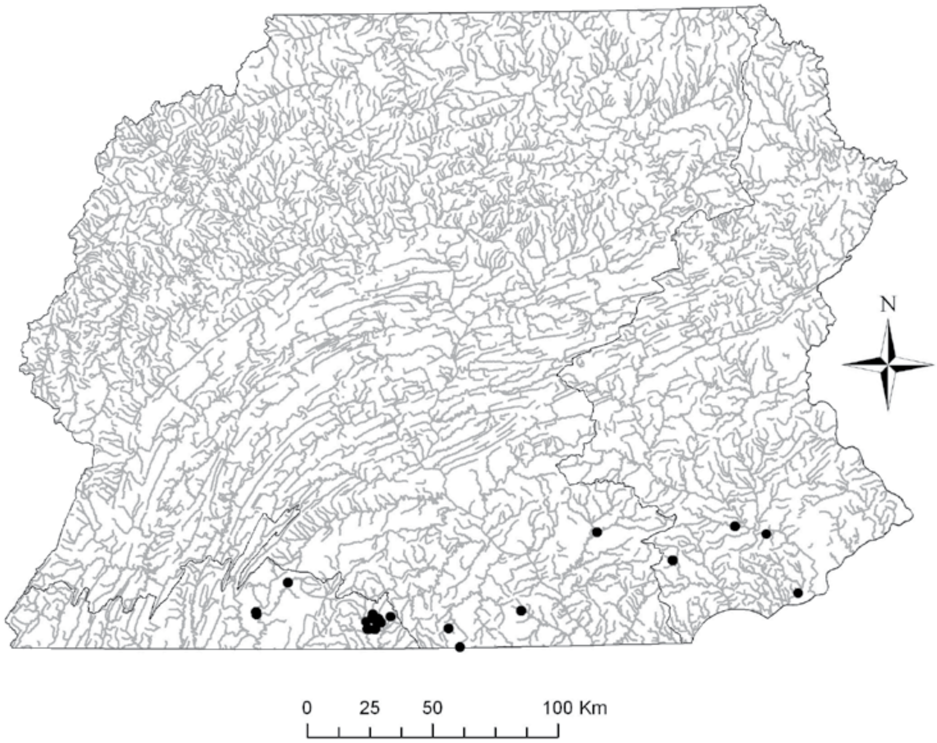


Figure 4. Map of eastern Pennsylvania with *Orconectes virilis* collection sites. From east to west, the Delaware, Susquehanna, and Potomac River drainages are delineated. For simplicity, streams that flow directly into the Chesapeake Bay are included in the Susquehanna drainage. Because the Back and Conococheague Creek sites near the town of Williamson (Potomac drainage) are close together, their site markers overlap. See Table 2 and Methods for additional details. Modified from Bouchard et al. (2007).

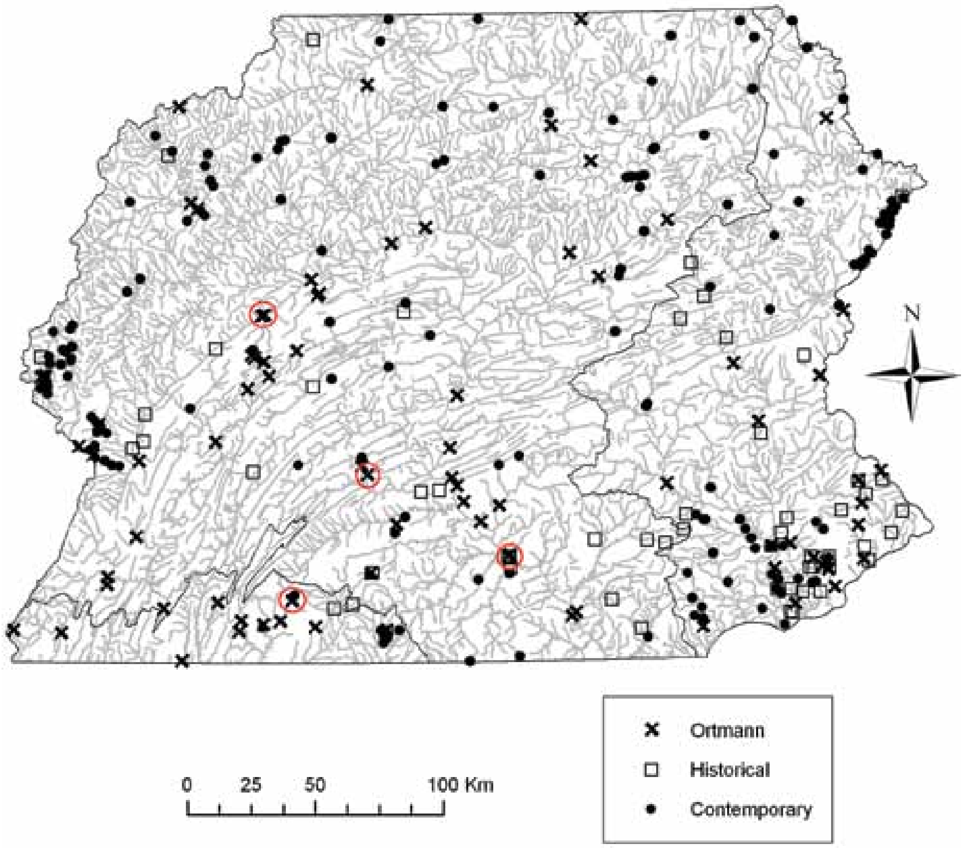


**Figure 5. Map of eastern Pennsylvania with historical and contemporary *Cambarus bartonii bartonii* collection sites. Sites from Ortmann (1906) are plotted separately from the remaining historical data. From east to west, the Delaware, Susquehanna, and Potomac River drainages are delineated. For simplicity, streams that flow directly into the Chesapeake Bay are included in the Susquehanna drainage. Historical *C. b. bartonii* sites in the Susquehanna and Potomac drainages that were resurveyed for crayfishes are enclosed by circles; *C. b. bartonii* was not found at three of them. See Table 2 and Methods for additional details. Modified from Bouchard et al. (2007).**

NHN. Due to the availability of historical and contemporary data, we were able to develop updated classifications for Pennsylvania (Table 3); those for Maryland and West Virginia are provided elsewhere (Kilian et al. 2010; Loughman and Welsh 2010). An updated range-wide classification is provided for *C. b. bartonii*. The range-wide status of *O. limosus* and *C.* (*P.*) sp. is discussed; however, updated classifications at that scale await the completion of additional taxonomic, genetic, and distributional studies.

## Conservation Classifications

### *Cambarus* (*Puncticambarus*) sp.

*Cambarus* (*P.*) sp. was recently discovered in Pennsylvania and has an extremely limited distribution in the state (Bouchard et al. 2007; Lieb et al. 2007b, 2008, 2011). More specifically, the species is only known from 13 sites in a small area (approximately 220 km$^2$) of southeastern (SE) Pennsylvania. Only four streams (Crum, Darby, Pickering, and Valley creeks) are known to support populations of *C.* (*P.*) sp. One of those populations (Valley Creek) was recently invaded by *O. rusticus* and appears to be in decline; the others are located close to dense populations of several exotic crayfishes, including *O. rusticus* (Lieb and Bhattarai 2009; Lieb et al. 2011). All four populations are in a rapidly urbanizing area within approximately 30 km of one of North America's largest cities (Philadelphia; Lieb et al. 2011).

Outside of Pennsylvania, the *C. acuminatus* complex occurs in central Maryland, Virginia, North Carolina, and South Carolina (Meredith and Schwartz 1960; Taylor et al. 2007; Kilian et al. 2010). *C.*(*P.*) sp. is not one of the described species in the complex from North Carolina and South Carolina (Lieb et al. 2008), where the complex is reasonably well known (Cooper 2001, 2006; Cooper and Cooper 2003). Much less is known to the north of the Carolinas, where additional taxonomic, distributional, and possibly genetic work is needed to determine whether members of the complex consist of one widely distributed species or multiple species with more restricted ranges.

Regardless, because historical collections from Pennsylvania do not include the *C. acuminatus* complex (Ortmann 1906), *C.* (*P.*) sp. is either an introduced species or a recently discovered native. Generally, the presence of a species where it was historically absent would suggest an introduction; however, historical data are not available for any of the sites where C. (*P.*) sp. is found (Ortmann 1906; Lieb et al. 2011).

Some authors cite the presence of disjunct distributions as evidence for crayfish introductions (Bouchard 1976b; Crocker 1979; Jezerinac et al. 1995). Although the distribution of the *C. acuminatus* complex is clearly disjunct, with populations in Pennsylvania separated from those in Maryland by approximately 125 km (Meredith and Schwartz 1960; Kilian et al. 2010; Lieb et al. 2011), introductions are probably not the cause. First, members of the *C. acuminatus* complex (*acuminatus* species) are not typically introduced outside of their native ranges (Hobbs et al. 1989; Rodriguez and Suarez 2001; Taylor et al. 2007), probably because they are generally not sold as bait or through biological warehouses. Second, naturally adjacent but disjunct ranges have been documented for other *Puncticambarus* species in eastern North America (Hobbs 1969). Third, it is possible that additional populations of the *C. acuminatus* complex once occurred in northern Maryland and southern Pennsylvania but that anthropogenic disturbances, such as crayfish introductions and urbanization, led to their elimination, resulting in the disjunct distribution currently observed. This is especially likely along the I-95 corridor from Washington, D.C. to Philadelphia, which is highly degraded and infested with exotic crayfishes (see Bouchard et al. 2007; Elmore and Kaushal 2008; Lieb et al. 2011). Such a scenario is similar to that suspected for another *Puncticambarus* species, *Cambarus veteranus*, which was believed to occur in two disjunct clusters of sites (one in West Virginia and one near the border of Virginia and Kentucky) due, at least partly, to the adverse effects of coal mining in intervening areas (Jezerinac et al. 1995). Finally, it is possible that in Pennsylvania and Maryland the range of the *C. acuminatus* complex is naturally disjunct but the degree of separation between clusters of sites has been exaggerated by extirpations in intervening areas.

Given these possibilities, the most likely scenario is that one or more species in the *acuminatus* complex once occupied a wider range in Maryland and Pennsylvania (although their distributions may have always been restricted as is common for species of *Puncticambarus*; Hobbs 1969, 1989) but that human activities reduced the range of the complex to two relic groups of populations. Therefore, C. (*P.*) sp. is likely native to Pennsylvania and has a very limited distribution in the state. The absence of C. (*P.*) sp. from the historical record is not surprising given that past surveys did not include some parts of SE Pennsylvania (Ortmann 1906). Thus, although historical surveys were sufficient to characterize the distribution of widespread species such as *O. limosus* and *C. b. bartonii*, very rare ones such as C. (*P.*) sp. could have been missed.

Due to rarity and proximity to urban centers and exotic crayfishes, C. (*P.*) sp. is clearly imperiled in Pennsylvania (Table 3) and in need of conservation attention. In other states, crayfishes with similarly restricted ranges (known from 9 to 27 sites) often garner conservation attention (Taylor and Schuster 2004; Westhoff et al. 2006; Eversole and Welch 2010), and a number of species of conservation concern in Pennsylvania have wider distributions and are less threatened than C. (*P.*) sp. (see Felbaum et al. 1995). Although undescribed, the lack of a specific epithet should not prevent C. (*P.*) sp. from being a conservation priority (see Bouchard 1976a; Harris 1990; Jelks et al. 2008; and others, which included undescribed species in lists of imperiled crayfishes and fishes).

If the *acuminatus* species in Pennsylvania is different from those to the south, then range-wide conservation attention and inclusion on lists of globally imperiled species (e.g., AFS, NHN) may be warranted, as has already been done for two *acuminatus* species (*Cambarus hystricosus*, *Cambarus johni*) known from approximately 25 to 55 locations (Cooper and Cooper 2003; Cooper 2006; Taylor et al. 2007; Simmons and Fraley 2010). Even if the Pennsylvania *acuminatus* species occurs elsewhere, such actions may be justified if Pennsylvania populations exhibit adaptations not present to the south, making them important for maintaining the genetic variability of the species (see Hamr 1998 for similar discussions regarding Canada's crayfishes and Hunter and Hutchinson 1994 and Lesica and Allendorf 1995 for more general discussions of the value of peripheral populations). Additionally, given the restricted distribution of the *C. acuminatus* complex in Maryland (less than 10 occurrences since 1989 and less than 30 overall; see Figure 4 in Kilian et al. 2010), even if the species in Pennsylvania is the same as that in Maryland, broader scale actions may be warranted. Overall, C. (*P.*) sp. is probably one of the most endangered aquatic species in the state and possibly in eastern North America (if its range is limited to Pennsylvania) and, without management action, faces an uncertain future.

### *Orconectes limosus*

Although *O. limosus* records exist for a large swath of the Atlantic drainage of eastern North America (Virginia northward to Canada; Ortmann 1906; Crocker 1957, 1979; Francois 1959; Meredith and Schwartz 1960; Hobbs 1989; McAlpine et al. 1991; Jezerinac et al. 1995; Lambert et al. 2007), recent large-scale surveys indicate that the species has been extirpated from a substantial part of its former range. For example, in Pennsylvania, the range of *O. limosus* has declined (retreated eastward) by approximately 225 km and the species has nearly been eliminated from the Susquehanna and Potomac basins (Figure 1; Bouchard et al. 2007). Resampling efforts at or near historical sites in those basins yielded hundreds of introduced congeners but no *O. limosus* (Table 2; Table 1 in Bouchard et al. 2007). Except for the presence of *O. limosus* in a few tributaries of the North Branch Potomac River, similar range reductions have occurred in northern Maryland (Kilian et al. 2010). The prevalence of introduced congeners in areas that

**Photo Spread 1. Densities of *Orconectes rusticus* (shown in all three pictures) are often extremely high in invaded systems such as the Susquehanna River in Pennsylvania (lower left and upper). Photos by K. Kelly (lower left and upper) and D. Lieb and P. Mooney (lower right).**

Photo Spread 2. *Cambarus bartonii bartonii* (left) and *Orconectes limosus* (right) are native to eastern Pennsylvania. Photos by C. Swecker and T. Jones (left) and D. Funk (right).

Photo Spread 3. *Cambarus* (*Puncticambarus*) sp., an undescribed member of the *Cambarus acuminatus* complex, has an extremely limited distribution in Pennsylvania. Photos by J. Fetzner.

lost populations of O. *limosus* suggests that crayfish introductions likely played a major role in those losses (Figures 1–4, Table 2; Bouchard et al. 2007; Kilian et al. 2010), although other factors may have also been important.

More focused efforts in the Patapsco drainage of Maryland, the upper Susquehanna drainage of New York, the Potomac drainage of West Virginia, and the lower Delaware drainage of Pennsylvania also documented the frequent replacement of O. *limosus* by introduced congeners (Schwartz et al. 1963; Kuhlmann and Hazelton 2007; Loughman et al. 2009; Loughman and Welsh 2010; Swecker et al. 2010; Lieb et al. 2011). Because the lower Delaware drainage of Pennsylvania and nearby areas are an important reservoir of genetic variability for O. *limosus* (Filipová et al. 2011), extirpations from that area may have implications for the long-term viability and conservation status of O. *limosus* in the state and the region (see Ehrlich and Daily 1993; Fetzner and Crandall 2002; and Luck et al. 2003 for discussions of the importance of genetic variability to species persistence).

These findings prompted Bouchard et al. (2007) to speculate that O. *limosus* may eventually be eliminated from the Piedmont of Pennsylvania and Maryland, persisting only in the Coastal Plain where it may be better able to compete with introduced crayfishes. Unfortunately, Pennsylvania's Coastal Plain is small, densely populated, and extensively modified (Bouchard et al. 2007), with additional alterations likely. Maryland's Coastal Plain is larger and less populated but also has a substantial human footprint (King et al. 2005; Utz et al. 2010), which will undoubtedly increase as the region's population centers, including Washington, D.C., and Baltimore, continue to expand.

Although recent losses have been substantial, it is important to note that some of the populations that have been lost from the mid-Atlantic may not have been native to begin with (see Ortmann 1906 and Bouchard et al. 2007 for discussions of the potential influence of man-made canals on O. *limosus* dispersal). Nonetheless, given the magnitude of the losses and the threats that O. *limosus* faces, the populations that remain in Pennsylvania and Maryland have significant conservation value at the state and regional levels.

This is ironic given that O. *limosus* has been introduced to Europe and Canada and has rapidly expanded its range, often at the expense of native crayfishes (Hamr 1998; Lambert et al. 2007; Taylor et al. 2007). As a result, O. *limosus* is viewed as a pest across much of its nonnative range (Hamr 2002; Filipová et al. 2011). Nonetheless, the conservation of native O. *limosus* is warranted because introduced populations lack the genetic diversity that is present in native stocks (Filipová et al. 2011).

Thus, although O. *limosus* is listed as globally secure/stable by AFS and NHN (Table 3), recent findings indicate that native stocks may not be as safe as previously thought. In Pennsylvania, range reductions and the threat posed by exotic crayfishes prompted us to downgrade O. *limosus* from apparently secure to vulnerable (Table 3). In West Virginia, O. *limosus* is listed as critically imperiled and may have been eliminated from the state by exotic crayfish (Loughman and Welsh 2010; Swecker et al. 2010). In Maryland, O. *limosus* is listed as demonstrably secure, but the species is threatened by exotic crayfish, and significant range reductions have occurred in recent years (Kilian et al. 2010). Additional surveys along with genetic work are needed to update the status of O. *limosus* in other regions and across its range. Overall, this assessment suggests that management intervention is likely needed to ensure the continued existence of O. *limosus* in Pennsylvania and possibly elsewhere in its native range and illustrates the importance of periodically reevaluating the status of native crayfishes (even widespread ones).



### *Cambarus b. bartonii*

Although the range of C. *b. bartonii* has remained relatively stable over the past century in Pennsylvania and Maryland (Figure 5; Bouchard et al. 2007; Kilian et al. 2010; Lieb et al. 2011), the species has been replaced by introduced crayfishes at some locations in those states and New York (Table 2; Schwartz et al. 1963; Daniels 1998; Kuhlmann and Hazelton 2007). Additionally, C. *b. bartonii* may be negatively affected by nonnative O. *virilis* in eastern West Virginia (Swecker et al. 2010) and is in serious decline in parts of Ontario, Canada, although introduced crayfishes are not the cause (Edwards et al. 2009).

Given this information and the continued expansion of introduced crayfishes in eastern North America, additional losses appear likely. Fortunately, because C. *b. bartonii* is widely distributed in eastern North America from Canada southward to Georgia and is still common in many areas (Hobbs 1989; Bouchard et al. 2007; Kilian et al. 2010; Loughman and Welsh 2010; Simmons and Fraley 2010), these losses do not pose an immediate threat to the species. However, it is possible that extirpations may eventually reduce the genetic variability and long-term viability of C. *b. bartonii* in some areas. Although such concerns are often expressed for species with restricted ranges and small population sizes, even widespread crayfish species can suffer substantial reductions in genetic variability due to anthropogenic disturbances (Buhay and Crandall 2005). Nonetheless, because resources are limited, it is important to emphasize that C. *b. bartonii* is not an immediate conservation concern regionally or globally (Table 3; Kilian et al. 2010; Loughman and Welsh 2010; Simmons and Fraley 2010).

## Management Needs and Implications

Given the imperiled status of C. (*P.*) sp. and O. *limosus* in Pennsylvania and elsewhere, efforts to prevent crayfish introductions and preserve the habitat and water quality at sites that support those species should be a management priority. In subsequent sections, we describe regulatory, educational, and conservation initiatives, which should aid in this regard. We also discuss the need for methods to safely eradicate introduced crayfishes; however, the successful development of such methods will not eliminate the need for policies aimed at preventing introductions, which should remain the first line of defense. Although most specific examples are from Pennsylvania, the general concepts and management strategies that are provided have broad applicability and would likely benefit many of North America's crayfishes, as well as other aquatic invertebrate species of concern.

### Crayfish Ban

Because introduced crayfishes occur in a number of water bodies in Pennsylvania (Bouchard et al. 2007; Lieb et al. 2007a, 2011) and are available from bait shops, biological warehouses, pet stores, live food vendors, and aquaculture facilities, which are, at best, loosely regulated, it would be difficult to prevent additional introductions in Pennsylvania without further regulations and their enforcement (see Lodge et al. 2000a, 2000b; Burkholder and Wallace 2001; and DiStefano et al. 2009). Although O. *rusticus* has been tightly regulated since 2005 and cannot be possessed, sold, transported, or cultured within the state (58 Pa Code § 71.6.d 2008; Pennsylvania Fish and Boat Commission [PFBC] 2009), other introduced crayfishes (*P. acutus*, C. *robustus*, O. *obscurus*, O. *virilis*) are unregulated and can be purchased from commercial dealers or collected from invaded water bodies and released legally into the state's waters. Additionally, although *P. clarkii* cannot be propagated in flow-through systems or introduced into Pennsylvania waters (PFBC 2009), the species is cultured in parts of Pennsylvania and can be possessed, sold, and transported legally within the state. This situation is not unusual because many places in North America do not strictly regulate all of their introduced or potentially introduced crayfish species (DiStefano et al. 2009; Peters and Lodge 2009).

Strict regulations that only apply to a few species will not prevent crayfish introductions in most areas. Extending existing bans to other species would be hard to enforce because most natural resource managers and conservation officers have difficulty identifying crayfish (Lodge et al. 2000b; Peters and Lodge 2009). For this reason, banning the possession, sale, transportation, and culture of all native and nonnative crayfishes in Pennsylvania and elsewhere (a complete ban) is warranted. Such a ban would make it illegal to use live crayfish as bait as recommended by Lodge et al. (2000b) and DiStefano et al. (2009) and as is already the case in Wisconsin, Virginia, and parts of Maryland and Canada (Taylor et al. 2007; DiStefano et al. 2009; Maryland Department of Natural Resources [MDDNR] 2009). The Wisconsin ban, enacted in 1983, received nearly universal approval from the public (comments 5:1 in favor of it), "caused no unusual controversy, and has not caused any apparent harm to Wisconsin's important fishing industry" (Lodge et al. 2000b:23). Due to our outreach efforts, including at least 13 articles in the popular media (newspapers, magazines, Internet) since 2004, and those of the Pennsylvania Sea Grant, residents of Pennsylvania are becoming increasingly aware of the threat that introduced crayfishes pose and would likely support a crayfish ban. Outreach efforts are also underway elsewhere (DiStefano et al. 2009; Kilian et al. 2010), increasing the likelihood that a complete ban would be supported by the public.

Ideally, the complete ban would apply to all water bodies; however, it may be possible to permit the use of crayfish as bait in selected locations that are already infested with introduced crayfish (a partial ban). Such a measure would maintain a ban on the sale, transportation, and culture of crayfish but allow anglers to collect and fish with crayfish at some infested locations (exempt sites). Because some noncompliance may occur (DiStefano et al. 2009), exempt sites should not be in the vicinity of imperiled crayfish. For example, substantial reaches of the Schuylkill River in Pennsylvania are completely dominated by introduced O. *rusticus* (Lieb et al. 2011) and would, in theory, qualify for exempt status. However, because those reaches are in the vicinity one of Pennsylvania's rarest crayfish (C. (*P.*) sp.; Lieb et al. 2011), they should not be exempt. Locations that have never been surveyed for crayfishes or have not been surveyed recently should also not be exempt. Although not risk free, a partial ban would provide recreational opportunities for anglers that use crayfish as bait while still reducing the chance of introductions.

Some will likely argue that anglers should be allowed to collect and fish with crayfish wherever they choose (not just at exempt sites), as long as crayfish are not moved from place to place. However, such a measure—which makes sense in theory and would allow crayfish to be possessed but not sold, transported, or cultured—would be difficult to enforce. This is because unless an individual is caught transporting, selling, or culturing crayfish it would be impossible to determine whether a violation had occurred. In contrast, a complete or partial ban would be much easier to enforce because anglers would either not be allowed to use crayfish as bait anywhere (complete ban) or would only be permitted to use them in certain waters (partial ban). Under a complete or partial ban, the job of law enforcement would be to prevent anglers from using crayfish as bait in restricted waters, which is much easier than trying to determine whether crayfish are being transported between sites.

## Education and Outreach

Although education and outreach programs targeting policy makers and the general public are vitally important in preventing crayfish introductions (Lodge et al. 2000b; Hamr 2002; Taylor 2002), until recently there was little up-to-date information to dispense in many areas, including Pennsylvania. Nonetheless, when this information became available in Pennsylvania, the state's regulatory agencies moved quickly, enacting a ban on O. *rusticus* in 2005, within approximately a year of being informed of the extent of the infestation. The general public has proven equally as responsive, providing crayfish specimens, helping to detect new invasions (also noted by Lodge et al. 2006), and urging the passage of additional regulatory measures to prevent introductions.

To date, most outreach efforts in Pennsylvania have been restricted to articles in the popular media, invasive species workshops, and presentations at scientific and management meetings. Although productive, the effectiveness of those efforts could be increased by targeting vulnerable areas (watersheds that support imperiled species and/or are at risk of invasion) and potential sources of exotics including bait shops, biological warehouses, pet stores, live food vendors, and aquaculture facilities (see Burkholder and Wallace 2001; Puth and Allen 2004; Keller et al. 2008; DiStefano et al. 2009). Town hall style gatherings in vulnerable areas and attempts to educate anglers and others who contact crayfish would likely extend current efforts to a different subset of the public.

The placement of warning signs along water bodies that support imperiled crayfish such as C. (*P.*) sp. and O. *limosus* (to prevent introductions) and along heavily infested waterways (to prevent the transfer of exotics elsewhere) would probably slow the spread of exotics, particularly in heavily fished areas. To decrease costs, signs could be strategically placed at boat launches and other popular access points.

## Role of Dams, Temperature, and Nutrients

Although the susceptibility of individual sites to crayfish invasions is potentially influenced by a number of factors (Kershner and Lodge 1995; Light 2003; Usio et al. 2006; Phillips et al. 2009; Capinha and Anastacio 2011), in this section, we focus on dams, temperature, and nutrients because they appear to be important for one of Pennsylvania's rarest crayfish (*C.* (*P.*) sp.; Lieb and Bhattarai 2009; Lieb et al. 2011) and have the potential to influence invasions in many areas.

The ecological benefits of dam removal have been thoroughly discussed in the scientific literature and are a major reason for the recent surge in removal projects; however, the negative effects of such removals have received much less attention and are typically limited to the downstream transport of sediments, nutrients, and toxic materials and the upstream movement of introduced fish (Bednarek 2001; Bushaw-Newton et al. 2002; Hart et al. 2002; Poff and Hart 2002; Stanley and Doyle 2003). Because dams can block the dispersal of crayfish (Meyer et al. 2007), their removal may facilitate crayfish invasions in some systems, with the potential for negative effects on native communities. Despite this possibility, the potential for such effects is rarely discussed in the scientific literature (but see Kerby et al. 2005; Bubb et al. 2008), or empirically tested, and is typically not considered by regulatory agencies charged with managing dam removals.

**These data suggest that barriers (dams, low temperatures, low nutrients) are likely preventing or slowing exotic crayfish from invading some sites in Pennsylvania that support imperiled crayfish.**

Continuing to ignore the potential influence of dams on crayfish invasions could have serious consequences, particularly for imperiled crayfishes. For example, in Pennsylvania, dams are located downstream of most of the known populations of an extremely rare crayfish (*C.* (*P.*) sp.) and may be protecting them from invasion (especially by *O. rusticus*; Lieb et al. 2011). At a minimum, surveys should be conducted prior to dam removal to ensure that removal will not facilitate the upstream migration of introduced crayfish. Ironically, dams that are protecting upstream areas from invasion may need to be left in place for conservation reasons. In areas prone to invasion, dams located downstream of imperiled crayfish should probably not be removed, regardless of whether exotics are present in the system or not.

Low temperatures may also play a role in protecting some uninvaded sites. For example, in Pennsylvania, water temperatures at sites with populations of *C.* (*P.*) sp. (hereafter termed *C.* (*P.*) sp. sites) are likely lower than that preferred by *O. rusticus*, possibly delaying or preventing its establishment at those sites (Lieb and Bhattarai 2009). Support for this possibility is provided by Mundahl and Benton (1990), who determined that *O. rusticus* growth was maximized at 26–28°C in laboratory experiments and predicted that the species would be most successful in systems with average summer water temperatures near that range. Stream surveys in Ohio, which indicated that *O. rusticus* was more successful in warmer, downstream reaches that remain above 20°C throughout the summer than in cooler headwater areas (Jezerinac 1986; Mundahl and Benton 1990; Thoma and Jezerinac 2000), appear to support their prediction. Because temperatures at *C.* (*P.*) sp. sites are known or suspected to be lower than 20°C for substantial parts of the summer (Steffy and Kilham 2006; Lieb and Bhattarai 2009), it is possible that *O. rusticus* has been slow to invade those sites, at least partly, because relatively low temperatures afford resident species a bioenergetic advantage over *O. rusticus* (see Momot et al. 1988 for a similar example).

The recent discovery of *O. rusticus* at the Valley Creek *C.* (*P.*) sp. sites suggests that, although not favored by *O. rusticus*, low temperatures may not prevent invasions indefinitely. The spread of *O. rusticus* into the northern United States and Canada (Hamr 2002; Taylor et al. 2007; Phillips et al. 2009) further indicates that low temperatures alone may not provide a permanent barrier against invasion. It is also possible that, in Valley Creek, recent temperature increases resulting from urbanization (Steffy and Kilham 2006) have tipped the bioenergetic balance in favor of *O. rusticus*. Mundahl and Benton (1990) and Whitledge and Rabeni (2002) voiced similar concerns regarding the potential influence of habitat- and climate-driven changes in temperature on *O. rusticus* invasions in Ohio and Missouri. Additional temperature increases in Valley Creek and the other *C.* (*P.*) sp. sites are likely due to continued urbanization (Steffy and Kilham 2006; Kaushal et al. 2010), increasing regional groundwater temperatures (Eggleston et al. 1999), and climate change (see Mohseni et al. 1999; Chang 2003; Kaushal et al. 2010). Such increases may eventually result in thermal conditions in many areas, including the *C.* (*P.*) sp. sites, which favor *O. rusticus*.

The relatively low nutrient status of the *C.* (*P.*) sp. sites (oligo-mesotrophic; Lieb and Bhattarai 2009) is probably not optimal for *O. rusticus*, which—due to its high metabolic rate, high growth rate, and large size—tend to do best in productive systems where nutrients are plentiful (Momot 1984; Momot et al. 1988). However, continued urbanization of the Philadelphia suburbs will likely increase nutrient levels at the *C.* (*P.*) sp. sites in the future (see Lenat and Crawford 1994; Carpenter et al. 1998). Additionally, it has been predicted that, as atmospheric $CO_2$ levels rise, SE Pennsylvania will become warmer and wetter, further increasing nutrient loading from urbanizing basins in the region (Chang 2004). Elevated nutrient levels may increase the likelihood of future *O. rusticus* invasions at the *C.* (*P.*) sp. sites and other locations that are not highly enriched, as appears to have already occurred in Ohio and West Virginia (Jezerinac et al. 1995; Thoma and Jezerinac 2000).

These data suggest that barriers (dams, low temperatures, low nutrients) are likely preventing or slowing exotic crayfish from invading some sites in Pennsylvania that support imperiled crayfish. Unfortunately, dam removals and expected in-

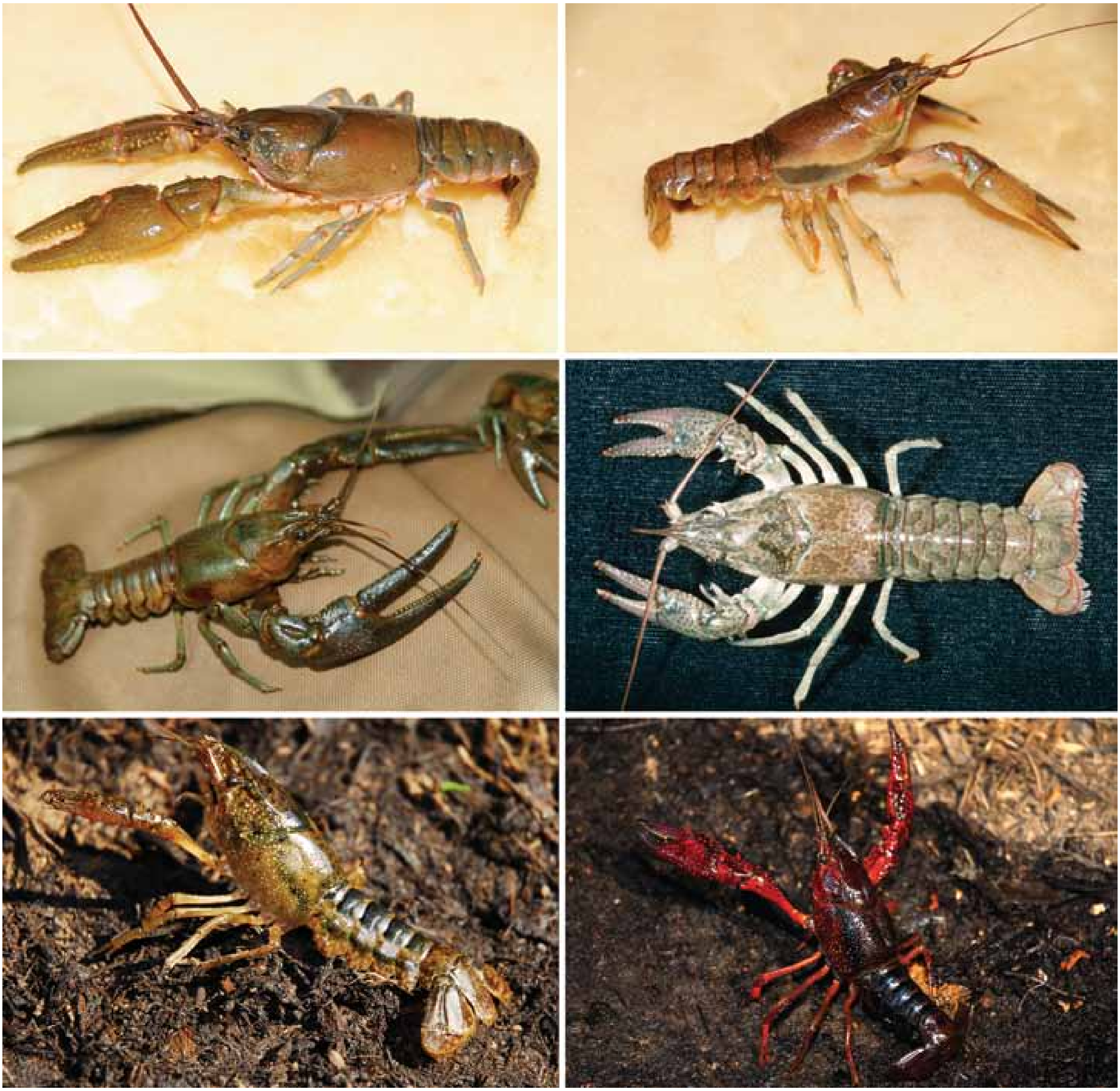

**Photo Spread 4.** ***Cambarus robustus*** **(upper left),** ***Orconectes obscurus*** **(upper right),** ***Orconectes rusticus*** **(middle left),** ***Orconectes virilis*** **(middle right), and** ***Procambarus clarkii*** **(lower right) have been introduced to eastern Pennsylvania, and** ***Procambarus acutus*** **(lower left) has greatly expanded its range in the region as a result of human activities. Photos by C. Swecker and T. Jones (lower left, lower right), J. Fetzner (upper left, upper right), M. Sell (middle left), and K. Crandall (middle right).**

creases in water temperature and nutrient levels resulting from climate change and urbanization may compromise or weaken those barriers in the future. More generally, these findings highlight the potentially important but often overlooked role that physical and chemical barriers of natural and anthropogenic origin play in preventing crayfish invasions. Ultimately, the preservation of native crayfish in some heavily infested areas may depend on management efforts that maintain, strengthen, or expand existing barriers.

## Eliminating Exotics

Although the negative effects of introduced crayfish are well documented, little is known about how to eliminate them from invaded waters. Chemical poisons are available; however, native crayfish are also killed (Gunderson 2008). Intensive harvesting may reduce population sizes but is laborious and unlikely to result in eradication (Hamr 1999; Holdich et al. 1999; Freeman et al. 2010). In a Wisconsin lake, *O. rusticus* densities were dramatically reduced (although extirpation was not achieved) using a combination of trapping and increased fish predation (Hein et al. 2007). Unfortunately, the effort required was substantial, and similar results in open systems (streams) are not assured. Pheromone baits could potentially reduce this effort by increasing trap efficiency (Holdich et al. 1999; Freeman et al. 2010) but are still in the early stages of development (Stebbing et al. 2003; Aquiloni and Gherardi 2010). These difficulties have led many authors (e.g., Lodge et al. 2000b; Hamr 2002; Gunderson 2008) to conclude that introduced crayfish can best be controlled by preventing future introductions.

Although we agree with this reasoning, additional introductions are likely unavoidable. As a result, the persistence of certain native crayfishes (particularly those with limited ranges such as *C.* (*P.*) sp.) may require the removal of exotics. Unfortunately, species-specific treatments that eliminate introduced crayfish with minimal effects on non-target species are currently not available (Lodge et al. 2000b; Gunderson 2008; Freeman et al. 2010). Their development should be possible; however, because crayfish species vary in their responses to a variety of substances (Hobbs and Hall 1974; Berrill et al. 1985; Eversole and Seller 1996; Nyström 2002; Wigginton and Birge 2007). Additionally, because molting crayfish are especially sensitive to toxicants (Wigginton and Birge 2007), it may be possible in some situations to apply treatments when exotics are at the peak of their molting cycle but natives are not to minimize effects on non-target species. The release of sterilized males, which has long been used to control insect pests (Myers et al. 2000) but has only recently been considered for crayfish (Holdich et al. 1999; Aquiloni et al. 2009); endocrine disruptors, which interfere with molting and reproductive processes in crustaceans (Rodriguez et al. 2007; Mazurova et al. 2008); and species-specific pathogens (Holdich et al. 1999; Davidson et al. 2010; Freeman et al. 2010) might also be effective for crayfish.

The objective of most treatment programs would be eradication, although for some abundant, highly fecund invaders such as *O. rusticus*, population control may be more feasible (Myers et al. 2000). Because introduced species are difficult to eradicate if well established (Myers et al. 2000; Lodge et al. 2006), watersheds that support imperiled crayfish should be routinely monitored (at least once per year) to ensure that invasions are detected quickly (see similar, albeit less specific, recommendations in Lodge et al. 2006). Given that eradication/control programs require public support and can be controversial, particularly if chemicals are used in populated areas, such efforts should include outreach and public education initiatives (Myers et al. 2000; Genovesi 2005). Due to the presence of *C.* (*P.*) sp. and recent invasion by *O. rusticus*, Valley Creek would be an obvious candidate for treatment. Eradication/control programs could be combined with restocking efforts to restore native crayfishes to systems where they have been extirpated.

## Reducing Environmental Degradation

Anthropogenic disturbances and associated declines in habitat and water quality are a serious threat to North America's native crayfishes (Wilcove et al. 1998; Guiaşu 2002; Taylor et al. 2007). Many of these disturbances can be related directly or indirectly to landscape-scale changes associated with agricultural and urban development. As a result, the preservation of native crayfish should include efforts to preserve natural areas, particularly in the riparian zone (Burskey and Simon 2010), and mitigate existing impacts. Riparian forests may be of particular value because they reduce pollutant, sediment, and nutrient loading (Lowrance et al. 1984; Peterjohn and Correll 1984; Pinho et al. 2008); lower water temperature (Burton and Likens 1973; Barton et al. 1985; Storey and Cowley 1997); and provide refugia from flooding (in the form of tree roots and woody debris; Smith et al. 1996; Parkyn and Collier 2004), which would benefit crayfish communities directly via improved habitat and water quality and indirectly by reducing the likelihood of crayfish invasions (see Role of Dams, Temperature, and Nutrients). In Pennsylvania, such benefits are particularly likely for *C.* (*P.*) sp. because it is typically found in streams with relatively low temperatures and nutrients and appears to be negatively affected by sedimentation and introduced crayfish (Lieb et al. 2008, 2011; Lieb and Bhattarai 2009). Nonetheless, because the benefits of riparian forests are not always apparent (particularly in highly developed areas; Roy et al. 2005, 2006, 2007), their presence alone will not necessarily assure the long-term survival of native crayfish.

In Pennsylvania, exceptional value (EV) status affords surface waters protection under state law and mandates that "water quality be maintained and protected" (25 Pa Code § 93.4a 2007). Surface waters qualify for EV status if they are of "exceptional ecological significance," defined as "important, unique, or sensitive ecologically" (25 Pa Code § 93.1 2007). Although surface waters that support imperiled crayfish such as *C.* (*P.*) sp. and *O. limosus* appear to meet those criteria, most are not classified as EV and need to be reevaluated (especially those with *C.*(*P.*) sp.). More generally, whenever possible, imperiled crayfish should be considered when surface waters are classified and anti-degradation priorities are assigned.

Because urban areas support imperiled crayfish and are crisscrossed by pipelines, railroads, and roadways that serve as conduits for wastes and toxic materials, efforts to prevent spilled materials from reaching imperiled crayfish are needed. Those efforts should include the diversion of road runoff away from populations of imperiled crayfish and the frequent inspection and maintenance of pipelines, railroads, and roadways that are in the vicinity of those populations. In Pennsylvania, such safeguards are especially pertinent to C. (P.) sp. because underground sewage conduits occur upstream of many C. (P.) sp. sites (Ryan and Packman 2006). Further, some of the largest and busiest highways and railroads in Pennsylvania are in the vicinity of those sites and are a major supply route for chemicals, fuels, and other toxic materials coming in and out of the Philadelphia area. Therefore, spills in this region could have serious consequences for C. (P.) sp. In recent years, at least two substantial releases of diesel fuel from tanker trucks involved in highway accidents have occurred downstream of C. (P.) sp. sites (National Response Center 2002; Schaefer and Mastrull 2007). Given the continued expansion of urban areas in SE Pennsylvania, future spills, including those upstream of C. (P.) sp. sites, seem likely.



## Additional Sampling

Because *O. limosus* and C. (P.) sp. are imperiled in Pennsylvania and elsewhere, efforts to better define their ranges and monitor populations are needed. Range refinement will require crayfish collections from watersheds that have not been sampled recently and more sampling of drainages that currently support C. (P.) sp. and *O. limosus*. Once their distributions have been refined, range-wide monitoring programs can be developed. Efforts to quickly detect crayfish invasions and relate population sizes to conditions at the reach scale (e.g., in stream habitat) and basin scale (e.g., land use) should be included in those programs. Regular monitoring should allow population declines to be detected and causative factors identified, ultimately providing the information needed to protect C. (P.) sp. and *O. limosus* across their ranges. Initiatives of this type should have widespread applicability, assisting efforts to conserve crayfish in a variety of settings.

## Acknowledgments

We thank Nellie Bhattarai, Hannah M. Ingram, and Jeremy Harper for their substantial contributions. The Wild Resources Conservation Fund, Pennsylvania Department of Conservation and Natural Resources (Project Number AG050523); the National Park Service (Grant Agreement H4560030064); and a Pennsylvania State Wildlife Grant (number PFBC050305.01) provided financial support. Christopher A. Urban, Matt R. Marshall, and Sarah Nichols administered grants and provided encouragement. Emily and Megan Lieb assisted in the field at some sites. Patrick Martinez, an anonymous reviewer, and Marybeth Lieb provided helpful critiques of the article.

## References

Aquiloni, L., A. Becciolini, R. Berti, S. Porciani, C. Trunfio, and F. Gherardi. 2009. Managing invasive crayfish: use of X-ray sterilisation of males. Freshwater Biology 54:1510–1519.

Aquiloni, L., and F. Gherardi. 2010. The use of sex pheromones for the control of invasive populations of the crayfish *Procambarus clarkii*: a field study. Hydrobiologia 649:249–254.

Barton, D. R., W. D. Taylor, and R. M. Biette. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario Canada streams. North American Journal of Fisheries Management 5:364–378.

Bednarek, A. T. 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management 27:803–814.

Berrill, M., L. Hollett, A. Margosian, and J. Hudson. 1985. Variation in tolerance to low environmental pH by the crayfish *Orconectes rusticus*, *Orconectes propinquus*, and *Cambarus robustus*. Canadian Journal of Zoology 63:2586–2589.

Bouchard, R. W. 1976a. Crayfishes and shrimps. Pages 13–20 *in* H. Boschung, editor. Endangered and threatened plants and animals of Alabama. Bulletin of the Alabama Museum of Natural History 2. University of Alabama, Tuscaloosa, Alabama.

———. 1976b. Geography and ecology of crayfishes of the Cumberland Plateau and Cumberland Mountains, Kentucky, Virginia, Tennessee, Georgia and Alabama, part II: the genera *Fallicambarus* and *Cambarus*. Pages 585–605 *in* J.W. Avault, Jr., editor. Freshwater crayfish. Louisiana State University Division of Continuing Education, Baton Rouge, Louisiana.

Bouchard, R. W., D. A. Lieb, R. F. Carline, T. R. Nuttall, C. B. Wengert, and J. R. Wallace. 2007. 101 Years of change (1906 to 2007). The distribution of the crayfishes of Pennsylvania. Part I. Eastern Pennsylvania. Academy of Natural Sciences of Philadelphia, Report No. 07-11, Philadelphia, Pennsylvania.

Bubb, D. H., T. J. Thom, and M. C. Lucas. 2008. Spatial ecology of the white-clawed crayfish in an upland stream and implications for the conservation of this endangered species. Aquatic Conservation-Marine and Freshwater Ecosystems 18:647–657.

Buhay, J. E., and K. A. Crandall. 2005. Subterranean phylogeography of freshwater crayfishes shows extensive gene flow and surprisingly large population sizes. Molecular Ecology 14:4259–4273.

Burkholder, C. L., and J. R. Wallace. 2001. Crayfish survey of Lancaster County: invasion of the rusty crayfish. Abstract. North American Benthological Society Conference, La Crosse, Wisconsin.

Burskey, J. L., and T. P. Simon. 2010. Reach- and watershed-scale associations of crayfish within an area of varying agricultural impact in west-central Indiana. Southeastern Naturalist 9:199–216.

Burton, T. M., and G. E. Likens. 1973. Effect of strip-cutting on stream temperatures in Hubbard Brook Experimental Forest, New Hampshire. Bioscience 23:433–435.

Bushaw-Newton, K. L., D. D. Hart, J. E. Pizzuto, J. R. Thomson, J. Egan, J. T. Ashley, T. E. Johnson, R. J. Horwitz, M. Keeley, J. Lawrence, D. Charles, C. Gatenby, D. A. Kreeger, T. Nightengale, R. L. Thomas, and D. J. Velinsky. 2002. An integrative approach towards understanding ecological responses to dam removal: the Manatawny Creek study. Journal of the American Water Resources Association 38:1581–1599.

Capinha, C., and P. Anastacio. 2011. Assessing the environmental requirements of invaders using ensembles of distribution models. Diversity and Distributions 17:13–24.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559–568.

Chang, H. 2003. Basin hydrologic response to changes in climate and land use: the Conestoga River Basin, Pennsylvania. Physical Geography 24:222–247.

———. 2004. Water quality impacts of climate and land use changes in southeastern Pennsylvania. The Professional Geographer 56:240–257.
Cooper, J. E. 2001. *Cambarus hobbsorum* (*Puncticambarus*), a new crayfish (Decapoda: Cambaridae) from North Carolina. Proceedings of the Biological Society of Washington 114:152–161.
———. 2006. A new species of crayfish of the genus *Cambarus* Erichson, 1846 (Decapoda: Cambaridae) from the eastern Blue Ridge foothills and western Piedmont Plateau of North Carolina. Proceedings of the Biological Society of Washington 119:67–80.
Cooper, J. E., and D. G. Cooper. 2003. A new crayfish of the genus *Cambarus* Erichson, 1846 (Decapoda: Cambaridae), from the Cape Fear River basin in the Sandhills of North Carolina. Proceedings of the Biological Society of Washington 116:920–932.
Crocker, D. W. 1957. The crayfishes of New York state (Decapoda, Astacidae). New York State Museum and Science Service Bulletin No. 355. State University of New York, Albany, New York.
———. 1979. The crayfishes of New England. Proceedings of the Biological Society of Washington 92:225–253.
Daniels, R. A. 1998. Changes in the distribution of stream-dwelling crayfishes in the Schoharie Creek system, eastern New York State. Northeastern Naturalist 5:231–248.
Davidson, E. W., J. Snyder, D. Lightner, G. Ruthig, J. Lucas, and J. Gilley. 2010. Exploration of potential microbial control agents for the invasive crayfish, *Orconectes virilis*. Biocontrol Science and Technology 20:297–310.
DiStefano, R. J., M. E. Litvan, and P. T. Horner. 2009. The bait industry as a potential vector for alien crayfish introductions: problem recognition by fisheries agencies and a Missouri evaluation. Fisheries 34:586–597.
Edwards, B. A., D. A. Jackson, and K. M. Somers. 2009. Multispecies crayfish declines in lakes: implications for species distributions and richness. Journal of the North American Benthological Society 28:719–732.
Eggleston, J. R., T. M. Kehn, and G. H. Wood, Jr. 1999. Anthracite. Pages 458–469 *in* G.H. Shultz, editor. The Geology of Pennsylvania. Pennsylvania Geological Survey and Pittsburgh Geological Society, Special Publication 1, Harrisburg and Pittsburgh, Pennsylvania.
Ehrlich, P. R., and G. C. Daily. 1993. Population extinction and saving biodiversity. Ambio 22:64–68.
Elmore, A. J., and S. S. Kaushal. 2008. Disappearing headwaters: patterns of stream burial due to urbanization. Frontiers in Ecology and the Environment 6:308–312.
Eversole, A. G., and B. C. Seller. 1996. Comparison of relative crayfish toxicity values. Freshwater Crayfish 11:274–285.
Eversole, A. G., and S. M. Welch. 2010. Conservation of imperiled crayfish—*Distocambarus* (*Fitzcambarus*) *youngineri* Hobbs and Carlson 1985 (Decapoda: Cambaridae). Journal of Crustacean Biology 30:151–155.
Felbaum, F., B. Mitchell, K. McKenna, J. Hassinger, A. Shiels, J. Hart, and D. Brauning. 1995. Endangered and Threatened Species of Pennsylvania. Wild Resources Conservation Fund, Harrisburg, Pennsylvania.
Fetzner, J. W., Jr., and K. A. Crandall. 2002. Genetic variation. Pages 291–326 *in* D.M. Holdich, editor. Biology of Freshwater Crayfish, Blackwell Science, Oxford, U.K.
Filipová, L., D. A. Lieb, F. Grandjean, and A. Petrusek. 2011. Haplotype variation in the spiny-cheek crayfish *Orconectes limosus*: colonization of Europe and genetic diversity of native stocks. Journal of the North American Benthological Society 30: 871–881.
Francois, D. D. 1959. The crayfishes of New Jersey. Ohio Journal of Science 59:108–127.
Freeman, M. A., J. F. Turnbull, W. E. Yeomans, and C. W. Bean. 2010. Prospects for management strategies of invasive crayfish populations with an emphasis on biological control. Aquatic Conservation-Marine and Freshwater Ecosystems 20:211–223.
Genovesi, P. 2005. Eradications of invasive alien species in Europe: a review. Biological Invasions 7:127–133.
Guiaşu, R. C. 2002. *Cambarus*. Pages 609-634 *in* D. M. Holdich, editor. Biology of Freshwater Crayfish. Blackwell Science, Oxford, U.K.
Gunderson, J. 2008. Rusty Crayfish: Nasty Invader. Publication No. X34 of the Minnesota Sea Grant. University of Minnesota, Duluth, Minnesota.
Hamr, P. 1998. Conservation Status of Canadian Freshwater Crayfishes. World Wildlife Fund Canada and the Canadian Nature Federation, Toronto, Canada.
———. 1999. The commercial harvest of the exotic rusty crayfish (*Orconectes rusticus*) summer 1998. Report to the Ministry of Natural Resources, Peterborough Region, Ontario, Canada.
———. 2002. *Orconectes*. Pages 585–608 *in* D.M. Holdich, editor. Biology of Freshwater Crayfish. Blackwell Science, Oxford, U.K.
Harris, S. C. 1990. Preliminary considerations on rare and endangered invertebrates in Alabama. Journal of the Alabama Academy of Science 61:64–92.
Hart, D. D., T. E. Johnson, K. L. Bushaw-Newton, R. J. Horwitz, A. T. Bednarek, D. F. Charles, D. A. Kreeger, and D. J. Velinsky. 2002. Dam removal: challenges and opportunities for ecological research and river restoration. Bioscience 52:669–681.
Hein, C. L., M. J. Vander Zanden, and J. J. Magnuson. 2007. Intensive trapping and increased fish predation cause massive population decline of an invasive crayfish. Freshwater Biology 52:1134–1146.
Hobbs, H. H., Jr. 1969. On the distribution and phylogeny of the crayfish genus *Cambarus*. Pages 93-178 in P. C. Holt, R. L. Hoffman, and C. W. Hart, editors. The Distributional History of the Biota of the Southern Appalachians, Part I: Invertebrates, Research Division Monograph 1. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.
———. 1989. An illustrated checklist of the American crayfishes (Decapoda: Astacidae, Cambaridae, and Parastacidae). Smithsonian Contributions to Zoology No. 480. National Museum of Natural History, Smithsonian Institution, Washington, D.C.
Hobbs, H. H., Jr., and E. T. Hall. 1974. Crayfishes (Decapoda: Astacidae). Pages 195–214 *in* C. W. Hart and L. H. Fuller, editors. Pollution Ecology of Freshwater Invertebrates. Academic Press, New York, New York.
Hobbs, H. H., III, J. P. Jass, and J. V. Huner. 1989. A review of global crayfish introductions with particular emphasis on two North American species (Decapoda, Cambaridae). Crustaceana 56:299–316.
Holdich, D. M., R. Gydemo, and W. D. Rogers. 1999. A review of possible methods for controlling nuisance populations of alien crayfish. Pages 245–270 *in* F. Gherardi and D. M. Holdich, editors. Crustacean Issues, volume 11, Crayfish in Europe as Alien Species: How to Make the Best of a Bad Situation? A.A. Balkema, Rotterdam, The Netherlands.
Hunter, M. L., and A. Hutchinson. 1994. The virtues and shortcomings of parochialism—conserving species that are locally rare,

but globally common. Conservation Biology 8:1163–1165.

Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Díaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren, Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33:372–407.

Jezerinac, R. F. 1986. Endangered and threatened crayfishes (Decapoda, Cambaridae) of Ohio. Ohio Journal of Science 86:177–180.

Jezerinac, R. F., G. W. Stocker, and D. C. Tarter. 1995. The crayfishes (Decapoda: Cambaridae) of West Virginia. Ohio Biological Survey Bulletin New Series 10:1–193.

Kaushal, S. S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. L. Wingate. 2010. Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment 8:461–466.

Keller, R. P., K. Frang, and D. M. Lodge. 2008. Preventing the spread of invasive species: economic benefits of intervention guided by ecological predictions. Conservation Biology 22:80–88.

Kerby, J. L., S. P. D. Riley, L. B. Kats, and P. Wilson. 2005. Barriers and flow as limiting factors in the spread of an invasive crayfish (*Procambarus clarkii*) in southern California streams. Biological Conservation 126:402–409.

Kershner, M. W., and D. M. Lodge. 1995. Effects of littoral habitat and fish predation on the distribution of an exotic crayfish, *Orconectes rusticus*. Journal of the North American Benthological Society 14:414–422.

Kilian, J. V., A. J. Becker, S. A. Stranko, M. Ashton, R. J. Klauda, J. Gerber, and M. Hurd. 2010. The status and distribution of Maryland crayfishes. Southeastern Naturalist 9:11–32.

King, R. S., M. E. Baker, D. F. Whigham, D. E. Weller, T. E. Jordan, P. F. Kazyak, and M. K. Hurd. 2005. Spatial considerations for linking watershed land cover to ecological indicators in streams. Ecological Applications 15:137–153.

Kuhlmann, M. L., and P. D. Hazelton. 2007. Invasion of the upper Susquehanna River watershed by rusty crayfish (*Orconectes rusticus*). Northeastern Naturalist 14:507–518.

Lambert, S. D., D. F. McAlpine, and A. Hebda. 2007. First establishment of an invasive crayfish, *Orconectes limosus* (Rafinesque, 1817) (Decapoda, Cambaridae) in Nova Scotia, Canada. Crustaceana 80:1265–1270.

Lenat, D. R., and J. K. Crawford. 1994. Effects of land use on water quality and aquatic biota of 3 North Carolina Piedmont streams. Hydrobiologia 294:185–199.

Lesica, P., and F. W. Allendorf. 1995. When are peripheral-populations valuable for conservation? Conservation Biology 9:753–760.

Lieb, D. A., and N. Bhattarai. 2009. The distribution, ecology, conservation status, and management needs of a newly discovered species of Pennsylvania crayfish. Final Report, Wild Resources Conservation Fund, Project Number AG050523, Grant Agreement WRCP-05102. Pennsylvania Fish and Boat Commission, Bellefonte, Pennsylvania.

Lieb, D. A., R. W. Bouchard, and R. F. Carline. 2011. The crayfish fauna of southeastern Pennsylvania: distributions, ecology, and changes over the last century. Journal of Crustacean Biology 31:166–178.

Lieb, D. A., R. F. Carline, and H. M. Ingram. 2007a. Status of Native and Invasive Crayfish in Ten National Park Service Properties in Pennsylvania. Technical Report NPS/NER/NRTR—2007/085. National Park Service, Philadelphia, Pennsylvania.

Lieb, D. A., R. F. Carline, and V. M. Mengel. 2007b. Crayfish Survey and Discovery of a Member of the *Cambarus acuminatus* Complex (Decapoda: Cambaridae) at Valley Forge National Historical Park in Southeastern Pennsylvania. Technical Report NPS/NER/NRTR—2007/084. National Park Service, Philadelphia, Pennsylvania.

Lieb, D. A., R. F. Carline, J. L. Rosenberger, and V. M. Mengel. 2008. The discovery and ecology of a member of the *Cambarus acuminatus* complex (Decapoda: Cambaridae) in Valley Creek, southeastern Pennsylvania. Journal of Crustacean Biology 28:439–450.

Light, T. 2003. Success and failure in a lotic crayfish invasion: the roles of hydrologic variability and habitat alteration. Freshwater Biology 48:1886–1897.

Lodge, D. M., C. A. Taylor, D. M. Holdich, and J. Skurdal. 2000a. Nonindigenous crayfishes threaten North American freshwater biodiversity: lessons from Europe. Fisheries 25:7–20.

———. 2000b. Reducing impacts of exotic crayfish introductions: new policies needed. Fisheries 25:21–23.

Lodge, D. M., S. Williams, H. J. MacIsaac, K. R. Hayes, B. Leung, S. Reichard, R. N. Mack, P. B. Moyle, M. Smith, D. A. Andow, J. T. Carlton, and A. McMichael. 2006. Biological invasions: recommendations for U.S. policy and management. Ecological Applications 16:2035–2054.

Loughman, Z. J., T. P. Simon, and S. A. Welsh. 2009. West Virginia crayfishes (Decapoda: Cambaridae): observations on distribution, natural history, and conservation. Northeastern Naturalist 16:225–238.

Loughman, Z. J., and S. A. Welsh. 2010. Distribution and conservation standing of West Virginia crayfishes. Southeastern Naturalist 9:63–78.

Lowrance, R., R. Todd, J. Fail, O. Hendrickson, R. Leonard, and L. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. Bioscience 34:374–377.

Luck, G. W., G. C. Daily, and P. R. Ehrlich. 2003. Population diversity and ecosystem services. Trends in Ecology & Evolution 18:331–336.

Master, L. L., S. R. Flack, and B. A. Stein. 1998. Rivers of Life: Critical Watersheds for Protecting Freshwater Biodiversity. The Nature Conservancy, Arlington, Virginia.

Master, L. L., B. A. Stein, L. S. Kutner, and G. A. Hammerson. 2000. Vanishing assets: conservation status of U.S. species. Pages 93–118 *in* B. A. Stein, L. S. Kutner, and J. S. Adams, editors. Precious Heritage: the Status of Biodiversity in the United States. Oxford University Press, New York, New York.

Mazurova, E., K. Hilscherova, R. Triebskorn, H. R. Kohler, B. Marsalek, and L. Blaha. 2008. Endocrine regulation of the reproduction in crustaceans: identification of potential targets for toxicants and environmental contaminants. Biologia 63:139–150.

McAlpine, D. F., W. E. Hogans, and T. J. Fletcher. 1991. *Orconectes limosus* (Crustacea: Cambaridae), an addition to the crayfish fauna of New Brunswick. Canadian Field-Naturalist 105:386–387.

MDDNR (Maryland Department of Natural Resources). 2009. 2009 Maryland Fishing Guide. Maryland Department of Natural Resources, Annapolis, Maryland.

Meredith, W. G., and F. J. Schwartz. 1960. Maryland Crayfishes. Educational Series No. 46, Maryland Department of Research and Education, Solomons Island, Maryland.

Meyer, K. M., K. Gimpel, and R. Brandl. 2007. Viability analysis of endangered crayfish populations. Journal of Zoology 273:364–371.

Mohseni, O., T. R. Erickson, and H. G. Stefan. 1999. Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resources Research 35:3723–3733.
Momot, W. T. 1984. Crayfish production—a reflection of community energetics. Journal of Crustacean Biology 4:35–54.
Momot, W. T., C. Hartviksen, and G. Morgan. 1988. A range extension for the crayfish *Orconectes rusticus*—Sibley Provincial Park, northwestern Ontario. Canadian Field-Naturalist 102:547–548.
Mundahl, N. D., and M. J. Benton. 1990. Aspects of the thermal ecology of the rusty crayfish *Orconectes rusticus* (Girard). Oecologia 82:210–216.
Myers, J. H., D. Simberloff, A. M. Kuris, and J. R. Carey. 2000. Eradication revisited: dealing with exotic species. Trends in Ecology and Evolution 15:316–320.
National Response Center. 2002. National response team incident summaries. United States Coast Guard, Washington, D.C.
NatureServe. 2010. An online encyclopedia of life. http://www.natureserve.org/explorer.
Nyström, P. 2002. Ecology. Pages 192–235 *in* D.M. Holdich, editor. Biology of Freshwater Crayfish. Blackwell Science, Oxford, U.K.
Ortmann, A. E. 1906. The crawfishes of the state of Pennsylvania. Memoirs of the Carnegie Museum 2:343–523.
Parkyn, S. M., and K.J. Collier. 2004. Interaction of press and pulse disturbance on crayfish populations: food impacts in pasture and forest streams. Hydrobiologia 527:113–124.
Peterjohn, W. T., and D. L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466–1475.
Peters, J. A., and D. M. Lodge. 2009. Invasive species policy at the regional level: a multiple weak links problem. Fisheries 34:373–381.
PFBC (Pennsylvania Fish and Boat Commission). 2009. Species by watershed approved for open system (flow-through) propagation and introductions. http://www.agriculture.state.pa.us/agriculture/lib/agriculture/animalhealthfiles/Approved_Species_List_Open_System_Aquaculture_for_Dep_of_Ag_2009_%284%29.pdf.
Phillips, I. D., R. D. Vinebrooke, and M. A. Turner. 2009. Ecosystem consequences of potential range expansions of *Orconectes virilis* and *Orconectes rusticus* crayfish in Canada—a review. Environmental Reviews 17:235–248.
Pinho, A. P., L. A. Morris, C. R. Jackson, W. J. White, P. B. Bush, and A. T. Matos. 2008. Contaminant retention potential of forested filter strips established as SMZs in the Piedmont of Georgia. Journal of the American Water Resources Association 44:1564–1577.
Poff, N. L., and D. D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience 52:659–668.
Possingham, H. P., S. J. Andelman, M. A. Burgman, R. A. Medellin, L. L. Master, and D. A. Keith. 2002. Limits to the use of threatened species lists. Trends in Ecology and Evolution 17:503–507.
Puth, L. M., and T. F. H. Allen. 2004. Potential corridors for the rusty crayfish, *Orconectes rusticus*, in northern Wisconsin (USA) lakes: lessons for exotic invasions. Landscape Ecology 20:567–577.
Rodriguez, E. M., D. A. Medesani, and M. Fingerman. 2007. Endocrine disruption in crustaceans due to pollutants: a review. Comparative Biochemistry and Physiology A - Molecular and Integrative Physiology 146:661–671.
Rodriguez, G., and H. Suarez. 2001. Anthropogenic dispersal of decapod crustaceans in aquatic environments. Interciencia 26:282–288.
Roy, A. H., C. L. Faust, M. C. Freeman, and J. L. Meyer. 2005. Reach-scale effects of riparian forest cover on urban stream ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 62:2312–2329.
Roy, A. H., J. Freeman, and M. C. Freeman. 2007. Riparian influences on stream fish assemblage structure in urbanizing streams. Landscape Ecology 22:385–402.
Roy, A. H., M. C. Freeman, B. J. Freeman, S. J. Wenger, J. L. Meyer, and W. E. Ensign. 2006. Importance of riparian forests in urban catchments contingent on sediment and hydrologic regimes. Environmental Management 37:523–539.
Ryan, R. J., and A. I. Packman. 2006. Changes in streambed sediment characteristics and solute transport in the headwaters of Valley Creek, an urbanizing watershed. Journal of Hydrology 323:74–91.
Schaefer, M. A., and D. Mastrull. 2007. Fuel spill fouls Darby Creek. The Philadelphia Inquirer. February 23, 2007, Philadelphia, Pennsylvania.
Schwartz, F. J., R. Rubelmann, and J. Allison. 1963. Ecological population expansion of the introduced crayfish *Orconectes virilis*. Ohio Journal of Science 63:265–273.
Simmons, J. W., and S. J. Fraley. 2010. Distribution, status, and life-history observations of crayfishes in western North Carolina. Southeastern Naturalist 9:79–126.
Smith, G. R. T., F. M. Learner, F. Slater, and J. Foster. 1996. Habitat features important for the conservation of the native crayfish *Austropotamobius pallipes* in Britain. Biological Conservation 75:239–246.
Stanley, E. H., and M. W. Doyle. 2003. Trading off: the ecological removal effects of dam removal. Frontiers in Ecology and the Environment 1:15–22.
Stebbing, P. D., G. J. Watson, M. G. Bentley, D. Fraser, R. Jennings, S. P. Rushton, and P. J. Sibley. 2003. Reducing the threat: the potential use of pheromones to control invasive signal crayfish. Bulletin Francais de la Peche et de la Pisciculture 370–371:219–224.
Steffy, L. Y., and S. S. Kilham. 2006. Effects of urbanization and land use on fish communities in the Valley Creek watershed, Chester County, Pennsylvania. Urban Ecosystems 9:119–133.
Storey, R. G., and D. R. Cowley. 1997. Recovery of three New Zealand rural streams as they pass through native forest remnants. Hydrobiologia 353:63–76.
Swecker, C. D., T. G. Jones, K. Donahue II, D. Mckinney, and G. D. Smith. 2010. The extirpation of *Orconectes limosus* (Spinycheek Crayfish) populations in West Virginia. Southeastern Naturalist 9:155–164.
Taylor, C. A. 2002. Taxonomy and conservation of native crayfish stocks. Pages 236–257 *in* D. M. Holdich, editor. Biology of Freshwater Crayfish. Blackwell Science, Oxford, U.K.
Taylor, C. A., and G. A. Schuster. 2004. The crayfishes of Kentucky. Illinois Natural History Survey, Special Publication No. 28, Champaign, Illinois.
Taylor, C. A., G. A. Schuster, J. E. Cooper, R. J. DiStefano, A. G. Eversole, P. Hamr, H. H. Hobbs III, H. W. Robison, C. E. Skelton, and R. F. Thoma. 2007. Endangered species—a reassessment of the conservation status of crayfishes of the United States and Canada after 10+years of increased awareness. Fisheries 32:372–389.

Taylor, C. A., M. L. Warren, J. F. Fitzpatrick, H. H. Hobbs, R. F. Jezerinac, W. L. Pflieger, and H. W. Robison. 1996. Conservation status of crayfishes of the United States and Canada. Fisheries 21:25–38.

Thoma, R. F., and R. F. Jezerinac. 2000. Ohio crayfish and shrimp atlas. Ohio Biological Survey Miscellaneous Contributions No. 7. Ohio Biological Survey, The Ohio State University, Columbus, Ohio.

Usio, N., H. Nakajima, R. Kamiyama, I. Wakana, S. Hiruta, and N. Takamura. 2006. Predicting the distribution of invasive crayfish (*Pacifastacus leniusculus*) in a Kusiro Moor marsh (Japan) using classification and regression trees. Ecological Research 21:271–277.

Utz, R. M., R. H. Hilderbrand, and R. L. Raesly. 2010. Regional differences in patterns of fish species loss with changing land use. Biological Conservation 143:688–699.

Westhoff, J. T., J. A. Guyot, and R. J. DiStefano. 2006. Distribution of the imperiled Williams' crayfish (*Orconectes williamsi*) in the White River drainage of Missouri: associations with multi-scale environmental variables. American Midland Naturalist 156:273–288.

Whitledge, G. W., and C. F. Rabeni. 2002. Maximum daily consumption and respiration rates at four temperatures for five species of crayfish from Missouri, U.S.A. (Decapoda, *Orconectes* spp.). Crustaceana 75:1119–1132.

Wigginton, A. J., and W. J. Birge. 2007. Toxicity of cadmium to six species in two genera of crayfish and the effect of cadmium on molting success. Environmental Toxicology and Chemistry 26:548–554.

Wilcove, D. S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. Bioscience 48:607–615.