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Present distribution and future spread of louisiana red swamp crayfish *Procambarus clarkii* (Crustacea, Decapoda, Astacida, Cambaridae) in Britain: Implications for conservation of native species and habitats

A. Ellis[(1)*], M.C. Jackson[(2)], I. Jennings[(1)], J. England[(1)], R. Phillips[(3)]

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ABSTRACT

Key-words: *freshwater crayfish,* Procambarus clarkii*, conservation, British isles, invasive species*

The Louisiana red swamp crayfish *Procambarus clarkii* is highly invasive. It is now common in Europe where it is causing problems to native wildlife and structural damage to habitats. *Procambarus clarkii* was first recorded in Britain in 1991 and is currently found in the Hampstead Heath ponds and Regents Canal in London, as well as a small lake 15 km outside of Greater London. This paper considers how conditions in Britain affect the life cycle, breeding habits and potential range expansion of *P. clarkii*. Results of trapping surveys are presented in an effort to map the current distribution of *P. clarkii* and predict which areas it could colonise in the future. The ecological impact of potential colonisation is discussed by considering the impact *P. clarkii* has in mainland Europe. It is concluded that *P. clarkii* is likely to spread from Regents Canal into the nearby Brent, Crane, Colne, Lee and Thames catchments within 50 years. This time would be reduced significantly if further deliberate or accidental introductions by humans occur since this is deemed a far greater risk than natural expansion. *P. clarkii* is expected to have a negative impact on aquatic ecosystems in Britain and therefore tighter enforcement is needed to slow the spread of this species.

RÉSUMÉ

Répartition actuelle et future propagation de l'écrevisse rouge de Louisiane *Procambarus clarkii* (Crustacea, Decapoda, Astacida, Cambaridae) en Grande-Bretagne : implications pour la conservation des espèces indigènes et des habitats

Mots-clés : *écrevisses d'eau douce,* Procambarus clarkii*,*

L'écrevisse rouge de Louisiane *Procambarus clarkii* est très envahissante. Elle est maintenant fréquente en Europe où elle est à l'origine de problèmes à la faune indigène et de dommages structurels sur les habitats. *Procambarus clarkii* a été signalée la première fois en Grande-Bretagne en 1991 et se trouve actuellement dans les étangs Hampstead Heath et le Regents Canal à Londres, ainsi que dans un petit lac à 15 km du Grand Londres. Le présent document examine

(1) Environment Agency, North-East Thames, Apollo Court, 2 Bishops Square, St Albans Rd West, Hatfield, Herts, AL10 9EX, UK
(2) School of Biological and Chemical Sciences, Queen Mary University of London, Mile End Road, London, E1 4NS, UK
(3) Kings College London, School of Biomedical Sciences, 1.14 Hodgkin Building, Guy's Campus, London, SE1 1UL, UK
* Corresponding author: adamgrahamellis@yahoo.co.uk

conservation, îles Britanniques, espèces envahissantes

comment les conditions en Grande-Bretagne affectent le cycle de vie, les traits de la reproduction et l'étendue potentielle d'expansion de *P. clarkii*. Les résultats de recherches par piégeage sont présentés en vue de cartographier la distribution actuelle de *P. clarkii* et de prédire quels domaines elle pourrait coloniser à l'avenir. L'impact écologique de la colonisation potentielle est discuté en tenant compte de l'impact *P. clarkii* en Europe continentale. Il est conclu que *P. clarkii* est susceptible de se propager à partir de Regents Canal dans les milieux proches de Brent, Crane, Colne, Lee et le bassin de la Tamise dans les 50 ans. Cette vitesse d'expansion devrait être sensiblement accélérée si les introductions délibérées ou accidentelles par l'homme se produisent car cela est considéré comme un risque beaucoup plus grand que l'expansion naturelle. *P. clarkii* est considérée comme ayant un impact négatif sur les écosystèmes aquatiques en Grande-Bretagne et l'application plus stricte des règlements est nécessaire pour ralentir la propagation de cette espèce.

INTRODUCTION

The Louisiana red swamp crayfish *Procambarus clarkii* is widely regarded to be the most invasive of all crayfish species (Capinha *et al.*, 2011) and has spread from its native range in south-central USA and north-eastern Mexico to all continents except Australia and Antarctica (Huner, 2002). The species was first introduced to Europe in 1973 when it was imported to Spain for commercial crayfish production (Gutierrez-Yurrita and Montes, 1999). Since, *P. clarkii* has dramatically expanded its range, both through natural expansion and illegal introductions, and is now common throughout south-western Europe and northern Italy (Chucholl, 2011a). It was first recorded in southern Portugal in 1981 (Ramalho *et al.*, 2008) and has since been recorded in Cyprus, England, France, Germany, Italy, Mallorca, the Netherlands, Austria, Belgium and Switzerland (Souty-Grosset *et al.*, 2006; Holdich *et al.*, 2009). The populations in the north-eastern end of this range are more isolated and scattered than those in the South (Chucholl, 2011b). The purpose of this paper is to review all research on *P. clarkii* populations in Britain and to use knowledge gained from mainland Europe to estimate potential spread and conservation implications.

HISTORY OF *PROCAMBARUS CLARKII* CRAYFISH IN BRITAIN

Procambarus clarkii was first recorded in Britain by the National Rivers Authority in 1991 in the Men's Bathing Pond at Hampstead Heath in North London (Figure 1). Hampstead Heath is a 320 ha park containing eleven ponds; many of which are connected through subterranean overflow channels or over ground ditches, which could facilitate the spread of *P. clarkii*. Non-native narrow-clawed crayfish *Astacus leptodactylus* were present prior to 1991 and before 2000, both *A. leptodactylus* and *P. clarkii* appeared to co-exist within the ponds (Richter, 2000). In the summer of 2000, catches of *A. leptodactylus* dropped to zero suggesting a mass mortality of the species (Richter, 2000). Further surveys between 2008 and 2010 found *P. clarkii* present in at least four connected ponds within the park (the Ladies Pond, Men's Pond, Boating Pond and Bird Sanctuary) and *A. leptodactylus* were found in Hampstead Pond No.1 (M.C. Jackson, unpublished data).

The populations of *P. clarkii* found in the Hampstead Heath ponds are unlikely to spread by natural means to other watercourses, as the ponds are isolated from any above ground water. The subterranean River Fleet connects Hampstead Health ponds with the Thames, however it is unclear if crayfish could survive here let alone use it as an expansion corridor.

The second confirmed population of *P. clarkii* in Britain was in Regents Canal in 2000 (Richter, 2000). Surveys in 2008 confirmed the presence of *P. clarkii* in Regents Canal, adjacent to the Zoological Society of London in Camden (Ellis and England, 2008). There is also a record of

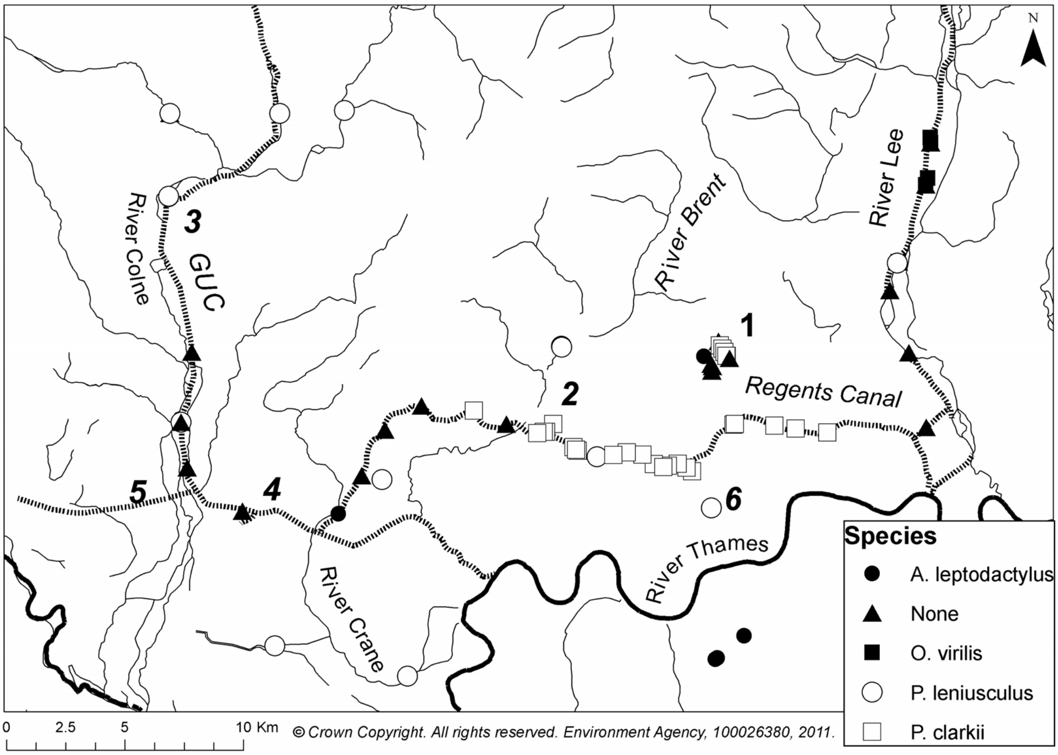

Figure 1

Current known distribution of crayfish in North London, UK. (1) Hampstead Health Ponds; (2) Brent feeder stream; (3) GUC Rickmansworth, reports of established P. leniusculus populations >10 years (Castle, personal com. 2011) ; (4) Yiewsley stretch of GUC & (5) Slough Arm: Lack of any crayfish, as reported by local angling clubs (Milford-Scott and Turton pers. com. 2011) (6) Serpentine Lake, Hyde Park. Environment Agency South-East Region crayfish records 2006 to 2011.

P. clarkii from a roadside ditch in Tilbury in 1990 and a record on the River Lee held by the Essex Biodiversity Group. More recent surveys have shown that if *P. clarkii* was previously present in Tilbury or the River Lee, the populations are either at levels below a detectable range or not present (A. Ellis, unpublished data).

There have also been instances where isolated individuals have been found in the wild, thought to be linked to aquarium escapees. Individuals were found at two separate locations in Kent during 1994, one berried female was kept in an aquaria at ambient temperature where the eggs hatched successfully (Foster, 1996). It was not thought that these individuals were linked to wild populations, and no further records exist in these areas (J. Foster, personal communication, February 2012).

A new population of *Procambarus* crayfish was found in a small fishing lake near Windsor (Figure 2) in May 2012, the exact species is yet to be confirmed but thought not to be *Procambarus clarkii*. This is approximately 25 km from the Regents Canal population, and represents a new population for the species in Britain. There is a ditch which runs close to the lake with connectivity to the River Thames (~23 km), although it is unclear if the species has migrated out of the lake. At the time of writing this population had only just been discovered and investigation is currently underway to discover the source of population.

THE NORTH LONDON CANAL SYSTEM AND ITS CRAYFISH FAUNA

British Waterways manage 3200 km of waterways, most of which have some fluvial connectivity. In some areas, where non-indigenous crayfish are not present, the native White-clawed

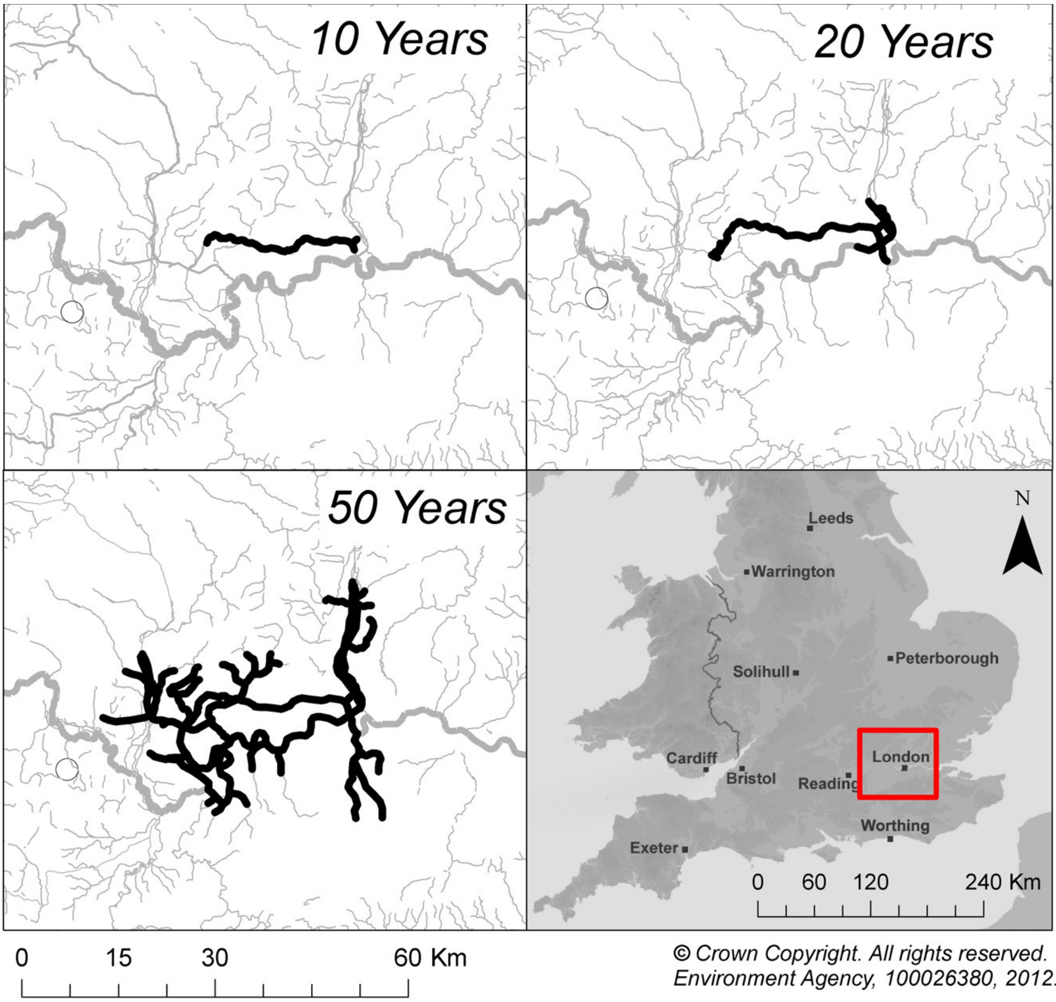

Figure 2
The predicted spread of Red Swamp Crayfish Procambarus clarkii in Britain in 10, 20 and 50 years based on knowledge of spread between 2000 and 2011. Black lines represent predicted range, thin grey lines rivers and canals and thick black line the River Thames. The new lake population found in 2012 is represented by a white circle. Insert shows location within a national context.

crayfish *Austropotamobius pallipes* can be found in high densities within the canal network (Brickland *et al.*, 2006).

Regents Canal and the Paddington arm are the most southerly section of the Grand Union Canal (GUC), the main 220 km arm of which connects London with Birmingham. Within the study site channel width varied between 15 m and 25 m, with mean depths of 1.2 m, edging is largely composed of metal and concrete sheet piling with small areas of naturalised banks.

The first record of crayfish in London's canals was in 1986 when *A. leptodactylus* were found in Hampstead Road Lock on the GUC (Ingle and Clark, 1989). By 1991 *A. leptodactylus* was present in 40 km of canal in North London as well as a record from the River Crane in 1994 (Holdich and Reeve, 1991). At some point between 1991 and 2008 the population of *A. leptodactylus* in the canals appears to have significantly declined, although no surveys appear to have been undertaken during this period.

Two separate sampling efforts were used to ascertain spread of *P. clarkii*, one covering 12 sites over a wide spatial range (5 baited traps per site, approximately 2 km apart for 48 h) at the end of May 2011 and the other in July at fourteen sites evenly spread over approximately 3 km. Each site in this sampling effort had one baited trap checked daily for fifteen days. All

Table I
Descriptive statistics for two sampling efforts carried out in May and July 2011. Results shown for Male (M), Female (F) and for both combined.

	Jul-11			May-11		
	F	M	Combine	F	M	Combined
Sample size	20	42	62	2	6	8
Carapace length (mm)						
Mean ± Std error	56.7 ± 1.5	54.5 ± 1.0	55.2 ± 0.9	64.4 ± 0.7	56.5 ± 3.8	58.4 ± 3.0
Min	47.5	36.3	36.3	63.7	40.0	40.0
Max	70.0	66.3	70.0	65.1	67.3	67.3

traps used were modified Swedish trappy traps, with fine mesh added to enable capture of a wider size range of crayfish, baited with fresh oily fish.

We found one *A. leptodactylus* (female, carapace length 32.5 mm) adjacent to an outflow to the River Crane, approximately 6 km to the west of the known *P. clarkii* range (Figure 1). This individual was found in a section of canal outside of the known range of *P. clarkii* and *P. leniusculus* and therefore may have been in an area unaffected by crayfish plague. Additionally, recent research has shown that *A. leptodactylus* may be able to develop a partial resistance to crayfish plague (Hokko *et al.*, 2012). Of the 26 sites surveyed over 41 km; 15 were found to have *P. clarkii* present, indicating an approximate linear range of 11 km (Figure 1). A single signal crayfish (*Pacifastacus leniusculus*; female, carapace length 57.3 mm) was found to be coexisting with *P. clarkii* at approximately the mid-point of their known range (Figure 1). This represents the first record of *P. leniusculus* in the Lower GUC, and might indicate range overlap between *P. clarkii* and *P. leniusculus* in the UK.

Mean CPUE (catch per unit effort, the number of crayfish caught per trap per 24 hour period) for *P. clarkii* was 0.2 and 0.32 in May and July, respectively (excluding sites trapped outside of the known range of the species). Catch statistics are summarised in Table I.

In the GUC, approximately 20 km north-west of the known *P. clarkii* range, there is an abundant *P. leniusculus* population which has been present for over 10 years (Figure 1, point 3; J.Castle, personal communication October 2011). Further south on the Paddington Arm (Figure 1, point 5) and GUC (Figure 1, point 4), there have been no reports of crayfish from local angling clubs (Milford-Scott and Turton, personal communication October 2011). To the east of the known *P. clarkii* population, the GUC is connected to the River Lee by Regents Canal and the Hertford Union Canal. The lower section of the River Lee, downstream of Tottenham Lock has no record of crayfish being present. This area suffers from periodic water quality issues which may prohibit crayfish from surviving. Upstream of Tottenham Lock, where water quality is improved, an established population of virile crayfish *Orconectes virilis* is present (Ahern *et al.*, 2008), as well as a recent record for *P. leniusculus* (M.C. Jackson, unpublished data).

In 2010 Environment Agency Fishery surveys found *P. leniusculus* on the lower River Crane. *P. leniusculus* were also observed in large numbers in the Brent Reservoir in 2009 and in the Serpentine Lake in Hyde Park in 2010, where they appear to have replaced a once abundant *A. leptodactylus* population (P. Clark, personal communication 2010).

A WARM-WATER CRAYFISH IN A TEMPERATE ENVIRONMENT

The potential for a species to be invasive depends on several factors such as its ability to withstand environmental change, utilisation of a wide range of food sources, early maturity, rapid growth, high fecundity and resistance to disease (Gherardi *et al.*, 2002b). *Procambarus clarkii* has all of these traits (Huner, 2002) and the species is well known for its ecological plasticity (Gutierrez-Yurrita and Montes, 1999; Alcorlo *et al.*, 2004). *Procambarus clarkii* can even adapt to extreme environments, including temporary streams and polluted water (Scalici and Gheradi, 2007).

As the native habitat of *P. clarkii* is subtropical, it is likely that northern Europe's cooler climate has a sub-optimal temperature range which may restrict the spread of the species. Britain has an oceanic temperate climate, and receives higher levels of precipitation and cooler temperatures than south-west continental Europe. Mean annual temperatures in London are 11 °C, with the coldest (January) and warmest (July) months having mean daily minimum temperatures of 3 °C and mean daily maximum 22.5 °C, respectively. (UK Met Office data, accessed June 2012). The preferred temperature of *P. clarkii* is 21–27 °C (Chucholl, 2011a), and lower temperatures may restrict the breeding season (Chucholl, 2011a). In London, mean temperatures of over 20 °C last for approximately three months of the summer. In the Hampstead Heath ponds it appears that, as in Germany, that *P. clarkii* only breed once a year, with juveniles found in October (Richter, 2000).

Procambarus clarkii is able to produce at least two generations a year in its native range (Huner, 2002) and in parts of its invasive range in southern Europe (Gherardi *et al.*, 1999; Gherardi, 2006; Scalici and Gheradi, 2007). In optimal conditions, over 600 eggs per berried female have been observed (Huner, 2002) and even in cooler climates the mean number of eggs was 285 per female (Chucholl, 2011b). In Germany, the most north-eastern range of *P. clarkii* in Europe, the mean lifespan was found to be 3.5 to 4 years (Chucholl, 2011b) compared to 12–18 months in its native and introduced sub-tropical range (Huner, 2002). The same study also found mean crayfish size was increased in colder climates indicating the species was adapting more k-selected life history traits (Chucholl, 2011b).

In laboratory conditions *P. clarkii* was found to grow faster in warmer water, and may cease growth at temperatures lower than 15 °C (Mazlum, 2007). However, the survival of *P. clarkii* was higher at lower temperatures, with ten times higher mortality at 18–26 °C than at 10 °C (Mazlum, 2007). There is evidence that *P. clarkii* is able to withstand cold winter temperatures by burrowing (Gherardi *et al.*, 2002a) and they have been shown to survive winters colder than those in England underneath ice in a German lake (Dehus *et al.*, 1999). As *P. clarkii* have already been found to be breeding in the Hampstead Heath ponds (Richter, 2000) it is unlikely that temperature is a limiting factor to their spread, at least in southern England.

In its native range *P. clarkii* prefers the habitat of temporary lentic waters and can survive the drying up of seasonal water bodies by burrowing or migrating across land to new habitats (Huner, 2002). In central and northern Europe *P. clarkii* has been chiefly found in lentic waters, despite lotic waters being present nearby (Chucholl, 2011a). At higher latitudes, it may be easier for *P. clarkii* to survive in slow flowing water which heats up faster and reaches higher summer temperatures than fast flowing water (Bernado *et al.*, 2011). This indicates that lentic waters represent a more suitable habitat for *P. clarkii* in Northern Europe (Chucholl, 2011a). The preference of *P. clarkii* for slow flowing waters may mean the species is less likely than other introduced crayfish species, *e.g. P.leniusculus*, to spread along river systems in Britain. On the other hand they are able to migrate across land for considerable distances, and by this means they have spread from an initial introduction in a lake in Germany to surrounding lakes with no connecting surface water (Chucholl, 2011a).

DISPERSAL OF *PROCAMBARUS CLARKII*

P. clarkii dispersed from Spain, where it was introduced in the 1970s, across the border to Portugal, France and Italy within 20 years (Dieguez-Uribeondo and Soderhall, 1993; Gherardi *et al.*, 2002a). It is difficult to determine to what extent the spread of *P. clarkii* in Europe is natural, but most likely a large proportion, especially inter-catchment movements are due to deliberate and accidental introductions by humans.

Rates of spread though river systems have been estimated at 1.74 km.yr^{-1} in Portugal (Bernado *et al.*, 2011). Radio telemetry studies have shown movements between 1.1 and 4.6 m.d^{-1} in an irrigation ditch in Italy (Gherardi *et al.*, 2002a) and 1 to 11 m.d^{-1} in a temporary stream in Southern Portugal (Gherardi *et al.*, 2002b). Movements of individual crayfish have been recorded up to 17 km in just four days in a wetland system in Spain (Gherardi and Barbaresi, 2000). In Regents Canal *P. clarkii* have been found over a range of 11 km; this area of canal is particularly homogenous with little or no discernible flow therefore we can assume upstream and downstream expansion rates to be similar. The first record of *P. clarkii* in Regents Canal was in 2000 (near Regents Park) so we can assume an approximate mean rate of spread of 0.5 km.y^{-1}. It is possible that the extent of the population is greater than 11 km, with the leading edge of a population difficult to detect, therefore actual rate of spread is likely to be higher. Additionally, the population may still be in a 'build-up' phase and therefore, if the population reaches larger densities, dispersal rates could accelerate (*i.e.* density-dependent dispersal; Anholt, 1995).

Based on estimated rates of expansion it is likely that *P. clarkii* will spread through most connected watercourses within Greater London within 50 years, including catchments such as the Crane, Brent, Colne, Lee and Thames (Figure 2). These estimates will be reduced if the species is able to cross land bridges between watercourses which is probable since they are known to leave water to feed (Grey and Jackson, 2012). Furthermore, agricultural drainage systems and the extensive canal network in London and environs will facilitate the spread of *P. clarkii* since they have fine substrate, slow flow and are highly connected, making them ideal corridors for *P. clarkii* dispersal (Peay *et al.*, 2010). All of these watercourses already harbour populations of *P.leniusculus* and Chinese Mitten Crab *Erichier sinensis* and the River Lee also has *O.virilis*. These invaders have the potential to compete with *P. clarkii* which may limit their range expansion. *Procambarus clarkii* would most likely not be limited by the presence of *P. leniusculus*, as *P. clarkii* has been shown to be able to out-compete this species in laboratory conditions (Richter, 2000) and in an American lake (Mueller, 2007). However, where *P. clarkii* and *P.leniusculus* co-exist in North-East Portugal the former was found to dominate in warmer lowland areas, while the latter showed a competitive advantage in cooler upper reaches (Bernado *et al.*, 2011) and hence, *P.leniusculus* might dominate in the cooler water temperatures found in the UK.

ECOLOGICAL AND CONSERVATION IMPLICATIONS

Crayfish are one of the most destructive invaders in freshwater habitats, altering the structure of ecosystems and instigating changes in ecosystem processes, for example, by homogenising community assemblages and altering rates of both primary production and decomposition (Gherardi and Acquistapace, 2007). *Procambarus clarkii* is an opportunistic omnivore which can feed on macrophytes, algae, invertebrates and detritus (Alcorlo *et al.*, 2004; Gherardi, 2006; Gherardi and Acquistapace, 2007, 2007) and therefore, can have profound impacts on food web structure. In Spain *P. clarkii* was found to be mainly herbivorous, but exploited invertebrates as prey when they were present in high densities and cannibalism also occurred when crayfish densities were high (Alcorlo *et al.*, 2004). In Europe, *P. clarkii* has caused considerably changes in benthic invertebrate community structure and has a particular strong negative impact on snails due to direct consumption (Gherardi and Acquistapace, 2007). The loss of snails can be detrimental since they have an important functional role as grazers and hence, their disappearance may lead to an increase in periphyton (Gherardi and Acquistapace, 2007). *P. clarkii* can also indirectly cause the loss of plants by increasing turbidity and eutrophication through disturbance of sediment while bottom feeding (Alcorlo *et al.*, 2004).

Many North American crayfish species, including *P. clarkii,* can carry the crayfish plague causative agent *Aphanomyces astaci* as a chronic latent infection (Dieguez-Uribeondo and Soderhall, 1993). *P. clarkii* could have a devastating impact if they occupy an environment where native *Austropotamobius pallipes* are present in Britain, not just through the spread of crayfish plague, but also by direct competition and by predator-prey interactions (Scalici and Gheradi, 2007).

Procambarus clarkii have been shown to burrow into river and lake edges (Correia and Ferreira, 1995; Huner, 2002) and this behavioural adaptation allows the species to avoid extremes of temperature, dry periods and provides refuge from predation (Gherardi *et al.*, 1999; Gherardi *et al.*, 2002a). Where a large number of burrows are found this can lead to significant de-stabilisation and erosion (Barbaresi *et al.*, 2004).

The adjacent Colne and Lee river catchments are home to ex-gravel pit and reservoir sites designated by the Habitats Directive (Special Protected Areas) and the RAMSAR convention, as well as Sites of Species Scientific Interest (SSSI). Although there are limited aquatic links to these water bodies, *P. clarkii* can easily move across land (Chucholl, 2011a) or the species could spread by piscivorous birds and through deliberate and accidental introductions by humans. These sites are nationally important for breeding and wintering birds, and in warmer climates it has been observed that the introduction of *P. clarkii* can cause loss of macrophytes and ultimately loss of avian diversity and abundance (Rodriguez *et al.*, 2003). Amphibian species richness can also be reduced in the presence of *P. clarkii* (Cruz *et al.*, 2006) through direct predation on eggs and larvae as well as habitat modification. There may be an implication locally if *P. clarkii* were to move into ponds containing Great Crested Newt *Triturus cristatus* populations.

CONCLUSIONS

Based on initial findings the rate of spread of *P. clarkii* in Britain is relatively slow compared to populations elsewhere. Semi-quantitative trapping has shown a relatively low density population compared to nearby crayfish populations on the River Lee Navigation ($>$11 CPUE *O.virilis* and $>$17 CPUE *P.leniusculus* using similar methodology; A. Ellis, unpublished data). The reasons for the relatively low density of crayfish is unclear, it is possible that habitat is limiting density however *O.virilis* in similar heavily modified canal habitat has expended rapidly in the same time scale. In the relatively cool climate of the UK it may be that the population has a long build up phase and that we are currently not observing an established population. Further work to look at the population dynamics of this population is needed.

There are currently no specific restrictions on the consenting of trapping applications for *P. clarkii* under section 27A of the Salmon and Freshwater Fisheries Act 1981. In 2011 there were five consents issued to trap in the area where *P. clarkii* are known to exist in the GUC (Environment Agency Live Fish Movement Database, accessed December 2011). An exemption in the Prohibition of Keeping of Live Fish (Crayfish) Order 1996 allows live crayfish to be transported and stored for human consumption. This increases the risk of both accidental and intentional introductions and provides a much greater threat than natural expansion, despite *P. clarkii* being listed on schedule 9 of the Wildlife and Countryside Act (1981), which prohibits their release into the wild, since 2010. The discovery of a new potentially established lentic population outside of London in 2012 suggests there may be *P. clarkii* populations yet undiscovered elsewhere in Britain. A combination of tighter enforcement and education is therefore needed to slow the spread of this species whilst they are still relatively isolated.

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