BioInvasions Records (2017) Volume 6, Issue 3: 291–296
DOI: https://doi.org/10.3391/bir.2017.6.3.15

Research Article

Assessing the spread and potential impact of Prussian Carp *Carassius gibelio* (Bloch, 1782) to freshwater fishes in western North America

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Received: 31 March 2017 / Accepted: 11 July 2017 / Published online: 31 July 2017
Handling editor: Ana Ruiz-Navarro

Abstract

Prussian Carp (*Carassius gibelio* Bloch, 1782) is one of the most successful invasive species in Eurasia. Recently, Prussian Carp were genetically confirmed in Alberta, Canada, documenting the first detection of this species in North America. Given the close morphological similarity to their sister species, the Goldfish (*Carassius auratus* Linnaeus, 1758), it is likely that this species has been undetected for some time. We document the spread of Prussian Carp since arrival (circa 2000), and contribute a trait-based risk assessment to potential recipient communities in western North America. Using a meta-analysis of geo-referenced fisheries data in conjunction with original sampling in 2014, we show that the Prussian Carp range has increased by eight- to eleven-fold over 15 years in Alberta at a rate of approximately 233–1,250 km^2 per year. Range expansions in the near future are possible through the Saskatchewan River drainage and south into the Missouri River basin, with easily accessible routes to Midwestern North America through irrigation canals. We show high life history trait overlap with other successful invasive species, such as Goldfish and Common Carp (*Cyprinus carpio* Linnaeus, 1758). Additionally, there was high life history trait overlap with several species of native sunfish (Centrarchidae) and suckers (Catostomidae). This study highlights Prussian Carp's potential to widely impact North American freshwater ecosystems and to successfully compete with native taxa. Considered one of the worst invaders in Eurasia, the arrival of Prussian Carp in North America poses serious concern for fisheries managers. There is an urgent need to develop management plans before further range expansion and disruption of freshwater ecosystems by this new invasive species.

Key words: ecological impact, Cyprinidae, spatio-temporal analysis, trait analysis, range expansion, risk assessment

Introduction

Biological invasions have been identified as one of the biggest threats to freshwater ecosystems over the next 100 years (Sala et al. 2000). Several species from the genus *Carassius* are invaders throughout the globe. Freshwater fishes of the genus *Carassius* are closely related to the Common Carp (*Cyprinus carpio* Linnaeus, 1758) and include Goldfish (*Carassius auratus* Linnaeus, 1758), one of the most widely distributed species globally (Rylková et al. 2013). *Carassius gibelio* (Bloch, 1782), generally referred to as Prussian Carp (also Giebel, Gibel Carp), is one of the most successful invasive species in Europe (van der Veer and Nentwig 2015), with the highest ecological and economic impact of all established invasive species (van der Veer and Nentwig 2015).

Prussian Carp were recently identified in Alberta, Canada and have the potential to establish and expand across much of North America (Elgin et al. 2014). Originally described from north-eastern central Europe, recent evidence suggests two possible clades of Prussian Carp may exist: one in western Mongolia, and a second from Europe, the Russian Federation, eastern Mongolia and China (Kalous et al. 2012). Kalous et al. (2012) described a neotype specimen of Prussian Carp from the Czech Republic as Prussian Carp, and specimens from Alberta, Canada appear to match with this description (Elgin et al. 2014).

Not all non-native species become invasive (i.e. cause negative economic or ecological impacts). However, many invasive species share similar life history characteristics, such as fast rate of growth, a wide tolerance to environmental variables, and a previous history of invasiveness (Kolar and Lodge 2002). Prussian Carp has all these characteristics, with a few additional ones. Among the life history attributes that make Prussian Carp a successful invader is its notable ability to reproduce asexually through gynogenesis (Kottelat and Freyhof 2007; Elgin et al. 2014). However, for successful reproduction, gynogenetic females require the sperm of related species (i.e. individuals from the family Cyprinidae) to activate the development of eggs (Elgin et al. 2014). Additionally, where clonal, triploid females are dominant, males do exist, but they are generally present at very low frequencies (< 1%) (Liasko et al. 2010). This reproductive process, alongside other generalist feeding and tolerance of marginal habitats, can lead to freshwater ecosystems that become overwhelmed by Prussian Carp.

Other life history traits allow Prussian Carp to be a successful invader. Analysis of oocytes (egg development) confirms that Prussian Carp in Turkey is capable of spawning multiple times a year (Şaşi 2008). Further, age at maturity is typically between one and three years, and the average life expectancy of Prussian Carp is 6 years, with a maximum age recorded as 10 years old (Kottelat and Freyhof 2007). Prussian Carp, like many invasive species, also exhibit rapid growth at a young age, affording it a competitive advantage over native species. As an omnivorous species, Prussian Carp also has a broad diet which consists of phytoplankton, zooplankton, benthos, detritus and macrophytes (Richardson et al. 1995; Meyer et al. 1998). Prussian Carp is also flexible in its diet, which can vary widely depending on season, habitat (i.e. lake *vs.* river), geographic location, and life stage (Balik et al. 2003). Finally, Prussian Carp can tolerate marginal eutrophic habitats that are often utilized sparingly by native species (Richardson et al. 1995).

Prussian Carp was genetically confirmed in western North America only recently (Elgin et al. 2014). However, given its close morphological similarity to its sister species, Goldfish, it is likely that Prussian Carp has been misidentified as Goldfish for some time. Historical specimens captured in the Red Deer River near Medicine Hat, Alberta in 2000 were recently identified as Prussian Carp (T. Clayton, *pers. comm*), representing the oldest known record. Other previous voucher specimens identified as goldfish were re-assessed by provincial biologists, and all specimens in the Red Deer River were classified as Prussian Carp (T. Clayton, *pers. comm*.). The latter has prompted calls to characterize the initial establishment and spread of Prussian Carp alongside the need to quantify potential risks to native taxa. Here, we contribute an evaluation of long-term census data to determine where populations may have initially established. We also conducted a recent, comprehensive survey of the general area where the species is thought to occur, but with limited sampling. Lastly, we assess the risks of further spread of Prussian Carp throughout North America by comparing life history trait overlap with native fish species in the North American Midwest.

Methods

To assess the spread of Prussian Carp since its establishment (circa 2000), we conducted an analysis of all available census data in river and lake systems throughout the provinces of Alberta and Saskatchewan in Canada from 2000–2013 (AEP 2015). This meta-analysis demonstrated significant data gaps so addition sampling was conducted in areas where Prussian Carp were thought to occur, but where sampling was deficient: from tributaries of the Red Deer River during more contemporary time periods (i.e. 2011–2014). Field surveys targeted the Red Deer River watershed, including the tributaries: Ghostpine Creek, Three Hills Creek, Kneehills Creek, Lonepine Creek, Rosebud River, Carstairs Creek, Crossfield Creek, West Michichi Creek, Michichi Creek, and three unnamed streams. Sampling was conducted using backpack electrofishing surveys using single-pass electrofishing in an upstream direction with a Smith-Root LR-24 backpack electrofisher, following Alberta's small stream survey protocol (Alberta Fisheries Management Branch 2013). Targeted survey time was 1500 seconds to ensure adequate sampling of the fish community (Poos et al. 2009).

To determine the rate of spread and density of Prussian Carp in Alberta, we evaluated spatial plots in 4-year intervals using a kernel density analysis and percent volume contours. Kernel densities are useful for calculating a species home range based on the likelihood that a species can be found in a specific region (Fortin et al. 2005). We calculated kernel density over a point with a specific radius of 25 km to summarize regional scale changes in their range following the methodology established by Worton (1989). As many of these areas are bifurcating tributaries, such a radius was deemed useful for determining epicenters of establishment. Each kernel is additive, therefore, areas with higher point densities will have higher kernel densities and be represented as darker regions in the map. Likewise, percent volume contours help estimate the potential core (50%) and range extent (95%) at each temporal stage of invasion. All calculations were performed using *ArcGIS 10.2* and *Geospatial Modeling Environment* (Beyer 2012).

To assess the potential risk of competitive success of Prussian Carp over native species, we compiled a list of freshwater fish species found within the Midwest of North America, including Alberta, Saskatchewan, Manitoba, Montana, North Dakota, South Dakota, Minnesota, Wisconsin, Illinois, Wyoming, Idaho, Nevada, Utah, Colorado, Nebraska, Kansas, Arkansas, Oklahoma, Texas, New Mexico, California, Arizona, Iowa, and Missouri based on published census data (Lee et al. 1980; Scott and Crossman 1998; Warren Jr. and Burr 2014), available as supplement (Table S1). We then populated a traits database for each species (n = 181) using information from Frimpong and Angermeier (2009), Scott and Crossman (1998) and Kottelat and Freyhof (2007), where each species was attributed 40 different traits (see Table S2). Finally, we used the Bray-Curtis similarity metric for binary data (Bray and Curtis 1957) to determine how similar species were to Prussian Carp in terms of all traits (40 traits), dietary requirements (11 food types), reproductive traits (7 characteristics), and habitat preferences (22 parameters). Using a Bray-Curtis multivariate distance matrix, we can determine whether species show high (close to 1) or low (close to 0) overlap with Prussian Carp across traits. All calculations were performed using the *vegan* package (Oksanen et al. 2016) in the *R programming environment* (R Development Core Team 2016).

Results

We sampled forty-two sites that covered a total area of approximately 4,700 km^2 in the Red Deer River watershed in 2014 (Table S3). Each site was surveyed for an average of 1734 electrofishing seconds (502–3173 seconds) and added to existed data compiled from the meta-analysis (described below).

Spatial analysis of the range expansion of Prussian Carp over the last 15 years (including sampling conducted in this study) demonstrates that the species has become well established in southern Alberta, Canada (Figure 1). Prussian Carp range extent has increased from about 1,800 km^2 in 2000 to over 20,000 km^2 in 2014, according to the kernel density analysis using a threshold of 95% representing the extended range estimate (Figures 1A–1D). The core range estimate based on a 50% kernel density threshold has a comparable eight-fold increase in area (500 km^2 versus 4,000 km^2; Figure 1A–1D). We found that the highest density of Prussian Carp in the north-western region of the study area, with a core distribution of about 4,000 km^2 (Figure 1D). The spatial arrangement of Prussian Carp appears to be organized into three contiguous and discrete populations. We also confirm the existence of Prussian Carp from a single location in the province of Saskatchewan, Canada (Table S3).

Prussian Carp showed high overlap with many native freshwater fishes. Within the top 25 most similar species, sunfish (family Centrarchidae) appear nine times (Table 1), including the endangered Sacramento Perch (*Archoplites interruptus* Girard, 1854). Specifically, sunfish show strong similarity in habitat preference parameters to Prussian Carp. Additionally, there are four species of suckers (family Catasomidae) that show high similarity in diet overlap (Table 1). Finally, we find that Prussian Carp have similarities with five well established North American invaders, including Goldfish, Tench (*Tinca tinca* Linnaeus, 1758), Oriental Weatherfish (*Misgumus anguillicaudatus* Cantor, 1842), Common Carp, and Mozambique Talapia (*Oreochromis mossambicus* Peters, 1852; Table 1).

Discussion

Prussian Carp have spread rapidly since their first confirmed detection. Since the year 2000, Prussian Carp extent has increased by eight- to eleven-fold, and are now confirmed present in the province of Saskatchewan. Overall, we estimate the spread of Prussian Carp to be between 233–1,250 km^2 per year, with an average doubling time of approximately five years. Although our sampling may have increased the measured extent of Prussian Carp, it is likely that further investigation into either unsampled or undersampled areas, and addressing the potential confusion with Goldfish, will show further range increases. Therefore, we expect the estimates provided here are an under-representation of Prussian Carp spread.

Prussian Carp were widely distributed across a landscape that has a number of known barriers. Given these barriers and wide detection-free distances between locations with this fish, it is likely that the spread of Prussian Carp has been facilitated by human meditated transport. For example, we show three contiguous and widely distributed populations of Prussian Carp from 2006 to present (Figure 1C–D). If these human mediated movements are due to anglers, as suspected, the potential for long-distance dispersal throughout the continental United States may be unknowingly high (Drake and Mandrak 2014), due in part to the large number of anglers in Alberta (> 270,000; AEP 2015) and the potential movement of anglers between Alberta and the United States (no data available).

The spread of Prussian Carp in Alberta, Canada appears to be enhanced not only by human mediated movement, but their utilization of artificial waterways. In most cases, Prussian Carp were found in slow moving riverine habitats, as well as artificial

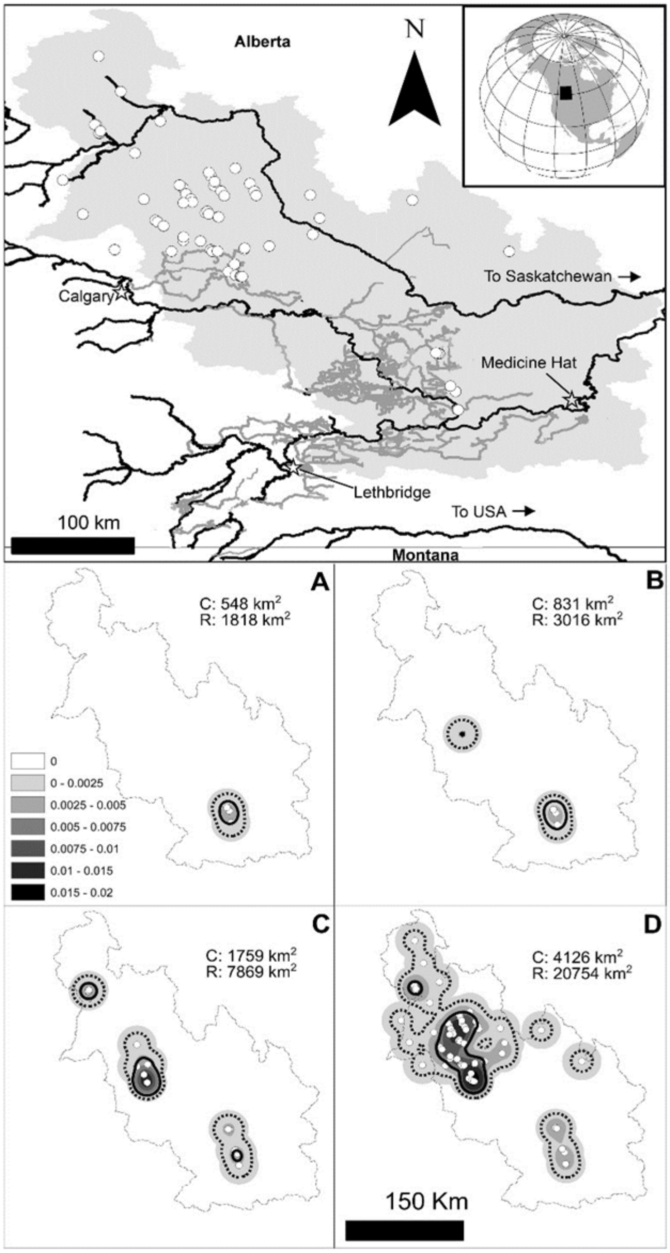

Figure 1. The study area around the Red Deer River watershed in Alberta, Canada with major rivers (black) and canals (grey) in reference to Prussian Carp (*Carassius gibelio*) occurrences from 1999–2014. Density of Prussian Carp is shown for: (A) 1999–2000, (B) 2001–2005, (C) 2006–2010, and (D) 2011–2014 (including sampling by the authors). Shown are occurrences (white circles) alongside core (50% kernel densities; solid lines) and range extent (95% kernel densities; dashed lines). The areas associated with core (C) and range (R) extents are given.

habitats such as ponds, reservoirs, and irrigation canals. Prussian Carp's ability to thrive in artificial habitats has previously been documented, with several studies showing their high affinity for canals, reservoirs and ponds that deviate from typical observed habitat preferences for native species (Ozulug et al. 2004; Sarı et al. 2008; Tarkan et al. 2012). In fact, during our sampling, we noted higher abundances of Prussian Carp in irrigation canals than in natural systems. This provides additional concern for the spread of Prussian Carp throughout North America. Of note is the distance of the current invasion front between the Red Deer watershed and to the Missouri River drainage (approximately 200 km), which is separated by numerous canals to the south, some of which are connected (Figure 1).

If Prussian Carp arrive in the continental United States, there is a high likelihood that they will spread and impact other freshwater systems. For example, an evaluation by the U.S. Fish and Wildlife Service (2012) deemed Prussian Carp to be a "high risk" invasive species. This assessments was based on its history in Eurasia, its biological characteristics, and its climatic compatibility with large areas of the

Table 1. List of the 25 most similar species to Prussian Carp (*Carassius gibelio*) using Bray-Curtis similarity index for all traits, feeding traits only, habitat traits only and reproductive traits only (similarity of all traits and all species is provided in Table S1). Invasive species are denoted by *, bold designates values ≥0.75.

Common Name	Scientific Name	Similarity to Prussian Carp			
		All	Feeding	Habitat	Reproductive
Prussian Carp*	*Carassius gibelio* (Bloch, 1782)	–	–	–	–
Redear Sunfish	*Lepomis microlophus* (Günther, 1859)	0.834	1.000	0.762	0.808
Goldfish*	*Carassius auratus* (Linnaeus, 1758)	0.817	1.000	0.842	0.686
Warmouth	*Lepomis gulosus* (Cuvier, 1829)	0.815	0.600	0.909	0.818
Fathead Minnow	*Pimephales promelas* (Rafinesque, 1820)	0.801	0.909	0.818	0.702
Golden Shiner	*Notemigonus crysoleucas* (Mitchill, 1814)	0.786	0.727	0.842	0.760
Bluegill	*Lepomis macrochirus* (Rafinesque, 1819)	0.784	0.769	0.842	0.739
Black Bullhead	*Ameiurus melas* (Rafinesque, 1820)	0.782	0.923	0.857	0.574
Tench*	*Tinca tinca* (Linnaeus, 1758)	0.769	0.769	0.737	0.795
Tahoe Sucker	*Catostomus tahoensis* (Gill & Jordan, 1878)	0.756	1.000	0.696	0.687
White Crappie	*Pomoxis annularis* (Rafinesque, 1818)	0.755	0.600	0.818	0.764
Black Crappie	*Pomoxis nigromaculatus* (Lesueur, 1829)	0.754	0.600	0.870	0.692
Threadfin Shad	*Dorosoma petenense* (Günther, 1867)	0.753	0.909	0.667	0.744
Sailfin Molly	*Poecilia latipinna* (Lesueur, 1821)	0.748	1.000	0.727	0.605
Gizzard Shad	*Dorosoma cepediannum* (Lesueur, 1818)	0.740	1.000	0.588	0.712
Green Sunfish	*Lepomis cyanellus* (Rafinesque, 1819)	0.733	0.600	0.750	0.786
Pumpkinseed	*Lepomis gibbosus* (Linnaeus, 1758)	0.722	0.667	0.750	0.722
Sacramento Perch	*Archoplites interruptus* (Girard, 1854)	0.719	0.600	0.737	0.761
Oriental Weatherfish*	*Misgurnus anguillicaudatus* (Cantor, 1842)	0.708	0.833	0.588	0.739
Bigmouth Buffalo	*Ictiobus cyprinellus* (Valenciennes, 1844)	0.705	0.909	0.667	0.635
Smallmouth Buffalo	*Ictiobus bubalus* (Rafinesque, 1818)	0.705	0.909	0.700	0.609
Tadpole Madtom	*Noturus gyrinus* (Mitchill, 1817)	0.703	0.600	0.800	0.648
Common Carp*	*Cyprinus carpio* (Linnaeus, 1758)	0.701	0.923	0.750	0.561
Mozambique Talapia*	*Oreochromis mossambicus* (Peters, 1852)	0.698	0.923	0.429	0.740
River Carpsucker	*Carpiodes carpio* (Rafinesque, 1820)	0.698	0.909	0.556	0.710
Rock Bass	*Ambloplites rupestris* (Rafinesque, 1817)	0.697	0.600	0.783	0.637

continental United States, particularly Midwestern North America and the Great Lakes region (U.S. Fish and Wildlife Service 2012; van der Veer and Nentwig 2015). Of particular importance is Prussian Carp's ability to reproduce asexually through gyno-genesis. This type of reproduction is most prevalent in recently colonized areas and is one of the main factors contributing to Prussian Carp's success in becoming established in new environments (Kalous et al. 2004).

Many Midwestern species share similar traits to Prussian Carp. Several of these appear susceptible to competition with Prussian Carp due to their high trait similarity in habitat, feeding and reproduction (Table 1). For example, the habitat preferences of Prussian Carp are the most similar to sunfish species. Sunfish tend to prefer slow moving water and the cover of aquatic vegetation (Scott and Crossman 1998; Frimpong and Angermeier 2009), which is similar to Prussian Carp (Kottelat and Freyhof 2007). Further, we find that suckers are also similar in their feeding preferences as they are benthic consumers of algae, detritus, and invertebrates (Kottelat and Freyhof 2007; Warren Jr. and Burr 2014). Trait overlap with these groups of fish species, indicates the potential for these native species to be displaced, especially if Prussian Carp populations increase dramatically in abundance through asexual reproduction.

The establishment and rapid spread of Prussian Carp in the last 15 years that we have documented in Alberta, Canada should serve as an alert for fisheries managers across North America. Prussian Carp are recognized as one of the most harmful invasive fish species in Eurasia (Kalous et al. 2004). Despite Prussian Carp's longstanding invasion throughout Europe and Asia, there are no successful eradications or management strategies developed to control this species. Awareness of their establishment and spread alongside risk assessments for native ecosystems and species will help to aid managers to reduce their impact in North America.

Acknowledgements

Thanks are due to Laura MacPherson (Alberta Environment and Parks) for providing the historical data used in this study. Funding for this work was provided by NSERC to MP. Sampling was conducted under an approved Alberta Fish Research Licence #14-1532FR and Animal Care Protocol AUP000000757. We thank Dr. Ana Ruiz Navarro (associate editor) and two anonymous reviewers for their helpful comments.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Summary of species similarity to Prussian Carp.

Table S2. Summary of life history traits assessed for similarity with Prussian Carp.

Table S3. Confirmed locations of Prussian Carp in Canada.

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2017/Supplements/BIR_2017_Docherty_etal_Supplement.xlsx