Rapid Communication

Documentation of invasive rusty crayfish *Faxonius rusticus* (Girard, 1852) in Kansas

John M. Smith Jr.[1,*], Zachary B. Klein[1] and Chris Steffen[2]

[1]*New Mexico State University, Department of Fish, Wildlife, and Conservation Ecology, 2980 South Espina St., Knox Hall 132 Las Cruces, NM 88003, USA*
[2]*Kansas Department of Wildlife and Parks, 1830 Merchant St. Emporia, KS 66801, USA*

**Corresponding author*
E-mail: *jsmith97@nmsu.edu*

Citation: Smith JM Jr., Klein ZB, Steffen C (2022) Documentation of invasive rusty crayfish *Faxonius rusticus* (Girard, 1852) in Kansas. *BioInvasions Records* 11(3): 766–775, https://doi.org/10.3391/bir.2022.11.3.18

Received: 11 January 2022
Accepted: 17 May 2022
Published: 27 July 2022

Handling editor: Laura Garzoli
Thematic editor: Kenneth Hayes

Abstract

The translocation of nonnative crayfish across the United States is of great concern given the ecological consequences of the taxon. Nonnative crayfish have been reported to reduce densities of native crayfish, alter benthic invertebrate communities, decrease macrophyte biomass, reduce reproductive success of fish, and diminish the genetic integrity of native crayfish through hybridization. As part of ongoing research into the development of a state-wide crayfish monitoring program, rusty crayfish *Faxonius rusticus* (Girard, 1852) were observed in McPherson State Fishing Lake, Kansas (decimal degrees = 38.4819, -97.4682). Sampling occurred at McPherson State Fishing Lake and Battle Creek between June 22 and July 1 2021. A total of three rusty crayfish were collected and consisted of two females and one male. Individual carapace lengths varied from 27 to 35 mm. No rusty crayfish were collected in Battle Creek upstream of the lake. Although the mode of introduction is unknown, anthropogenic releases of live crayfish have been implicated in other rusty crayfish introductions. Therefore, greater restrictions on the use of live crayfish in Kansas may be an important consideration for management agencies. Furthermore, additional research is needed to determine the exact mode of introduction to curtail future spread of the species in the state. Our results highlight the need to consistently monitor crayfish populations to document the occurrence and distribution of a potentially deleterious species.

Key words: invasive crayfish, aquatic invasive species, anthropogenic releases, monitoring, freshwater

Introduction

Nonnative species are one of the primary threats to freshwater ecosystems globally (Rahel 2002; Reid et al. 2019). Nonnative species have been shown to displace native species (Taniguchi et al. 2002; Mills et al. 2004; McDowall 2006), alter aquatic habitats (Pimentel et al. 2005; McDowall 2006), and serve as vectors of disease (Hoffman 1990; Holdich and Reeve 1991). Aquatic invasive species also result in economic losses. For instance, Cuthbert et al. (2021) estimated that aquatic invasive species have cost approximately US$345 billion, globally. Although many nonnative species adversely affect freshwater ecosystems, anthropogenic activities continue to facilitate the spread of nonnative species (Fuller et al. 1999; Rahel 2002). For instance, nonnative zebra mussels *Dreissena polymorpha* (Pallas, 1771) and Asian clams *Corbicula fluminea* (O. F. Müller, 1774) have been broadly introduced into freshwater habitats as the result of human activity (Sousa et al. 2008; Strayer 2009). Copp et al. (2005) reported that 185 nonnative freshwater fishes have been introduced in the United States. Of the aquatic fauna that have been introduced within the United States, nonnative crayfish species are of particular concern due to the detrimental effects they can have on aquatic ecosystems.

The negative ecological effects of nonnative crayfish species have been well documented (Twardochleb et al. 2013). Nonnative crayfishes have been shown to greatly reduce densities of native crayfishes (Hill and Lodge 1994; Hill and Lodge 1999), alter benthic invertebrate assemblages (Hill and Lodge 1995; Perry et al. 1997; Ruokonen et al. 2016), decrease macrophyte biomass (Lodge et al. 1994; Hill and Lodge 1995; Matsuzaki et al. 2009), reduce reproductive success of benthic nesting fishes (Dorn and Wojdak 2004; Wilson et al. 2004; Morse et al. 2013), diminish the genetic integrity of native crayfishes through hybridization (Capelli and Capelli 1980; Hill and Lodge 1994; Perry et al. 2001), and spread disease (Holdich et al. 2009; Capinha et al. 2013; Martín-Torrijos et al. 2021). In addition to ecological effects, nonnative crayfish populations cause economic losses in regions where they are established. For instance, burrowing activity of red swamp crayfish *Procambarus clarkii* (Girard, 1852) can result in shoreline collapse, increased erosion, and can compromise infrastructure such as levees or dams (Correia and Ferreira 1995; Barbaresi et al. 2004). Nonnative rusty crayfish *Faxonius rusticus* (Girard, 1852) were estimated to cost \$1.5 million annually to Vilas County, Wisconsin, due to the losses in angler expenditure resulting from poor-quality fisheries influenced by invasion (Keller et al. 2008). The ecological and economic effects of nonnative crayfishes remain a concern in areas where they have been introduced.

Within the United States, one of the most detrimental crayfish species is the rusty crayfish. Rusty crayfish are a fast-growing, highly fecund species (Hamr 2002). Rusty crayfish are native to the lower Ohio River basin (Hobbs et al. 1989) but have been introduced throughout North America (Momot 1997; Olden et al. 2006; Olden et al. 2009; Hamr 2010; Sorenson et al. 2012). The spread of the species throughout the United States is of great concern given the potential ecological consequences of established populations (Lodge et al. 1994; Hill and Lodge 1999; Morse et al. 2013). However, crayfishes are rarely monitored due to lack of prioritization, funding, and limited sampling methods (Price and Welch 2009; Stoeckel et al. 2015; Taylor et al. 2019). As such, any opportunity to document the spread of crayfish is of critical importance for resource agencies to make informed management decisions.

Materials and methods

Sampling was conducted as part of ongoing research into the development of a crayfish sampling protocol. Sampling occurred at McPherson State Fishing Lake and Battle Creek, McPherson, Kansas (decimal degrees = 38.4819, −97.4682) between June 22 and July 1, 2021. McPherson State Fishing Lake was divided into 100 m^2 sampling grids to allocate sampling effort. Forty grids were randomly selected, and each grid was sampled with minnow traps, modified minnow traps, and pillow traps (Larson and Olden 2016). Minnow traps were constructed with 6.4-mm vinyl-dipped steel mesh and measure 42.0 × 23.0 cm. Each minnow trap had a 6.0-cm diameter entrance on either end of the trap. Modified minnow traps had a construction similar to minnow traps, but entrance diameters measured 3.0 cm. Pillow traps were constructed with 19-mm PVC-coated steel mesh and measured 60.0 × 30.0 cm. Pillow traps had three 6.0-cm diameter openings. Prior to deployment, each trap was baited with approximately 15 ml of canned dog food (Pedigree Chopped Chicken and Rice Dinner, Mars Petcare, McLean, Virginia) in a 125-ml perforated bottle. Traps were deployed in water varying in depth from 0.5–2.0 m. Traps were allowed to soak overnight and were checked the following day. Each grid was sampled for three consecutive nights with a single gear, for a total of nine sampling events.

Stream sampling occurred in a 2-km section of Battle Creek located upstream of McPherson State Fishing Lake. The 2-km section of stream was divided into twenty 100-m reaches, and ten reaches were randomly selected for sampling. Each reach was separated into macrohabitat units (i.e., riffle, run, pool), and macrohabitats were sampled independently. Sampling was conducted using minnow traps, modified minnow traps, and backpack electrofishing (Larson and Olden 2016). Sampling with minnow traps was conducted as described above. For electrofishing, power output was standardized to 50–60 Hz, 4–5 ms pulse width, and 300–400 V (Barnett et al. 2020). Each macrohabitat was sampled for three consecutive days with a single gear for a total of nine sampling events. Regardless of sampling location and gear, all collected crayfish were identified to species, enumerated, sexed, and measured for carapace length (0.1 mm). Crayfish were identified in the field based on morphological characteristics such as rust-colored spots on either side of the carapace, S-shaped dactyl, and black bands at the tips of the chelae (DiStefano et al. 2008). Rusty crayfish were further identified in the lab by examining the mandible (Figure 1) and the first form male gonopods (Figure 2; Swecker et al. 2010).

Results

A total of 336 crayfish were collected between June 22–July 1, 2021. Of the total crayfish collected, 259 crayfish were collected in Battle Creek and 77 crayfish were collected in McPherson State Fishing Lake (Table 1). In Battle

Figure 1. View of the anterior cusp of the mandibles of a rusty crayfish sampled from McPherson State Fishing Lake from June 22–July 1, 2021. Photo by JM Smith Jr.

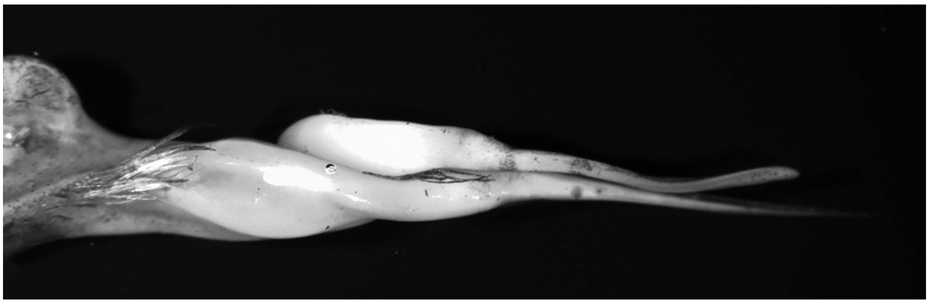

Figure 2. View of a gonopod of a first form male rusty crayfish sampled from McPherson State Fishing Lake from June 22–July 1, 2021. Photo by JM Smith Jr.

Table 1. Number of crayfish by gear type for McPherson State Fishing Lake and Battle Creek.

Gear type	Northern crayfish	White River crayfish	Rusty crayfish	Total
McPherson State Fishing Lake				
Pillow trap	11	0	0	11
Minnow trap	24	0	2	26
Modified minnow trap	38	1	1	40
Battle Creek				
Minnow trap	4	2	0	6
Modified minnow trap	6	2	0	8
Backpack electrofishing	245	0	0	245

Creek, 255 individuals were identified as northern crayfish *Faxonius virilis* (Hagen, 1870; 98.4% of the sample) and 4 individuals were identified as White River crayfish *Procambarus acutus* (Girard, 1852; 1.6% of the sample). In McPherson State Fishing Lake three species were collected and comprised northern crayfish, White River crayfish, and rusty crayfish (Figure 3). Of the 77 crayfish collected in McPherson State Fishing Lake, 73 individuals were identified as northern crayfish (94.8% of the sample), three individuals

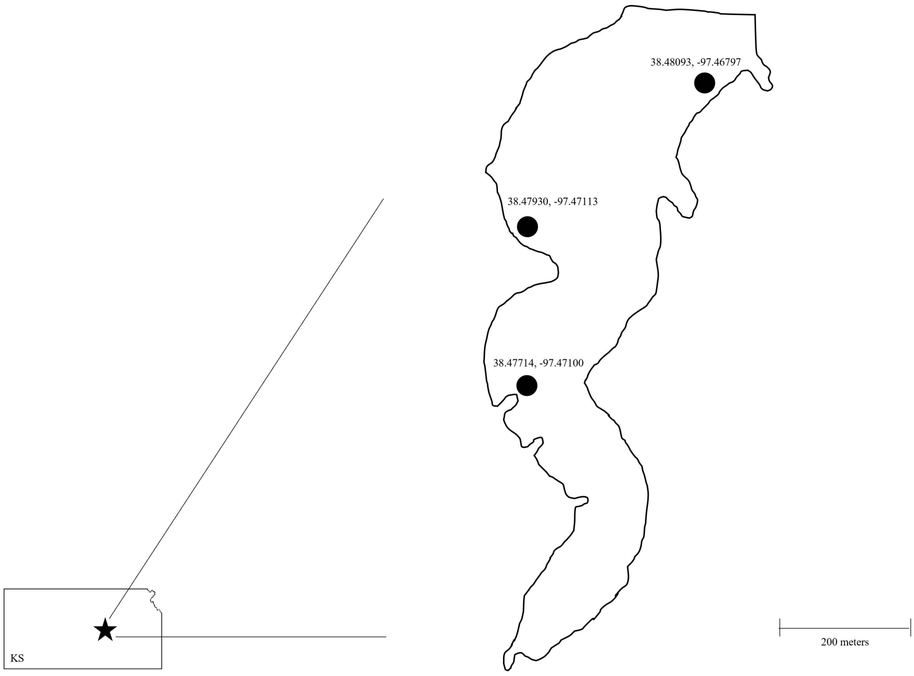

Figure 3. A map of McPherson State Fishing Lake including collection locations (black circles) of identified rusty crayfish.

were identified as rusty crayfish (3.9% of the sample), and one individual was identified as a White River crayfish (1.3% of the sample). Two of the rusty crayfish were females and measured 27 and 30 mm. The third rusty crayfish was identified as a male and had a carapace length of 35 mm.

Discussion

Rusty crayfish may have been previously encountered in the wild in the state of Kansas in 1890, 1912, and 1931 (Faxon 1890; Harris 1903; Guiașu and Labib 2021); however, the validity of these records is questionable. Upon reexamination of voucher specimens, Wetzel et al. (2004) determined that many of the records of rusty crayfish in Iowa and Minnesota were in fact golden crayfish *F. luteus* (Creaser, 1933). Golden crayfish are native to Kansas, and may have contributed to erroneous accounts of rusty crayfish in the state via misidentification. Notwithstanding, our results are the first documented account of rusty crayfish in Kansas in nearly a century, thereby highlighting the need to regularly monitor crayfish populations. Unfortunately, crayfish populations are rarely monitored across much of the United States due to a lack of prioritization and funding (Taylor et al. 2019). Although crayfish continue to gain more attention within management agencies (Taylor et al. 2019), monitoring programs may also be hindered by inefficient sampling methods. However, new technologies such as environmental DNA may aid in improving crayfish monitoring efforts (Dougherty et al. 2016; Chucholl et al. 2021; King et al. 2022). Regardless, our results highlight the value of monitoring crayfish populations for documenting the occurrence and distribution of a potentially invasive species.

The mode of introduction of rusty crayfish in Kansas is currently unknown. It is possible that a remnant isolated population of rusty crayfish has occurred undetected since the 1930s. However, it is also likely that the occurrence of rusty crayfish in McPherson State Fishing Lake is the result of anthropogenic activities. Anthropogenic actives have been implicated in previous rusty crayfish introductions. For instance, the use of live crayfish as bait, aquaculture, the ornamental pet trade, and the biological supply industry are all common modes of introduction of rusty crayfish (Larson and Olden 2008; DiStefano et al. 2009; Manfrin et al. 2019). McPherson State Fishing Lake is adjacent to a large city (Salina, Kansas) and receives a high amount of recreational activity. As such, any of the aforementioned modes of introduction could have occurred in the system. Although the exact mode of introduction of rusty crayfish into McPherson State Fishing Lake is unknown, the occurrence of the species highlights the need to improve education and regulation surrounding transport of invasive species. For instance, 87% of contacted bait shops that sold crayfish in Missouri could not identify the species they sold (DiStefano et al. 2009). Improved education and outreach may enhance the public's ability to identify potentially deleterious crayfish and curtail their sale (DiStefano et al. 2009). Similarly, greater restrictions on the sale of live crayfish in Kansas should also be considered given the challenge of identifying crayfish and the substantial ecological risk nonnative species pose for aquatic systems in the state. Although further research is needed to identify the true mode of introduction of rusty crayfish in McPherson State Fishing Lake, our results highlight the need to employ preventative measures to mitigate the spread of a potentially detrimental species.

Although preventative measures may reduce the spread of nonnative crayfish in Kansas, continued monitoring is needed to understand the ecological ramifications of rusty crayfish in McPherson State Fishing Lake. It is difficult to know duration and extent of establishment of rusty crayfish in McPherson State Fishing Lake. However, the presence of sexually mature individuals suggests the potential for reproduction. Invasive populations often experience a lag between initial introduction and rapid population growth (Sakai et al. 2001; Crooks 2005). For example, Walsh et al. (2016) estimated that a population of spiny water fleas *Bythotrephes longimanus* (Leydig, 1860) occurred at low densities for at least a decade before optimal thermal conditions allowed rapid population growth in Lake Mendota, Wisconsin. In the Great Lakes, nonnative rusty crayfish experienced a lag between introduction and rapid expansion that lasted approximately 100 years (Peters et al. 2014). In McPherson State Fishing Lake, northern crayfish outnumbered rusty crayfish about 24 to 1. Although these results may be due to gear-specific selectivity (Ogle and Kret 2008), the relatively low catch rate of rusty crayfish suggests the species was discovered prior to rapid population growth. If the population of rusty crayfish in McPherson State Fishing Lake is early in the invasion process, mechanical removal may be a cost effective method for controlling population expansion. Messager and Olden (2018) concluded that control of rusty crayfish in the John Day River, Oregon, would have been both possible and cost-effective if removal efforts had been initiated early in the invasion process. Therefore, McPherson State Fishing Lake may serve as a model system for testing population control efforts and examining population expansion of this invasive species.

Given the uncertainty surrounding the distribution of potentially deleterious crayfish species in Kansas, additional monitoring efforts are needed. Continued monitoring of rusty crayfish in McPherson State Fishing Lake will likely provide critical insight into the population growth and ecological effects this species may have in Kansas. Although rusty crayfish are likely a small component of the crayfish assemblage in Kansas, their presence may necessitate increased regulation (e.g., live bait sales, live crayfish transport) to reduce the spread of this species. Additionally, prevention of the initial introduction of nonnative species via education and outreach may serve as the most cost-effective management option (Dresser and Swanson 2013; Lodge et al. 2016; DiStefano et al. 2016). Overall, management should focus on preventing initial introductions, monitoring existing populations, and documenting the occurrence and spread of nonnative crayfish species throughout Kansas.

Acknowledgements

This study was supported by Kansas Department of Wildlife and Parks. We thank our research technician B. Jones for assisting with data collection and New Mexico State University. We also thank four anonymous reviewers who provided valuable comments and helped to improve the overall quality of this manuscript.

Funding declaration

Funding for this research was provided by Kansas Department of Wildlife and Parks. C. Steffen of Kansas Department of Wildlife and Parks was critical in the study design, preparation of this manuscript, and the decision to publish.

Authors' contribution

J. Smith – Sample design and methodology, data collection, data analysis, original draft: writing and editing; Z. Klein – Research conceptualization, sample design and methodology, data collection, original draft: review and editing; C. Steffen – Research conceptualization, sample design and methodology, funding agency representative, original draft: review and editing.

Ethics and permits

The authors acknowledge that institutional and national policies governing the humane and ethical treatment of experimental subjects were complied with and are willing to share original data and materials if so requested. Ethics approval was not required for this research. All research pertaining to this article was conducted under a Scientific, Education, or Exhibition Wildlife Permit, State of Kansas, permit number SC-052-2021.

References

Barbaresi S, Tricarico E, Gherardi F (2004) Factors inducing the intense burrowing activity of the red swamp crayfish, *Procambarus clarkii*, an invasive species. *Naturwissenschaften* 91: 342–345, https://doi.org/10.1007/s00114-004-0533-9

Barnett ZC, Ochs CA, Hoeksema JD, Adams SB (2020) Multipass electrofishing sampling efficiency for stream crayfish population estimates. *North American Journal of Fisheries Management* 40: 840–851, https://doi.org/10.1002/nafm.10443

Capelli GM, Capelli JF (1980) Hybridization between crayfish of the genus *Orconectes*: morphological evidence (Decapoda, Cambaridae). *Crustaceana* 39: 121–132, https://doi.org/10.1163/156854080X00021

Capinha C, Larson ER, Tricarico E, Olden JD, Gherardi F (2013) Effects of climate change, invasive species, and disease on the distribution of native European crayfishes. *Conservation Biology* 27: 731–740, https://doi.org/10.1111/cobi.12043

Chucholl F, Fiolka F, Segelbacher G, Epp LS (2021) eDNA detection of native and invasive crayfish species allows for year-round monitoring and large-scale screening of lotic systems. *Frontiers in Environmental Science* 9: 23, https://doi.org/10.3389/fenvs.2021.639380

Crooks JA (2005) Lag times and exotic species: the ecology and management of biological invasions in slow-motion. *Ecoscience* 12: 316–329, https://doi.org/10.2980/i1195-6860-12-3-316.1

Copp GH, Bianco PG, Bogutskaya N, Erős T, Falka I, Ferreira MT, Fox MG, Freyhof J, Gozlan RE, Grabowska J, Kováč V, Moreno-Amich R, Naseka AM, Peňáz M, Povž M, Przybylski M, Robillard M, Russell IC, Stakėnas S, Šumer S, Vila-Gispert A, Wiesner C (2005) To be, or not to be, a non-native freshwater fish? *Journal of Applied Ichthyology* 2: 242–262, https://doi.org/10.1111/j.1439-0426.2005.00690.x

Correia AM, Ferreira Ó (1995) Burrowing behavior of the introduced red swamp crayfish *Procambarus clarkii* (Decapoda: Cambaridae) in Portugal. *Journal of Crustacean Biology* 15: 248–257, https://doi.org/10.2307/1548953

Cuthbert RN, Pattison Z, Taylor NG, Verbrugge L, Diagne C, Ahmed DA, Leroy B, Angulo E, Briski E, Capinha C, Catfor JA, Dalu T, Essl F, Gozlan RE, Haubrock PJ, Kourantidou M, Kramer AM, Renault D, Wasserman RJ, Courchamp F (2021) Global economic costs of aquatic invasive alien species. *Science of the Total Environment* 775: 145238, https://doi.org/10.1016/j.scitotenv.2021.145238

DiStefano RJ, Litvan ME, Meyer A, Taylor CA (2008) Identifying crayfish a guide for bait vendors and aquaculturists. Missouri Department of Conservation, Jefferson City, Missouri, USA, pp 1–8

DiStefano RJ, Litvan ME, Horner PT (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, https://doi.org/10.1577/1548-8446-34.12.586

DiStefano RJ, Reitz RA, Imhof EM (2016) Examining one state's regulation development process to manage alien crayfish introductions. *Fisheries* 41: 726–737, https://doi.org/10.1080/03632415.2016.1246871

Dorn NJ, Wojdak JM (2004) The role of omnivorous crayfish in littoral communities. *Oecologia* 140: 150–159, https://doi.org/10.1007/s00442-004-1548-9

Dougherty MM, Larson ER, Renshaw MA, Gantz CA, Egan SP, Erickson DM, Lodge DM (2016) Environmental DNA (eDNA) detects the invasive rusty crayfish *Orconectes rusticus* at low abundances. *Journal of Applied Ecology* 53: 722–732, https://doi.org/10.1111/1365-2664.12621

Dresser C, Swanson B (2013) Preemptive legislation inhibits the anthropogenic spread of an aquatic invasive species, the rusty crayfish (*Orconectes rusticus*). *Biological Invasions* 15: 1049–1056, https://doi.org/10.1007/s10530-012-0349-z

Faxon W (1890) Notes on North American crayfishes-family Astacidae. *Proceedings of the US National Museum* 12: 619–634, https://doi.org/10.5479/si.00963801.785.619

Fuller PL, Nico LG, Williams JD (1999) Nonindigenous fishes introduced into inland waters of the United States. AFS Special Publication 27, American Fisheries Society, 622 pp, https://doi.org/10.47886/9781888569148

Guiaşu RC, Labib M (2021) The unreliable concept of native range as applied to the distribution of rusty crayfish (*Faxonius rusticus*) in North America. *Hydrobiologia* 848: 1177–1205, https://doi.org/10.1007/s10750-021-04523-y

Harris JA (1903) An ecological catalogue of the crayfishes belonging to the genus *Cambarus*. *Kansas University Science Bulletin* 2: 51–187

Hamr P (2002) *Orconectes*. In: Holdich DM (ed), Biology of Freshwater Crayfish. Blackwell Science Ltd, Ames, Iowa, USA, pp 585–608

Hamr P (2010) The biology, distribution and management of the introduced rusty crayfish, *Orconectes rusticus* (Girard), in Ontario, Canada. *Freshwater Crayfish* 17: 85–90

Hill AM, Lodge DM (1994) Diel changes in resource demand: interaction of competition and predation in species replacement by an exotic crayfish. *Ecology* 75: 2118–2126, https://doi.org/10.2307/1941615

Hill AM, Lodge DM (1995) Multi-trophic-level impacts of sublethal interactions between bass and omnivorous crayfish. *Journal of the North American Benthological Society* 14: 306–314, https://doi.org/10.2307/1467782

Hill AM, Lodge DM (1999) Evaluating competition and predation as mechanisms of crayfish species replacements. *Ecological Applications* 9: 678–690, https://doi.org/10.1890/1051-0761(1999)009[0678:RORCBA]2.0.CO;2

Hobbs III HH, Jass JP, Huner JV (1989) A review of global crayfish introductions with particular emphasis on two North American species (Decapoda, Cambaridae). *Crustaceana* 56: 299–316, https://doi.org/10.1163/156854089X00275

Hoffman GL (1990) *Myxobolus cerebralis*, a worldwide cause of salmonid whirling disease. *Journal of Aquatic Animal Health* 2: 30–37, https://doi.org/10.1577/1548-8667(1990)002<0030:MCAWCO>2.3.CO;2

Holdich DM, Reeve ID (1991) Distribution of freshwater crayfish in the British Isles, with particular reference to crayfish plague, alien introductions and water quality. *Aquatic Conservation: Marine and Freshwater Ecosystems* 1: 139–158, https://doi.org/10.1002/aqc.3270010204

Holdich DM, Reynolds JD, Souty-Grosse C, Sibley PJ (2009) A review of the ever increasing threat to European crayfish from non-indigenous crayfish species. *Knowledge and Management of Aquatic Ecosystems* 394–395: 1–46, https://doi.org/10.1051/kmae/2009025

King AC, Krieg R, Weston A, Zenker AK (2022) Using eDNA to simultaneously detect the distribution of native and invasive crayfish within an entire country. *Journal of Environmental Management* 302: 113929, https://doi.org/10.1016/j.jenvman.2021.113929

Keller RP, Frang K, Lodge DM (2008) Preventing the spread of invasive species: economic benefits of intervention guided by ecological predictions. *Conservation Biology* 22: 80–88, https://doi.org/10.1111/j.1523-1739.2007.00811.x

Larson ER, Olden JD (2008) Do schools and golf courses represent emerging pathways for crayfish invasions? *Aquatic Invasions* 3: 465–468, https://doi.org/10.3391/ai.2008.3.4.18

Larson ER, Olden JD (2016) Field sampling techniques for crayfish. In: Longshaw M, Stebbing P (eds), Biology and Ecology of crayfish. CRC Press, Boca Raton, FL, pp 287–324

Lodge DM, Kershner MW, Aloi JE, Covich AP (1994) Effects of an omnivorous crayfish (*Orconectes rusticus*) on a freshwater littoral food web. *Ecology* 75: 1265–1281, https://doi.org/10.2307/1937452

Lodge DM, Simonin PW, Burgiel SW, Keller RP, Bossenbroek JM, Jerde CL, Kramer AM, Rutherford ES, Barnes MA, Wittmann ME, Chadderton WL, Apriesnig JL, Beletsky D, Cooke RM, Drake JM, Egan SP, Finnoff DC, Gantz CA, Grey EK, Hoff MH, Howeth JG, Jensen RA, Larson EF, Mandrak NE, Mason DM, Martinez FA, Newcomb TJ, Rothlisberger JD, Tucker AJ, Warziniack TW, Zhang H (2016) Risk analysis and bioeconomics of invasive species to inform policy and management. *Annual Review of Environment and Resources* 41: 453–488, https://doi.org/10.1146/annurev-environ-110615-085532

Manfrin C, Souty-Grosset C, Anastácio PM, Reynolds J, Giulianini PG (2019) Detection and control of invasive freshwater crayfish: from traditional to innovative methods. *Diversity* 11: 1–16, https://doi.org/10.3390/d11010005

Martín-Torrijos L, Correa-Villalona AJ, Azofeifa-Solano JC, Villalobos-Rojas F, Wehrtmann IS, Diéguez-Uribeondo J (2021) First detection of the crayfish plague pathogen *Aphanomyces astaci* in Costa Rica: European mistakes should not be repeated. *Frontiers in Ecology and Evolution* 9: 623814, *https://doi.org/10.3389/fevo.2021.623814*

Matsuzaki SS, Usio N, Takamura N, Washitani I (2009) Contrasting impacts of invasive engineers on freshwater ecosystems: an experiment and meta-analysis. *Oecologia* 158: 673–686, https://doi.org/10.1007/s00442-008-1180-1

McDowall RM (2006) Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxoid fishes? *Reviews in Fish Biology and Fisheries* 16: 233–422, https://doi.org/10.1007/s11160-006-9017-7

Messager ML, Olden JD (2018) Individual-based models forecast the spread and inform the management of an emerging riverine invader. *Diversity and Distributions* 24: 1816–1829, https://doi.org/10.1111/ddi.12829

Mills DM, Radar RB, Belk MC (2004) Complex interactions between native and invasive fish: the simultaneous effects of multiple negative interactions. *Oceologia* 141: 713–721, https://doi.org/10.1007/s00442-004-1695-z

Momot WT (1997) History of the range extension of the crayfish *Orconectes rusticus* into northwestern Ontario and Lake Superior. *Freshwater Crayfish* 11: 61–72

Morse JW, Baldridge AK, Sargent LW (2013) Invasive crayfish *Orconectes rusticus* (Decapoda, Cambaridae) is a more effective predator of substrate nesting fish eggs than native crayfish (*O. virilis*). *Crustaceana* 86: 387–402, https://doi.org/10.1163/15685403-00003187

Olden JD, McCarthy JM, Maxted JT, Fetzer WW, Vander Zanden MJ (2006) The rapid spread of rusty crayfish (*Orconectes rusticus*) with observations on native crayfish declines in Wisconsin (USA) over the past 130 years. *Biological Invasions* 8: 1621–1628, https://doi.org/10.1007/s10530-005-7854-2

Olden JD, Adams JW, Larson ER (2009) First record of *Orconectes rusticus* (Girard 1852) west of the Great Continental Divide in North America. *Crustaceana* 82: 1347–1351, https://doi.org/10.1163/156854009X448934

Ogle DH, Kret L (2008) Experimental evidence that captured rusty crayfish (*Orconectes rusticus*) exclude uncaptured rusty crayfish from entering traps. *Journal of Freshwater Ecology* 23: 123–129, https://doi.org/10.1080/02705060.2008.9664563

Peters JA, Cooper MJ, Creque SM, Kornis MS, Maxted JT, Perry WL, Schueler FW, Simon TP, Taylor CA, Thoma RF, Uzarski DG, Lodge DM (2014) Historical changes and current status of crayfish diversity and distribution in the Laurentian Great Lakes. *Journal of Great Lakes Research* 40: 35–46, https://doi.org/10.1016/j.jglr.2014.01.003

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics* 52: 273–288, https://doi.org/10.1016/j.ecolecon.2004.10.002

Perry WL, Lodge DM, Lamberti GA (1997) Impact of crayfish predation on exotic zebra mussels and native invertebrates in a lake-outlet stream. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 120–125, https://doi.org/10.1139/f96-255

Perry WL, Felder JL, Lodge DM (2001) Implications of hybridization between introduced and resident *Orconectes* crayfishes. *Conservation Biology* 15: 1656–1666, https://doi.org/10.1046/j.1523-1739.2001.00019.x

Price JE, Welch SM (2009) Semi-quantitative methods for crayfish sampling: sex, size, and habitat bias. *Journal of Crustacean Biology* 29: 208–216, https://doi.org/10.1651/08-3018R.1

Rahel FJ (2002) Homogenization of freshwater faunas. *Annual Review of Ecology and Systematics* 33: 291–315, https://doi.org/10.1146/annurev.ecolsys.33.010802.150429

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCorrmack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews* 94: 849–873, https://doi.org/10.1111/brv.12480

Ruokonen TJ, Ercoli F, Hämäläinen H (2016) Are the effects of an invasive crayfish on lake littoral macroinvertebrate communities consistent over time? *Knowledge and Management of Aquatic Ecosystems* 417: 31, https://doi.org/10.1051/kmae/2016018

Sakai AK, Allendorf FW, Hold JS, Lodge DM, Molofsky J, With KA, Baughman S, Cabin RJ, Cohen JE, Ellstrand NC, McCauley DE, O'Neil P, Parker IM, Thompson JN, Weller SG (2001) The population biology of invasive species. *Annual Review of Ecology and Systematics* 32: 305–332, https://doi.org/10.1146/annurev.ecolsys.32.081501.114037

Sorenson KL, Bollens SM, Counihan T (2012) Rapid range expansion of rusty crayfish *Orconectes rusticus* (Girard, 1852) in the John Day River, Oregon, USA. *Aquatic Invasions* 7: 291–294, https://doi.org/10.3391/ai.2012.7.2.017

Sousa R, Antunes C, Guihermino L (2008) Ecology of the invasive Asian clam *Corbicula fluminea* (Muller, 1774) in aquatic ecosystems: an overview. *International Journal of Limnology* 44: 85–94, https://doi.org/10.1051/limn:2008017

Strayer DL (2009) Twenty years of zebra mussels: lessons from the mollusk that made headlines. *Frontiers in Ecology and the Environment* 7: 135–141, https://doi.org/10.1890/080020

Stoeckel J, Helms B, Catalano M, Miller JM, Gibson K, Stewart PM (2015) Field and model-based evaluation of a low-cost sampling protocol for a coordinated, crayfish life-history sampling effort. *Freshwater Crayfish* 21: 131–141, https://doi.org/10.5869/fc.2015.v21-1.131

Swecker CD, Jones TD, Kilian JV, Roberson LF (2010) Key to the crayfish of Maryland. Maryland Department of Natural Resources, Annapolis, Maryland, USA, pp 1–35

Taniguchi Y, Fausch KD, Nakano S (2002) Size-structured interactions between native and introduced species: can intrigued predation facilitate invasion by stream salmonids? *Biological Invasions* 4: 223–233

Taylor CA, Stefano RJ, Larson ER, Stoeckel J (2019) Towards a cohesive strategy for the conservation of the United States' diverse and highly endemic crayfish fauna. *Hydrobiologia* 846: 39–58, https://doi.org/10.1007/s10750-019-04066-3

Twardochleb LA, Olden JA, Larson ER (2013) A global meta-analysis of the ecological impacts of nonnative crayfish. *Freshwater Science* 32: 1367–1382, https://doi.org/10.1899/12-203.1

Walsh JR, Munoz SE, Vander Zanden MJ (2016) Outbreak of an undetected invasive species triggered by a climate anomaly. *Ecosphere* 7: e01628, https://doi.org/10.1002/ecs2.1628

Wetzel JE, Poly WJ, Fetzner JW (2004) Morphological and genetic comparisons of golden crayfish, *Orconectes luteus*, and rusty crayfish, *O. rusticus*, with range corrections in Iowa and Minnesota. *Journal of Crustacean Biology* 24: 603–617, https://doi.org/10.1651/C-2483

Wilson KA, Magnuson JJ, Lodge DM, Hill AM, Kratz TK, Perry WL, Willis TV (2004) A long-term rusty crayfish (*Orconectes rusticus*) invasion: dispersal patterns and community change in a north temperate lake. *Canadian Journal of Fisheries and Aquatic Sciences* 61: 2255–2266, https://doi.org/10.1139/f04-170