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The effects of non-native signal crayfish (*Pacifastacus leniusculus*) on fine sediment and sediment-biomonitoring

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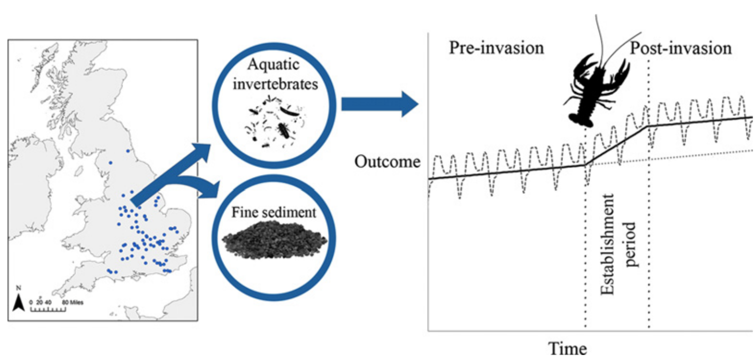
HIGHLIGHTS

- The North American signal crayfish has invaded freshwaters throughout Europe.
- Signal crayfish may influence biomonitoring tools and/or fine sediment conditions.
- Long-term environmental data is analysed using Interrupted Time Series analysis.
- Small changes to biomonitoring tools and fine sediment followed crayfish invasions.
- Signal crayfish appear unlikely to lead to incorrect diagnoses of sediment pressure.

GRAPHICAL ABSTRACT



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ABSTRACT

The North American signal crayfish (*Pacifastacus leniusculus*) has invaded freshwater ecosystems across Europe. Recent studies suggest that predation of macroinvertebrates by signal crayfish can affect the performance of freshwater biomonitoring tools used to assess causes of ecological degradation. Given the reliance on biomonitoring globally, it is crucial that the potential influence of invasive species is better understood. Crayfish are also biogeomorphic agents, and therefore, the aim of this study was to investigate whether sediment-biomonitoring tool outputs changed following signal crayfish invasions, and whether these changes reflected post-invasion changes to deposited fine sediment, or changes to macroinvertebrate community compositions unrelated to fine sediment.

A quasi-experimental study design was employed, utilising interrupted time series analysis of long-term environmental monitoring data and a hierarchical modelling approach. The analysis of all sites ($n = 71$) displayed a small, but statistically significant increase between pre- and post-invasion index scores for the Proportion of Sediment-sensitive Invertebrates (PSI) index biomonitoring tool (4.1, $p < 0.001$, 95%CI: 2.1, 6.2), which can range from 0 to 100, but no statistically significant difference was observed for the empirically-weighted PSI (0.4, $p = 0.742$, 95%CI: −2.1, 2.9), or fine sediment (−2.3, $p = 0.227$, 95%CI: −6.0, 1.4). Subgroup analyses demonstrated changes in biomonitoring tool scores ranging from four to 10 percentage points. Importantly, these subgroup analyses showed relatively small changes to fine sediment, two of which were statistically significant, but these did not coincide with the expected responses from biomonitoring tools. The results suggest that sediment-biomonitoring may be influenced by signal crayfish invasions, but the effects appear to be context

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dependent, and perhaps not the result of biogeomorphic activities of crayfish. The low magnitude changes to biomonitoring scores are unlikely to result in an incorrect diagnosis of sediment pressure, particularly as these tools should be used alongside a suite of other pressure-specific indices.

1. Introduction

Biological invasions of non-native species (herein invasive species) represent a significant threat to global biodiversity (Simberloff et al., 2013). Invasive species can exert strong pressures on the resident native biota of invaded habitats, both directly, through predation, competition or displacement, and indirectly by disrupting trophic dynamics (Lodge et al., 2012; Early et al., 2016), and altering the physical and chemical characteristics of the habitat (Johnson et al., 2011; Fei et al., 2014; Greenwood and Kuhn, 2014). With freshwater invasions expected to increase as a result of climate change and globalisation, invasive species have the potential to result in widespread ecological impacts; defined as measurable changes to the state of an ecosystem (Ricciardi et al., 2013; Kumschick et al., 2015).

In Europe, one widespread freshwater invasive species is the North American signal crayfish (*Pacifastacus leniusculus*). Signal crayfish are omnivorous, opportunistic feeders, consuming algae, detritus, macrophytes, benthic macroinvertebrates, fish and other crayfish (Harvey et al., 2011). Recent research has suggested that predation on macroinvertebrates by signal crayfish (McCarthy et al., 2006; Mathers et al., 2016a), can lead to changes to biomonitoring tool outputs (Mathers et al., 2016b). Given the reliance of regulatory agencies globally on biomonitoring tools to diagnose ecological degradation in freshwater ecosystems (Birk et al., 2012), it is crucial that the potential for invasive species to influence tool outputs is better understood (MacNeil et al., 2013).

Sediment-specific indices (e.g. Proportion of Sediment-sensitive Invertebrates index; PSI, Extence et al., 2013, and Empirically-weighted Proportion of Sediment-sensitive Invertebrates index; E-PSI, Turley et al., 2016), which use macroinvertebrate community composition, have been developed to monitor fine sediment impacts. The PSI index has been shown to exhibit inflated scores following crayfish invasions (Mathers et al., 2016b). Higher PSI scores are normally indicative of lower fine sediment conditions, however, Mathers et al. (2016b) suggested that the post-invasion inflation of PSI scores were likely the result of selective predation by crayfish. Other research has shown decreased abundance of Gastropoda, Bivalvia and Hirudinea (preferential prey of crayfish; Crawford et al., 2006; Haddaway et al., 2012; Dorn, 2013), and a shift in community composition towards more mobile taxa that are able to avoid predation (Mathers et al., 2016a). These taxa generally score highly in the PSI index, resulting in a higher overall PSI score being recorded.

Crayfish are considered to be biogeomorphic agents, with the ability to rework substrate, increase suspended particulate matter, and alter stream sediment dynamics, primarily due to their burrowing in river banks (increasing erosion and bank collapse), construction of pits and mounds, their large size, aggressive nature, and general movement and foraging on the river bed (Harvey et al., 2011; Johnson et al., 2011; Rice et al., 2012; Albertson and Daniels, 2016). Therefore, whilst the effects on sediment-biomonitoring tool outputs may be the result of shifts in community composition from direct predation and/or the resulting changes to food web dynamics, they could also be partly the result of alterations to fine sediment conditions (i.e. resuspension of deposited fine sediment) caused by signal crayfish - a confounding factor that was not investigated by Mathers et al. (2016b).

The aim of this study was to utilise a quasi-experimental study design and interrupted time series (ITS) analysis to investigate whether inflation of sediment-biomonitoring tool (PSI and E-PSI) scores occurred following signal crayfish invasions, and whether this was associated with changes to deposited fine sediment over time, or shifts in macroinvertebrate community composition resulting from other effects of crayfish invasion (direct or indirect). Interrupted time series analysis is able to estimate the effects of an intervention (e.g. invasion), taking account of pre-intervention long-term and seasonal trends, and autocorrelation, which are common in ecological applications (Friberg et al., 2009). The application of such techniques in epidemiology and clinical research is relatively common (Bernal et al., 2016; Gasparrini, 2016), however its use within invasion ecology is rare (e.g. Brown et al., 2011), likely due to the challenges of obtaining long term data for pre- and post-invasion periods. Time since invasion is an important consideration when studying the impact of invasive species on the receiving ecosystem and therefore, time series data are likely to provide important insights into these impacts (Strayer et al., 2006; Kumschick et al., 2015).

A further aim of this study was to investigate the influence of stream characteristics; habitat heterogeneity and percentage of coarse substrate, on invader impacts. A stream with high habitat heterogeneity/complexity is likely to provide a greater variety of habitat for benthic macroinvertebrate refugia, than those with homogeneous habitat, potentially resulting in increased community stability and resilience to predation (Brown and Lawson, 2010; Kovalenko et al., 2012). Substrate composition is a characteristic typically related to longitudinal gradients associated with channel gradient, stream power and flow (Church, 2002), and is thought to be an important driver of macroinvertebrate community composition (Minshall, 1984). Macroinvertebrate taxa have a variety of habitat preferences as a result of their biological traits (Extence et al., 2013), and as such, a stream with a high percentage of coarse substrate is likely to be inhabited by a different macroinvertebrate assemblage to one dominated by fine sediment. Signal crayfish invasions may impact these different assemblages to varying degrees, for example, due to the availability of preferential prey items.

This study was led by the following five hypotheses:

Hypothesis 1. The family-level PSI and E-PSI index scores are inflated after signal crayfish invasions.

Hypothesis 2. The percentage of fine sediment is lower at sites post-invasion compared with pre-invasion.

Hypothesis 3. The abundances of preferential crayfish prey taxa (e.g. Gastropoda and Hirudinea) are lower in the post-invasion periods.

Hypothesis 4. Changes to PSI and E-PSI index scores in post-invasion periods will be greatest at sites with low habitat heterogeneity.

Hypothesis 5. Changes to PSI and E-PSI index scores in post-invasion periods will be greatest at sites with low percentages of coarse substrate.

2. Methods

2.1. Site selection

The stream and river sites were selected from a database comprising all past macroinvertebrate samples collected by the Environment Agency of England. A systematic search of the entire database for "*Pacifastacus leniusculus*" returned all stream and river sites in England