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Research Article

Environmental conditions can affect the spatiotemporal variation of invasive crayfish abundance in agricultural marshlands

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Abstract

Understanding the long-term trends of biological invasions and their drivers is a pivotal issue. However, it is challenging because collecting presence/abundance data of invasive species as well as environmental/biotic factors over a period of years is time-consuming and therefore such data is scarce compared to short-term studies. Here, we investigated whether environmental and biotic factors in highly regulated eutrophic marshlands (water regime, physico-chemistry, habitat features, and predatory fish biomass) successfully accounted for spatiotemporal trends in abundance of small and large red swamp crayfish (*Procambarus clarkii*) in drainage ditches over seven consecutive years. For this, we used length-frequency data collected during the annual peak in crayfish activity. We also explored whether variation in crayfish abundance over time was due to density-dependent effects (temporal autocorrelation). We found large variation in crayfish abundance expressed in capture per unit effort (CPUE) between ditches and for different years (by a factor of 10 and 6 for small and large individuals) but with no specific trend over time. No density-dependent effect was found in any of the ditches. While crayfish CPUE was poorly related to the water regime (in particular dryness intensity of ditches for small crayfish), it was favoured by densely vegetated banks and negatively linked to the density of surrounding ditches for the two life stages. No relationship was detected with predatory fish biomass or any of the other environmental factors studied. Controlling crayfish abundance by managing environmental conditions seems possible in some cases, but likely costly for other components of biodiversity. Trapping could be a possible strategy when populations dropped to low densities in places. Finally, further studies are needed in ecosystems covering a wider range of environmental conditions to provide a more comprehensive understanding of the long-term trend of the species.

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Key words: Ditch network, length-frequency data, riparian vegetation, seasonally flooded marshland, size classes, time-series, water regime

Introduction

Biological invasions are currently recognised as one of the major threats to biodiversity and ecosystem functioning worldwide (Simberloff et al. 2013; Bellard et al. 2016). In comparison to some specific related issues (in particular, ecosystem vulnerability to invasions, life-history traits of invasive species, and impacts of biological invasions; Fridley et al. 2007; Lowry et al. 2012; Hui et al. 2016; Hovick et al. 2023), though, the long-term population dynamics of invasive species (*sensu* Haubrock et al. 2022) are surprisingly poorly documented. However, such knowledge is critical in the field of invasion management (Haubrock et al. 2023). The local abundance of invasive populations can vary considerably over time (Simberloff and Gibbons 2004; Sandström et al. 2014; Cooling and Hoffmann 2015; Ewers et al. 2023) due to both density-dependent and density-independent processes (Hui and Richardson 2017). Therefore, coupling demographic data with environment factors can provide an understanding of the dynamics of biological invasions, and the possible applied implications (Clavero and Villero 2014; Guareschi et al. 2021). However, for local non-equilibrium populations of invasive species (see the boom-bust population dynamics; Lester and Gruber 2016; Strayer et al. 2017; Wasson et al. 2020; Pintar et al. 2023), it can be challenging to explain variation in abundance as related to environmental conditions (Pili et al. 2020). In addition, studying the influence of environmental factors requires time-series datasets because of possible time lag effects (Sandlund et al. 1999).

Freshwater ecosystems are particularly impacted by biological invasions (Ervin et al. 2006; Lázaro-Lobo and Ervin 2021), notably by invasive crayfish, which are considered to be some of the most widespread and harmful invasive aquatic species worldwide (Gherardi 2006; Savini et al. 2010; Lodge et al. 2012; Twardochleb et al. 2013). In Western Europe, inland waters in particular have been largely colonised by the American red swamp crayfish (*Procambarus clarkii*, Girard 1852), historically in Spain [in the course of the 1970s (Gherardi et al. 1999; Gherardi 2006)]. In France, where the present study took place, the species was introduced in 1974, and is nowadays widely distributed throughout the country [for a detailed invasion history, country by country, see Oficialdegui et al. (2020)]. Its successful invasion dynamics is generally explained by its high tolerance to a wide range of environments, its remarkable ecological plasticity (Nyström 2002), and also by intentional or accidental introductions facilitating its expansion (Banha and Anastácio 2015; Oficialdegui et al. 2020). Its impacts on recipient ecosystems, biodiversity, and human health have been extensively documented (Rodríguez et al. 2005; Siesa et al. 2014; Souty-Grosset et al. 2016; Watanabe and Ohba 2022).

A number of studies have investigated the relationships between natural fluctuations of red swamp crayfish abundance and environmental conditions (including water regime, water physico-chemistry and habitat features) in a diversity of inland waters (see the non-exhaustive review in Table 1). By comparison, the influence of biotic factors (specifically predators) on natural fluctuations of red swamp crayfish abundance remains poorly studied (Table 1), even though there are many known predators of red swamp crayfish (birds, mammals, reptiles, and fish; Correia 2006; Aquiloni et al. 2010; Tablado et al. 2010; Reynolds 2011). Our review highlights the preponderance of short-time studies, the fact that many environmental factors have often been considered independently in various invasion contexts and histories (from a few years to up to 80 years when specified) across studies. These limitations prevent clear conclusion from having been drawn up to now on the main drivers of natural fluctuations in red swamp crayfish abundance over the long term. More specifically, there is no unequivocal observed effect of environmental factors on red swamp

Table 1. Non-exhaustive review of the observed effects (effect sign: +, - or 0) of environmental variables (water regime, water quality, habitat features and a biotic one) on adult (large) red swamp crayfish abundance (number or biomass data). Time from invasion, study duration and study habitats are added. One study is cited several times when it involves different environmental variables.

Environmental variables		Effect sign	Time from invasion (year)	Study duration (year)	Habitats	Reference
Water regime	Hydroperiod	+	30	1	Canal, marsh, ricefield, river	Alcorlo et al. 2009
	Hydroperiod	+	20	1	Canal, marsh, ricefield, temporary pond	Meineri et al. 2014
	Hydroperiod	-	20	1	Canal, marsh, ricefield, temporary pond	Meineri et al. 2014*
	Water depth	-	3	2	Marsh, lake	Donato et al. 2018
	Water depth	-	15	1	Canal, river	Gavioli et al. 2018
	Water depth	+	NA	2	Ricefield, ditch,	Zhou et al. 2023
	Water flow	-	15	1	Canal, river	Gavioli et al. 2018
	Water flow	0	25	4	River	Sousa et al. 2013
Water physi-co-chemistry	Chlorophyll a	+	15	1	Canal, river	Gavioli et al. 2018
	Dissolved organic matter	+	30	1	Canal, marsh, ricefield, river	Alcorlo et al. 2009
	Dissolved solids	0	30	15	Canal, marsh, ricefield, river	Alcorlo et al. 2009
	Dissolved solids	0	15	30	Canal, river	Gavioli et al. 2018
	Dissolved oxygen content	-	NA	30	Lake	Yuyu et al. 2022
	Dissolved oxygen content	-	15	1	Canal, river	Gavioli et al. 2018
	pH	0	30	1	Canal, marsh, ricefield, river	Alcorlo et al. 2009
	pH	+	NA	3	Lake	Yuyu et al. 2022
	Redox	-	NA	3	Lake	Yuyu et al. 2022
	Salinity	0	30	1	Canal, marsh, ricefield, river	Alcorlo et al. 2009
	Salinity	0	80	1	Pond	Kobayashi et al. 2011
	Salinity	-	20	1	Canal, marsh, ricefield, temporary pond	Meineri et al. 2014*
	Salinity	0	25	4	River	Sousa et al. 2013
	Temperature	+	30	1	Canal, marsh, ricefield, river	Alcorlo et al. 2009
	Temperature	0	3	2	Lake	Donato et al. 2018
	Temperature	+	25	4	River	Sousa et al. 2013
	Temperature	+	NA	3	Lake	Yuyu et al. 2022
	Total N and P	+	NA	3	Lake	Yuyu et al. 2022
	Turbidity	0	15	1	Canal, river	Gavioli et al. 2018
	Turbidity	-	NA	3	Lake	Yuyu et al. 2022
	Turbidity	0	NA	2	Ricefield, ditch,	Zhou et al. 2023
Habitat features	Aquatic vegetation	0	80	1	Pond	Kobayashi et al. 2011
	Bank vegetation	+	3	2	Marsh, lake	Donato et al. 2018
	Bank vegetation	+	15	1	Canal, river	Gavioli et al. 2018
	Litter input	+	80	1	Pond	Kobayashi et al. 2011
	Bottom substrate	+	3	2	Marsh, lake	Donato et al. 2018
	Bottom substrate	0	15	1	Canal, river	Gavioli et al. 2018
	Habitat area	-	80	1	Pond	Kobayashi et al. 2011
Biotic variable	Presence of fish	-	15	1	Canal, river	Gavioli et al. 2018

*: reference also considering juveniles.

crayfish abundance across existing studies (Table 1). Besides, the time from introduction influences the extent of red swamp crayfish spread [see Tréguier et al. (2018)] and is likely to obscure the putative effects of environmental factors on its abundance. Moreover, as red swamp crayfish is an r-selected species (Souty-Grosset et al. 2016; Huner 2002), rapid demographic changes can be found in conjunction with changing environments and this cannot be detected using one-year studies, as they are too

short. Finally, juvenile and adult crayfish may respond differently to environmental and biotic factors, notably to satisfy life-stage-specific nutrient requirements (Correia 2003; Alcorlo and Baltanás 2013). It is important to explore variations in abundance of the two life stages separately, which has scarcely been done to date (Table 1).

In the present study, we aimed to resolve some of these limitations using a 7-year time-series of red swamp crayfish abundance together with environmental and biotic data collected in a range of drainage ditches of a large eutrophic agricultural marshland invaded by the species 10–20 years ago. We aimed to capture inter-annual variations in local crayfish abundances of both small and large individuals using routine length-frequency data and to identify environmental drivers from among the factors known to be of great importance in the functioning of highly regulated marshlands (Mauchamp et al. (2021) and references therein). By identifying which factors explain the variation in crayfish abundance, we wish to provide management levers for controlling crayfish populations. In particular, we focused on the water regime (i.e., the temporal variations of water levels) in the ditch networks of the marshland. We expected the water regime, and notably the intermittency of water in ditches, to negatively impact crayfish abundance [as found in Meineri et al. (2014)]. When adjacent natural grasslands are flooded in spring they may be used as nursery habitats by crayfish (Meineri et al. 2014). Accordingly, a long duration of spring flooding of the grasslands surrounding the ditches is expected to result in high crayfish abundance in adjacent ditches. We also expected that ditch density around each study ditch would influence the population dynamics of crayfish because some ditches may constitute refuges or source habitats for crayfish when environmental conditions deteriorate in the ditches under study (notably during drying-up episodes). As an observational study, environmental factors were not controlled, so we also explored the possible influence of additional factors related to water physico-chemistry, ditch features (mainly aquatic and riparian vegetation), and biomass of predatory fish in each study ditch.

Methods

Study area

The Marais poitevin is a ca. 1,020-km^2 eutrophic agricultural marshland located on the French Atlantic coast (46°30'N–46°15'N, 1°30'W–0°35'W, Fig. 1). The marshland was reclaimed during the Middle Ages and an 8,200-km long network of lentic drainage ditches has progressively been set up (EPMP 2015). The Marais poitevin is divided into ca. 250 distinct embanked hydrological blocks ranging from 0.05 to 60 km^2, in which the water regime is controlled relatively independently from the surrounding blocks and managed mainly for agricultural purposes (mainly thanks to hydraulic structures; EPMP 2015). The land surrounding the ditch network is dominated by grasslands, croplands and woodlands (45, 32, and 13% of the hydrological blocks under study, respectively, see below).

The red swamp crayfish was recorded for the first time in the Marais poitevin in 2003 (EPMP 2015), but it was probably introduced before: it was detected at least 10 years earlier in the adjacent Charente department (Changeux 2003). Since this date, crayfish have colonised the whole marshland. Therefore, they had been present for ca. 10–20 years at the beginning of the study. To investigate whether the water regime is an important driver of the population dynamics of crayfish, we selected eleven hydrological blocks representative of water regime diversity in the Marais poitevin (Fig. 1). Water regime is controlled independently from one block to another because of different water regulations fixed by local management

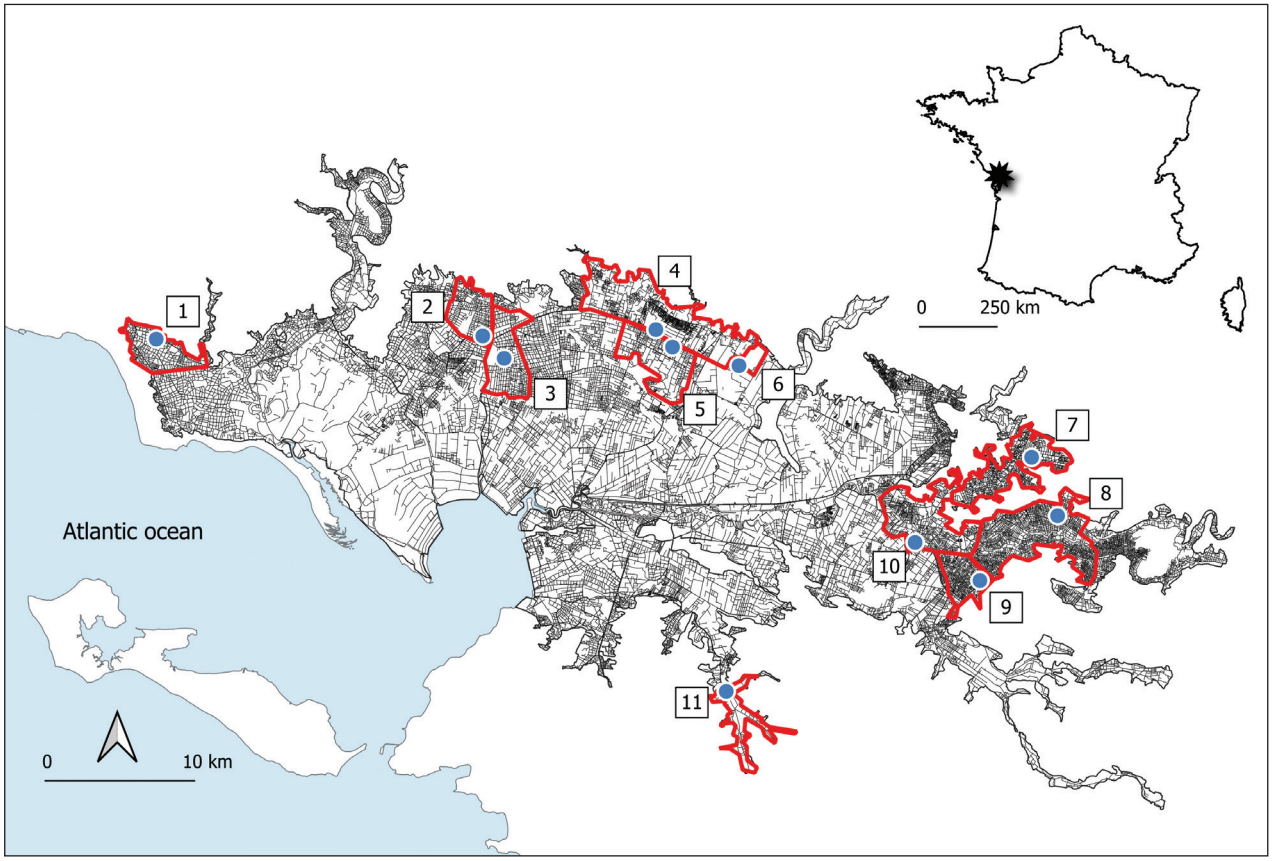

Figure 1. Localisation of the 11 selected hydrologically independent blocks within the Marais poitevin (delimited by a red line) where crayfish were sampled in specific ditches (blue dots) within dense networks of ditches.

committees. This leads to different hydrological patterns between blocks [see also Crabot et al. (2023)]. The climate is a warm Atlantic one, with mild temperatures and heavy precipitation in winter, and hot, dry summers.

Crayfish sampling

Crayfish were collected in one medium-sized ditch (4–10 m wide and 0.30–1.00 m deep, Fig. 2) typical of the local ditch network in each of the eleven hydrological blocks. On average, the Euclidian distance to the closest studied ditch was 6.4 km (6.7 standard deviation, range 1.6 to 22.5 km). Crayfish were collected once a year over seven consecutive years (2015–2021), during the annual peak in crayfish activity, around mid-June (similar pattern to other French regions; Paillisson et al. 2012; Meineri et al. 2014). No extreme meteorological event occurred during the fieldwork itself, or the preceding few days, in particular heat waves or heavy rainfall which can impact crayfish activity. Sampling was performed using 25 unbaited funnel traps (wire minnow trap characteristics: length × width × height: 50 × 29 × 21 cm, 5.5 mm mesh size with two conical side entrances, 4 cm inner opening diameter) set approximately every 10 m along the shoreline of each ditch for a period of 24 h [a somewhat similar protocol to that used in Paillisson et al. (2012); Meineri et al. (2014)]. Using this type of trap without bait limits the risk that captures are biased by size and sex unlike other types of traps (Frutiger and Müller 2002; Paillisson et al. 2011). Besides, trapping was limited to a 24 h period because extending the trapping duration to longer periods has been found to reduce trapping efficiency per unit effort due to avoidance behaviour of crayfish towards other individuals

Figure 2. Pictures of study ditches (by Aquascop).

already in the traps [by a factor of 3–4 in Paillisson et al. (2012)] and to significantly underestimate the abundance of small crayfish due to cannibalism occurring inside the traps (Paillisson et al. 2012). Thanks to all these precautions, our data are truly indicative of local crayfish (structure) populations. All individuals were collected in accordance with French regulations and preserved by freezing until further processing. In the laboratory, defrosted crayfish were basically sexed by inspection of the first pair of pleopods and measured to the nearest millimeter from the tip of the rostrum to the end of the telson (total body length) to distinguish small from large crayfish (see below and Suppl. material 1: fig. S1). Captures were then expressed in capture per unit effort (CPUE), i.e., the number of small and large crayfish per trap per 24 h. Lastly, we assumed that the number of individuals collected was too low to impact natural fluctuations of crayfish abundance over time.

Environmental variables

The water regime in the ditches was described using three independent variables: i) the monthly water level (cm) in June, when crayfish were sampled, ii) the duration of the dry period over the past annual water cycle (days, over the previous 12 months), and iii) the length of the spring period (days, March to May) during which at least 20% of the grassland area adjacent to each ditch was inundated, as a proxy of the amount of potential temporary habitats for crayfish, in particular as nursery habitats for small individuals (Meineri et al. 2014). The first two variables were obtained by automatic daily monitoring of the water level in a nearby, permanent,

and deeper ditch in each hydrological block, in combination with the topography of the bottom of each sampled ditch which was measured in situ using a graduated pole and was found to be stable over the study period (see values in Suppl. material 1: table S1). The water level in June correlates strongly with the monthly water level from March to May (Mauchamp et al. 2021) and was therefore considered representative of the spring water conditions. The third variable was calculated based on the principle that a pixel of 1 m^2 of grasslands on a LIDAR image raster was considered as flooded when its altitude on the digital elevation model of the Marais poitevin was lower than the water depth recorded in situ using piezometers (see Rapinel et al. (2018) for a complete description of calculation). Flooding duration values calculated for other grassland area quantiles (5 and 10%) were highly correlated and were therefore not retained for subsequent analyses.

Physico-chemistry variables were collected in a companion study (UNIMA, unpublished data). Water conductivity (µS cm^{-1}), the chlorophyll a content (mg L^{-1}), and dissolved organic matter (mg L^{-1}) were measured in a large reference ditch for each hydrological block every two months. Water conductivity was measured in the top 30 cm of the water column using a portable electronic multi-parameter probe (WTW 3430, Thermo Fisher Scientific Inc.) while chlorophyll a (measured by spectrophotometry after acetone extraction) and dissolved organic carbon contents were measured in the laboratory from a water sample collected from the top 30 cm of the water column. Average values were calculated over the February-June period each year to account for conditions during the water cycle prior to crayfish sampling (Suppl. material 1: table S1).

We also considered some habitat features expected to be relevant for crayfish diet and burrowing activities (Souty-Grosset et al. 2016). They were i) ditch bottom substrate type – determinant for crayfish (Donato et al. 2018; Palmas et al. 2019) –, and more specifically mud depth (cm) since all ditches had a muddy bottom, ii) aquatic plant cover (%) and iii) riparian vegetation cover, differentiating herbaceous vegetation from trees using scaled indices and visual evaluation [following Mauchamp et al. (2021)], all as proxies of shelter and litter input in ditches (Kobayashi et al. 2011), and iv) ditch density (m Ha^{-1}) in a 500-m buffer area around each ditch studied as ditches may constitute refuges or source habitats for crayfish (map source: IGN topographical database version 2008, calculation using QGIS 3.2, QGIS Development Team 2018; Suppl. material 1: table S1). Riparian vegetation was characterized on the basis of the 2015 in situ measurements as no management actions (such as pruning) have been observed over the study period.

Finally, since predatory fish may control red swamp crayfish populations (Aquiloni et al. 2010; Tablado et al. 2010; Reynolds 2011), we also used annual predatory fish biomass as a proxy of predation pressure. It was estimated for each ditch using electrofishing [data from Crabot et al. (2023)]. We took the following species into account: black bullhead (*Ameiurus melas*), European eel (*Anguilla anguilla*), pike (*Esox lucius*), pikeperch (*Sander lucioperca*), largemouth black bass (*Micropterus salmoides*), pumpkinseed (*Lepomis gibbosus*), and European perch (*Perca fluviatilis*).

Statistical analyses

All statistical analyses were run with R 4.3.0 (R Core Team 2023).

To distinguish small from large crayfish, we used a polymodal decomposition method that consists in fitting Gaussian components to body length-frequency data using the mixtools package (Benaglia et al. 2009). Length-frequency data showed a bimodal distribution with two distinct cohorts each year (small and large individuals, Suppl. material 1: fig. S1) with a body length threshold set at 78 mm (seven years

pooled) and no difference in body size between sexes (data not shown). We tested for possible temporal autocorrelation of local crayfish CPUE (all individuals combined). In practice, we calculated correlations between CPUE in year t and year t+lag, lag ranging from 1 to 3 years in accordance with crayfish life time values (Scalici and Gherardi 2007; McLay and van den Brink 2016; van Kuijk et al. 2021) using the autocorr function in R. We also explored the relationships between the CPUE of large crayfish in a given year and the CPUE of small crayfish in the previous or the next year using linear correlations. These two complementary analyses were conducted to better understand crayfish demography and detect possible density-dependent effects.

We studied possible relationships between variation of the CPUE of the two size classes and environmental variables (Suppl. material 1: table S2) using generalised linear modelling. Dissolved organic matter in water was excluded from the suite of candidate predictors due to high multicollinearity with the chlorophyll a concentration [variance inflation factor procedure, $r > 0.7$ (Dormann et al. 2013), usdm package (Naimi 2017)]. All (continuous) environmental variables were scaled. Generalised linear mixed models (GLMMs) were run separately for small and large crayfish data, with a negative binomial error distribution, a log-link function, and 'year' as a random effect [glmer.nb function, lme4 package (Bates et al. 2015)]. We computed models from all additive combinations of up to five candidate environmental variables (and the null model) to limit model complexity [dredging procedure, MuMin package (Bartoń 2016)]. The models were ranked according to the AICc corrected for small sample sizes (Burnham and Anderson 2002), and marginal R^2 was provided for each model [r.squaredGLMM function in the MuMin package (Nakagawa et al. 2017)]. Conditional model-averaged estimates for each selected variable were calculated when several competitive models occurred in the model selection with $\Delta AICc < 2$. Results were qualitatively identical over different model selections ($\Delta AICc < 3$ and $\Delta AICc < 4$, data not shown).

Results

Variation in crayfish CPUE over time

The CPUE of the two size classes varied among ditches and over time throughout the study period, but no global trend emerged (Fig. 3A, B; mean ± SD values in Suppl. material 1: table S3A, B). Small crayfish were predominant (70.7%, n = 6,272 individuals, Fig. 3A) and the sex ratio was slightly skewed (57% females). Large between-year variation in crayfish CPUE was observed in five of the 11 ditches (ditch 3, 5, 7, 10, and 11 depending on size classes). CPUE varied up to ten- and six-fold between years for small and large crayfish, respectively (Fig. 3A, B). Crayfish CPUE was sometimes very low locally; for instance, only one large crayfish was captured in ditch 1 in 2015, and none at all in ditch 5 in 2019.

No temporal auto-correlation of crayfish CPUE was found in any ditch, whatever the time lag and the size class (Suppl. material 1: fig. S2A, B). Moreover, no significant correlation was found between the CPUE of large crayfish in one year and the CPUE of small ones in the previous or following year.

Relationships between crayfish CPUE and environmental variables

Variation of crayfish CPUE was consistently related to three habitat features, at both size classes: crayfish were more abundant in ditches with densely vegetated banks [both for tree hedge (estimate ± 95% CI: 0.82 ± 0.32 for small and 0.96 ± 0.28 for large crayfish) and herbaceous vegetation covers (0.39 ± 0.26 for small and 0.70 ±

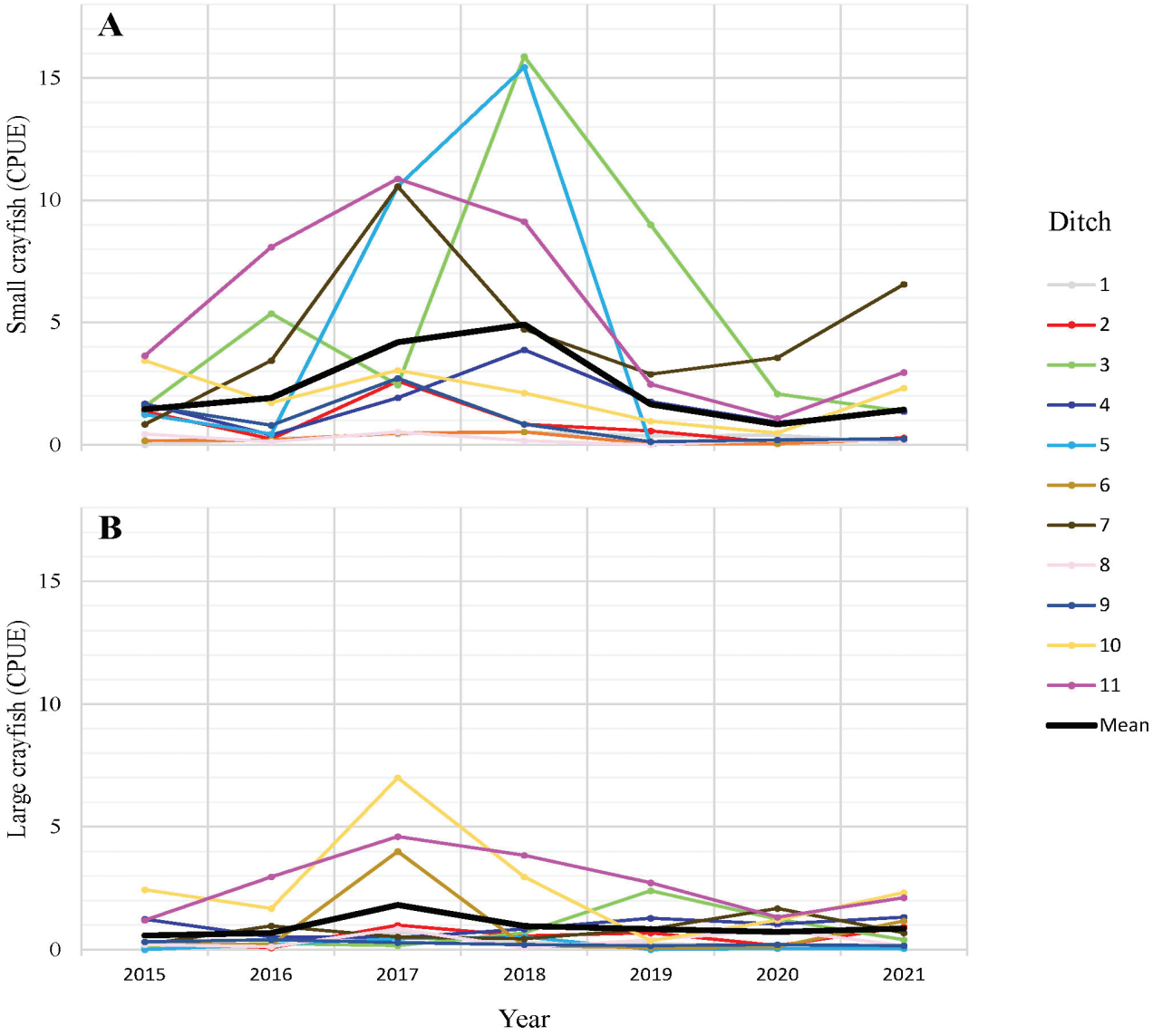

Figure 3. Variation of red swamp crayfish in 11 ditches (one per hydrological block) expressed in capture per unit effort (CPUE, number of individuals per trap per 24 h) during the seasonal peak over time (2015 to 2021): A) small, B) large crayfish. Bold black lines represent average values for all ditches.

0.21 for large crayfish, Fig. 4A, B)] and less abundant when the ditches were part of a dense network of ditches (-0.46 ± 0.31 and -0.85 ± 0.23 for small and large crayfish, respectively, Fig. 4A, B). In addition, variation of small crayfish CPUE was positively related to water conductivity (0.53 ± 0.33, Fig. 4A). Only one water regime descriptor was found to be significant to crayfish: dryness duration of ditches had a positive effect on the CPUE of small crayfish (0.46 ± 0.44, Fig. 4A). Aquatic plant cover and predatory fish biomass did not explain the variation in crayfish CPUE for either size class. The significant environmental variables all together explained 54 and 57% of variance of small and large crayfish CPUE, respectively (Suppl. material 1: table S4).

Discussion

Our study shows that CPUE of red swamp crayfish varied unevenly among ditches about 20 years after they were first detected. Variation of crayfish CPUE did not show any clear pattern over time and did not reflect demography-dependent processes. It was relatively consistently driven by a few habitat variables for small and large crayfish.

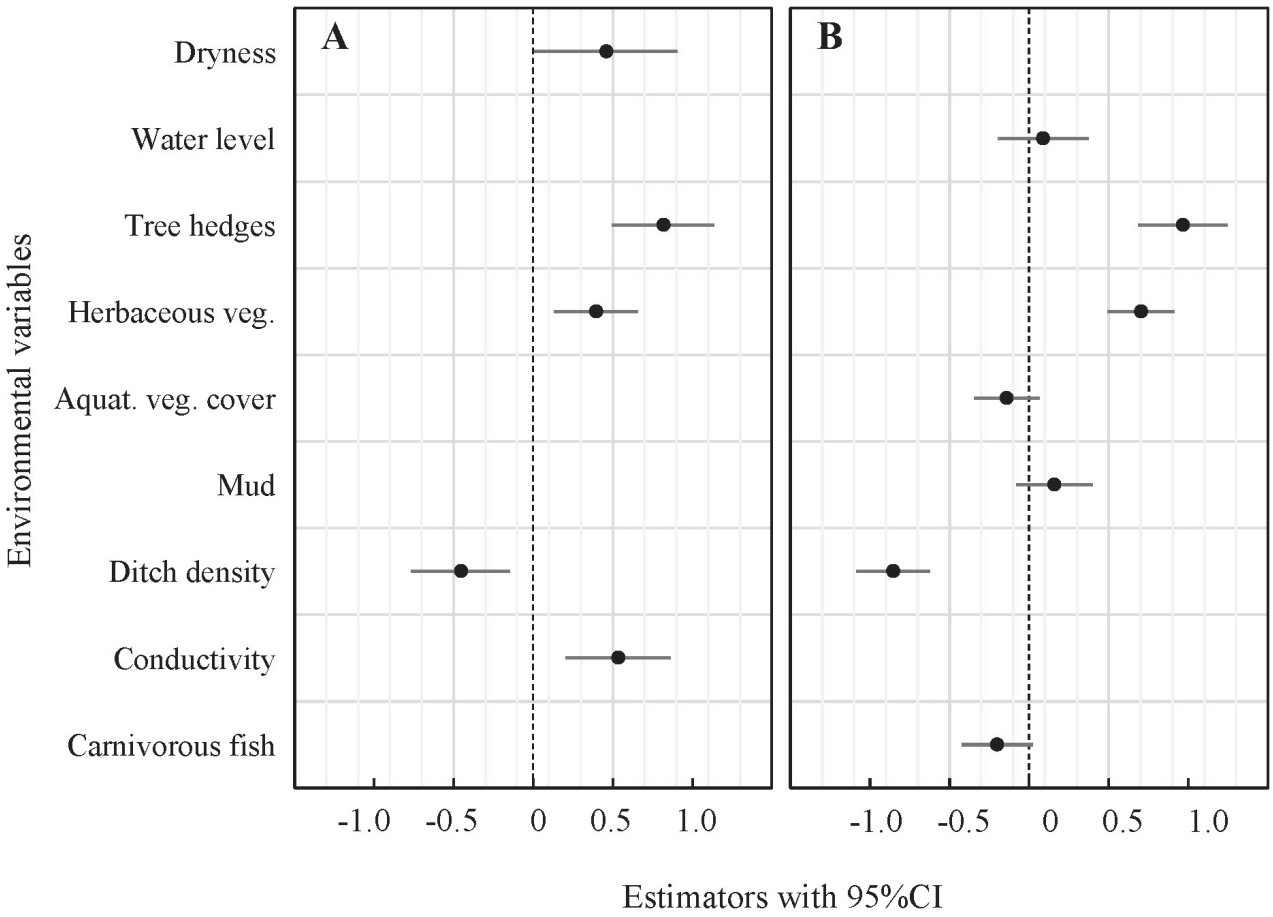

Figure 4. Forest plot of estimates (with 95% confidence intervals) of the environmental variables predicting the local CPUE of red swamp crayfish: A) small (R^2_m = 0.54), B) large crayfish (R^2_m = 0.57, model-averaging procedure). Values were calculated from the model selection ΔAICc < 2 (provided in Suppl. material 1: table S4). The sign of the relationship between a predictor and crayfish CPUE was ascertained when its 95% confidence interval did not include zero. No estimate was provided for some predictors because they were not in the model selection.

Between-year variation of abundance

Crayfish CPUE varied over time, more so in specific ditches. In no case did they increase continuously over time, suggesting that the classical boom stage after introduction has already been reached (Strayer et al. 2017). Crayfish CPUE values fall within the same range as the CPUE values found in a similar French marshland colonised for 30 years (Bélouard et al. 2019 (Suppl. material 1: table S4); using the same sampling methodology). No case of local extinction has been observed in our study area (despite the absence of crayfish on one occasion in one ditch and occasional low abundance values in some ditches). All this suggests that crayfish were in the persistent phase characterised by no specific long-term abundance trend (Strayer et al. 2017). Different scenarios of long-term dynamics trends have been documented for red swamp crayfish in European regions: no trend in abundance (Sousa et al. 2013, the present study), positive trends (Soto et al. 2023), and negative trends (Bélouard et al. 2019; Soto et al. 2023). Bélouard et al. (2019) even observed a global decline in red swamp crayfish abundances in ponds in a nearby region of our study area, with few cases of local population collapse (personal communication). We suggest that the particularly high density of the ditch network in the Marais poitevin (11.9 km per km^2 in our specific study area) might facilitate possible local ditch recolonisation from nearby crayfish sources (see also below), since no prolonged local population collapse was recorded.

Besides, the high proportion of small crayfish reported in all ditches is in line with what is reported in the literature (Anastácio and Marques 1995; Scalici and Gherardi 2007; Paillisson et al. 2012) and reflects the high reproductive potential of the red swamp crayfish (Huner 2002). However, in some populations (e.g. Scalici et al. 2010), the occurrence of large individuals is higher, but data in the literature are often biased by the traps used which are selective for large individuals.

Variation of crayfish abundance in relation with environmental conditions

Contrary to our expectations, variation of CPUE of the two crayfish size classes is only weakly associated with water conditions, with only a positive effect of dryness duration of ditches on juvenile abundance. Crayfish CPUE was not higher where adjacent grasslands were inundated for long periods of time, whereas opposite findings have been reported, for instance, in Paillisson et al. (2011) and Meineri et al. (2014); temporarily flooded habitats were found attractive for small red swamp crayfish. Focusing on adults, Gavioli et al. (2018) showed that high water levels had a negative effect on the population size of red swamp crayfish and this holds true in a wide range of habitat types (from canals to flowing rivers). Here, as in most studies (Table 1), no such outcome has been found. It can be speculated that the extent of variation in water conditions was not large enough to influence crayfish abundance, in the Marais poitevin or in most of studies gathered in Table 1. We also interpreted the absence of an effect of water conditions as a consequence of the ability of crayfish to adapt to deteriorated environmental conditions (e.g. drying-up episodes) either by pulling back into burrows (Huner and Barr 1991; Nyström 2002) or by temporarily moving to more favourable nearby habitats (Fonteneau and Paillisson 2014). Further investigations would be needed to explore these hypotheses.

Small and large crayfish were more abundant both in ditches with densely vegetated banks and in hydrological blocks composed of a less dense ditch network. Densely vegetated banks principally provide crayfish refuges (notably tree roots and woody debris jams) from predators (Holdich et al. 2006) and also food resources (input of decaying plant matter; Kobayashi et al. 2011). Regarding aquatic vegetation, it is expected to be attractive for crayfish, but negative feedback effects of red swamp crayfish on aquatic vegetation have also been extensively documented (e.g., consumption, bioturbation; Rodríguez et al. 2005; Twardochleb et al. 2013). No such relationship was found in our study, as in others (Table 1), suggesting that observed crayfish abundances were too low to significantly impact the aquatic plant cover. It may also be that dominant plant species (*Elodea canadensis*, *E. nutalii*, *Stuckenia pectinata* and *Ceratophyllum demersum*; Mauchamp et al. 2021) have the ability to efficiently regrow after being consumed by crayfish (Hessen et al. 2004); alternatively, some species are not impacted by red swamp crayfish (e.g. *E. nutalii*; Chucholl 2013). A third hypothesis could be that annual drying-up episodes do not allow crayfish to constitute large populations limiting their impact on aquatic plants, while, concomitantly, drying periods promote aquatic vegetation (in particular amphibious plant species) as shown by Mauchamp et al. (2021) in the same study ditches.

The negative relationship we found between crayfish CPUE and ditch density could be tentatively interpreted by a dilution effect of crayfish abundance with increasing availability of aquatic habitats. With a dense network of ditches, crayfish may also easily escape unfavourable – dry – conditions and, conversely, (re) colonise ditches. Concomitantly, the aquatic continuum between ditches is frequently disrupted by artificial impoundments and local drought (field observations), suggesting that a relationship between density and connectivity may not be

straightforward. Additional investigations are clearly needed to better interpret the relationship between crayfish abundance and ditch density.

Finally, the absence of an effect of water conductivity on large crayfish was expected since the observed values were mostly below the known tolerance threshold (Kang and King 2012; Meineri et al. 2014; Palmas et al. 2019; Dörr et al. 2020). However, small crayfish were more abundant in ditches with higher water conductivity and this remains unexplained because they have a lower tolerance to water salinity than large ones (5 g L^{-1} vs. 10 g L^{-1}; Paillisson et al. 2012; Meineri et al. 2014).

Potential study limitations

As indicated above, the first challenge of this study was to provide robust long-term data on the structure of local populations in drainage ditches using one sampling per year. The second objective was to identify environmental drivers of crayfish abundance, some being calculated on a yearly basis. For this purpose, sampling was performed during the typical annual peak in crayfish activity in spring (see also Meineri et al. 2014). At this time of year, adjacent temporary habitats have dried up and crayfish retreat into ditches, which corresponds to the best conditions for providing a good overview of local crayfish populations in ditches. Moreover, great care has been taken to limit trapping bias, although we cannot exclude potential short-term confounding factors (e.g. weather conditions) that may influence crayfish activity. In any event, the sampling protocol was consistent within each time-series which allowed us to compare spatiotemporal trends of red swamp crayfish abundance between ditches. As a result, environmental factors explained a significant part of variation in small and large crayfish CPUE over time and are thus reliable and robust. For all these reasons, the present results come from consistent datasets. A potential improvement would be to consider additional biotic factors, notably food resources to which crayfish are likely to be sensitive; however, such information is difficult to acquire explaining why they are so scarce even in short-time studies. Lastly, considering the sexual maturation status of red swamp crayfish rather than their body size could provide a valuable perspective since size-at-maturity is very variable; it can be influenced by environmental conditions (Anastácio and Marques 1995; Huner 2002) and it can, in turn, impact local population dynamics.

Conclusions and management insights

There is a broad consensus within the scientific community on the need to understand how invasive species are influenced by environmental conditions to predict their population dynamics (Simberloff et al. 2013). However, as reported by Soto et al. (2023), long biomonitoring data of crayfish invasions (on crayfish themselves as well as environmental data) are lacking preventing large spatio-temporal analyses of their population dynamics. The conclusions from our time-series study strengthen some of the findings derived from short-term studies. In particular, much of the variation in crayfish abundance we found was weakly explained by water conditions (temporary droughts) in drainage ditches – at least within the range of values tested in the present study –, whereas it was positively related to riparian vegetation and negatively linked to the density of surrounding habitats (ditches). Predatory fish biomass did not explain crayfish abundance. Studying growth and mortality parameters using length-frequency data collected at an increased frequency in conjunction with environmental conditions would provide additional valuable information, but it remains highly challenging when conducting time-series studies.

A direct application of our study is to provide recommendations to managers for mitigating red swamp crayfish populations, although the management of biological invasions is a complex task (Simberloff et al. 2013). Managing the riparian vegetation of ditches would be an interesting lever to reduce refuges from predators and food resources for red swamp crayfish. However, it would probably result in undesirable negative effects on other aquatic organisms, as shown in companion studies (Mauchamp et al. 2021; Crabot et al. 2022, 2023). An alternative management option would be to target management actions on small populations. Classical control actions, notably harvesting as reviewed in Freeman et al. (2010) and Gherardi et al. (2011), can significantly reduce crayfish abundance in small patchy habitats. The challenge in our study area is to mitigate crayfish abundance in connected aquatic habitats. This means that limiting crayfish dispersal using physical barriers would be required in parallel with control operations (Coignet et al. 2012; Reisinger et al. 2024). However, such management actions are very time-consuming and cannot be conducted over the long term (Strayer et al. 2017). More broadly, any management action aimed at maintaining or increasing local biodiversity should make ecosystems more resistant to invasive species. Finally, we encourage long-term studies to be carried-out on red swamp crayfish (as well as environmental and biotic factors) in a diversity of aquatic ecosystems to better understand their population dynamics (see Soto et al. (2023) in European rivers).

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Author contribution

AM: Data analysis and interpretation, writing – original draft, reviewing and editing. AB: Research conceptualization, sampling design and methodology, funding provision, writing – reviewing and editing. JC Writing – reviewing and editing. BB: Writing – reviewing and editing. OG: investigation and data collection, writing – reviewing and editing. JMP: Research conceptualization, sampling design and methodology, funding provision, writing – reviewing & editing.

Ethics and permits

Red swamp crayfish were collected under permits delivered by the Préfectures de Vendée, de Charente-Maritime and des Deux-Sèvres (notably permits n°15EB0793 and 15-DTM85-181).

Data availability

Species georeferenced records are available at the European Alien Species Information Network: https://easin.jrc.ec.europa.eu/easin/RJD/Download/f116aafa-ba01-4ccc-bff4-d41ade4ab861.

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References

Alcorlo P, Baltanás A (2013) The trophic ecology of the red swamp crayfish (*Procambarus clarkii*) in Mediterranean aquatic ecosystems: a stable isotope study. Limnetica 32: 121–138. https://doi.org/10.23818/limn.32.12

Alcorlo P, Geiger W, Otero M (2009) Reproductive biology and life cycle of the invasive crayfish *Procambarus clarkii* (Crustacea: Decapoda) in diverse aquatic habitats of South-Western Spain: Implications for population control. Fundamental and Applied Limnology 173: 197–212. https://doi.org/10.1127/1863-9135/2008/0173-0197

Anastácio PM, Marques JC (1995) Population biology and production of the red swamp crayfish *Procambarus clarkii* (Girard) in the lowae Mondegog river valley, Portugal. Journal of Crustacean Biology 15: 156–168. https://doi.org/10.1163/193724095X00659

Aquiloni L, Brusconi S, Cecchinelli E, Tricarico E, Mazza G, Paglianti A, Gherardi F (2010) Biological control of invasive populations of crayfish: the European eel (*Anguilla anguilla*) as a predator of *Procambarus clarkii*. Biological Invasions 12: 3817–3824. https://doi.org/10.1007/s10530-010-9774-z

Banha F, Anastácio PM (2015) Live bait capture and crayfish trapping as potential vectors for freshwater invasive fauna. Limnologica – Ecology and Management of Inland Waters 51: 63–69. https://doi.org/10.1016/j.limno.2014.12.006

Bartoń K (2016) MuMIn: Multi-Model Inference. R package version 1.15.6.

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67: 1–48. https://doi.org/10.18637/jss.v067.i01

Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. Biology Letters 12: 20150623. https://doi.org/10.1098/rsbl.2015.0623

Bélouard N, Paillisson J-M, Oger A, Besnard A-L, Petit EJ (2019) Genetic drift during the spread phase of a biological invasion. Molecular Ecology 28: 4375–4387. https://doi.org/10.1111/mec.15238

Benaglia T, Chauveau D, Hunter D, Young D (2009) mixtools: an R package for analyzing mixture models. Journal of Statistical Software 32: 1–29. https://doi.org/10.18637/jss.v032.i06

Burnham K, Anderson D (2002) Model Selection and Multimodel Inference. A practical Information-Theoretic Approach. Springer Verlag, New York, Berlin, Heidelberg, 488 pp.

Changeux T (2003) Évolution de la répartition des écrevisses en France métropolitaine selon les enquêtes nationales menées par le Conseil Supérieur de la Pêche. Bulletin Français de la pêche et de la pisciculture 370–371: 14–41. https://doi.org/10.1051/kmae:2003002

Clavero M, Villero D (2014) Historical ecology and invasion biology: long-term distribution changes of introduced freshwater species. Bioscience 64: 145–153. https://doi.org/10.1093/biosci/bit014

Chucholl C (2013) Feeding ecology and ecological impact of an alien 'warm-water' omnivore in cold Lakes. Limnologica 43: 219–229. https://doi.org/10.1016/j.limno.2012.10.001

Coignet A, Pinet F, Souty-Grosset C (2012) Estimating population size of the red swamp crayfish (*Procambarus clarkii*) in fish-ponds (Brenne, Central France). Knowledge and Management of Aquatic Ecosystems 406: 02. https://doi.org/10.1051/kmae/2012019

Cooling M, Hoffmann BD (2015) Here today, gone tomorrow: declines and local extinctions of invasive ant populations in the absence of intervention. Biological Invasions 17: 3351–3357. https://doi.org/10.1007/s10530-015-0963-7

Correia A (2003) Food choice by the introduced crayfish *Procambarus clarkii*. Annales Zoologici Fennici 40: 517.

Correia AM (2006) Seasonal and interspecific evaluation of predation by mammals and birds on the introduced red swamp crayfish *Procambarus clarkii* (Crustacea, Cambaridae) in a freshwater marsh (Portugal). Journal of Zoology 255: 533–541. https://doi.org/10.1017/S0952836901001625

Crabot J, Mauchamp A, Bergerot B, Bonis A, Gore O, Rossignol N, Paillisson J-M (2022) How hydrology and landscape shape Odonata assemblages in marshlands crossed by ditches. Freshwater Biology 67: 1228–1241. https://doi.org/10.1111/fwb.13913

Crabot J, Bergerot B, Bonis A, Gore O, Mauchamp A, Paillisson J-M (2023) Do highly anthropized hydrological conditions in marshes influence fish communities according to their life-history strategies? River Research and Applications 39: 1551–1577. https://doi.org/10.1002/rra.4150

Donato R, Rollandin M, Favaro L, Ferrarese A, Pessani D, Ghia D (2018) Habitat use and population structure of the invasive red swamp crayfish *Procambarus clarkii* (Girard, 1852) in a protected area in northern Italy. Knowledge and Management of Aquatic Ecosystems 419: 12. https://doi.org/10.1051/kmae/2018002

Dormann CF, Elith J, Bacher S, Buchmann C, Carl G, Carré G, Marquéz JRG, Gruber B, Lafourcade B, Leitão PJ, Münkemüller T, McClean C, Osborne PE, Reineking B, Schröder B, Skidmore AK, Zurell D, Lautenbach S (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36: 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Dörr AJM, Scalici M, Caldaroni B, Magara G, Scoparo M, Goretti E, Elia AC (2020) Salinity tolerance of the invasive red swamp crayfish *Procambarus clarkii* (Girard, 1852). Hydrobiologia 847: 2065–2081. https://doi.org/10.1007/s10750-020-04231-z

EPMP (2015) Atlas du Marais poitevin. Etablissement Public du Marais poitevin, Lucon, France. http://www.epmp-marais-poitevin.fr/atlas-marais-poitevin/ [Accessed 25 September 2024]

Ervin G, Smothers M, Holly C, Anderson C, Linville J (2006) Relative importance of wetland type versus anthropogenic activities in determining site invasibility. Biological Invasions 8: 1425–1432. https://doi.org/10.1007/s10530-006-0006-5

Ewers C, Normant-Saremba M, Keirsebelik H, Schoelynck J (2023) The temporal abundance-distribution relationship in a global invader sheds light on species distribution mechanisms. Aquatic Invasions 18: 179–197. https://doi.org/10.3391/ai.2023.18.2.105548

Fonteneau F, Paillisson J (2014) Flux d'écrevisses de Louisiane et de poissons entre un lac et ses prairies inondables lors de la phase de décrue. Aestuaria – Paroles des Marais Atlantiques, Premières rencontres françaises sur les écrevisses exotiques invasives. Actes du colloque sciences et gestion, 19 et 20 juin 2013, Saint-Lyphard, 45–51.

Freeman MA, Turnbull JF, Yeomans WE, Bean CW (2010) Prospects for management strategies of invasive crayfish populations with an emphasis on biological control. Aquatic Conservation: Marine and Freshwater Ecosystems 20: 211–223. https://doi.org/10.1002/aqc.1065

Fridley JD, Stachowicz JJ, Naeem S, Sax DF, Seabloom EW, Smith MD, Stohlgren TJ, Tilman D, Holle BV (2007) The invasion paradox: reconciling pattern and process in species invasions. Ecology 88: 3–17. https://doi.org/10.1890/0012-9658(2007)88[3:TIPRPA]2.0.CO;2

Frutiger A, Müller R (2002) Controlling unwanted *Procambarus clarkii* populations by fish predation. Freshwater Crayfish 13: 309–315.

Gavioli A, Milardi M, Lanzoni M, Mantovani S, Aschonitis V, Soana E, Fano EA, Castaldelli G (2018) Managing the environment in a pinch: red swamp crayfish tells a cautionary tale of ecosystem based management in northeastern Italy. Ecological Engineering 120: 546–553. https://doi.org/10.1016/j.ecoleng.2018.07.013

Gherardi F (2006) Crayfish invading Europe: the case study of *Procambarus clarkii*. Marine and Freshwater Behaviour and Physiology 39: 175–191. https://doi.org/10.1080/10236240600869702

Gherardi F, Baldaccini GN, Ercolini P, Barbaresi S, Luise GD, Mazzoni D, Mori M (1999) The situation in Italy. In: Gherardi F, Holdich DM (Eds) Crayfish in Europe as Alien Species. AA Balkema, Rotterdam, 107–128. https://doi.org/10.1201/9781315140469-8

Gherardi F, Aquiloni L, Diéguez-Uribeondo J, Tricarico E (2011) Managing invasive crayfish: is there a hope? Aquatic Sciences 73: 185–200. https://doi.org/10.1007/s00027-011-0181-z

Guareschi S, Laini A, England J, Barrett J, Wood PJ (2021) Multiple co-occurrent alien invaders constrain aquatic biodiversity in rivers. Ecological Applications 31: e02385. https://doi.org/10.1002/eap.2385

Haubrock PJ, Ahmed DA, Cuthbert RN, Stubbington R, Domisch S, Marquez JRG, Beidas A, Amatulli G, Kiesel J, Shen LQ, Soto I, Angeler DG, Bonada N, Cañedo-Argüelles M, Csabai Z, Datry T, de Eyto E, Dohet A, Drohan E, England J, Feio MJ, Forio MAE, Goethals P, Graf W, Heino J, Hudgins EJ, Jähnig SC, Johnson RK, Larrañaga A, Leitner P, L'Hoste L, Lizee M-H, Maire A, Rasmussen JJ, Schäfer RB, Schmidt-Kloiber A, Vannevel R, Várbíró G, Wiberg-Larsen P, Haase P (2022) Invasion impacts and dynamics of a European-wide introduced species. Global Change Biology 28: 4620–4632. https://doi.org/10.1111/gcb.16207

Haubrock PJ, Carneiro L, Macêdo RL, Balzani P, Soto I, Jessen Rasmussen J, Wiberg-Larsen P, Csabai Z, Várbíró G, Murphy JF, Jones JI, Verdonschot RCM, Verdonschot P, van der Lee G, Ahmed DA (2023) Advancing our understanding of biological invasions with long-term biomonitoring data. Biological Invasions 25: 3637–3649. https://doi.org/10.1007/s10530-023-03141-0

Hessen DO, Skurdal J, Braathen JE (2004) Plant exclusion of a herbivore; crayfish population decline caused by an invading waterweed. Biological Invasions 6: 133–140. https://doi.org/10.1023/B:BINV.0000022131.40783.f0

Holdich DM, Peay S, Foster J, Hiley PD, Brickland JH (2006) Studies on the white-clawed crayfish (*Austropotamobius pallipes*) associated with muddy habitats. Bulletin Français de la Pêche et de la Pisciculture 380–381: 1055–1078. https://doi.org/10.1051/kmae:2006011

Hovick S, Adams C, Anderson N, Kettenring K (2023) Progress on mechanisms and impacts of wetland plant invasions: a twenty-year retrospective analysis and priorities for the next twenty. Critical Reviews in Plant Sciences 42: 239–282. https://doi.org/10.1080/07352689.2023.2233232

Hui C, Richardson DM (2017) Invasion Dynamics. Oxford University Press, Oxford, 322 pp. https://doi.org/10.1093/acprof:oso/9780198745334.001.0001

Hui C, Richardson DM, Landi P, Minoarivelo HO, Garnas J, Roy HE (2016) Defining invasiveness and invasibility in ecological networks. Biological Invasions 18: 971–983. https://doi.org/10.1007/s10530-016-1076-7

Huner JV, Barr JE (1991) Red swamp crayfish: biology and exploitation. Sea Grant College Program, Louisiana State University, Baton Rouge, Louisiana, 128 pp.

Huner JV (2002) Procambarus. In: Holdich DM (Ed.) Biology of Freshwater Crayfish. Blackwell Science Ltd. Osney Mead, Oxford, 541–584.

Kang S-R, King SL (2012) Influence of salinity and prey presence on the survival of aquatic macroinvertebrates of a freshwater marsh. Aquatic Ecology 46: 411–420. https://doi.org/10.1007/s10452-012-9410-3

Kobayashi R, Maezono Y, Miyashita T (2011) The importance of allochthonous litter input on the biomass of an alien crayfish in farm ponds. Population Ecology 53: 525–534. https://doi.org/10.1007/s10144-011-0268-3

van Kuijk T, Biesmeijer JC, van der Hoorn BB, Verdonschot PFM (2021) Functional traits explain crayfish invasive success in the Netherlands. Scientific Reports 11: 2772. https://doi.org/10.1038/s41598-021-82302-4

Lázaro-Lobo A, Ervin GN (2021) Wetland invasion: a multi-faceted challenge during a time of rapid global change. Wetlands 41: 64. https://doi.org/10.1007/s13157-021-01462-1

Lester PJ, Gruber MAM (2016) Booms, busts and population collapses in invasive ants. Biological Invasions 18: 3091–3101. https://doi.org/10.1007/s10530-016-1214-2

Lodge DM, Deines A, Gherardi F, Yeo DC, Arcella T, Baldridge AK, Barnes MA, Chadderton WL, Feder JL, Gantz CA, Howard GW, Jerde CL, Peters BW, Peters JA, Sargent LW, Turner CR, Wittmann ME, Zeng Y (2012) Global introductions of crayfishes: evaluating the impact of spe-

cies invasions on ecosystem services. Annual Review of Ecology, Evolution and Systematics 43: 449–472. https://doi.org/10.1146/annurev-ecolsys-111511-103919

Lowry E, Rollinson EJ, Laybourn AJ, Scott TE, Aiello-Lammens ME, Gray SM, Mickley J, Gurevitch J (2012) Biological invasions: a field synopsis, systematic review, and database of the literature. Ecology and Evolution 3: 182–196. https://doi.org/10.1002/ece3.431

Mauchamp A, Gore O, Paillisson J-M, Bergerot B, Bonis A (2021) Delineating the influence of water conditions and landscape on plant communities in eutrophic ditch networks. Wetland Ecology and Management 29: 1–16. https://doi.org/10.1007/s11273-021-09792-x

McLay C, van den Brink A (2016) Crayfish growth and reproduction. In: Longshaw M, Stebbing P (Eds) Biology and Ecology of crayfish. CRC Press, Boca Raton, 62–116.

Meineri E, Rodriguez-Perez H, Hilaire S, Mesleard F (2014) Distribution and reproduction of *Procambarus clarkii* in relation to water management, salinity and habitat type in the Camargue. Aquatic Conservation: Marine and Freshwater Ecosystems 24: 312–323. https://doi.org/10.1002/aqc.2410

Naimi B (2017) usdm: uncertainty analysis for species distribution models. R package version 1.1-18.

Nakagawa S, Johnson PCD, Schielzeth H (2017) The coefficient of determination R^2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. Journal of the Royal Society Interface 14: 20170213. https://doi.org/10.1098/rsif.2017.0213

Nyström P (2002) Ecology. In: Holdich DM (Ed.) Biology of Freshwater Crayfish. Blackwell Science, Oxford, 192–235.

Oficialdegui FJ, Sánchez MI, Clavero M (2020) One century away from home: how the red swamp crayfish took over the world. Reviews in Fish Biology and Fisheries 30: 121–135. https://doi.org/10.1007/s11160-020-09594-z

Paillisson J, Roussel J, Tréguier A, Surzur G, Damien J (2012) Préservation de la biodiversité face aux invasions d'écrevisse de Louisiane (*Procambarus clarkii*). Synthèse. CNRS, INRAE, PNR de Brière, Onema.

Paillisson J-M, Soudieux A, Damien J-P (2011) Capture efficiency and size selectivity of sampling gears targeting red-swamp crayfish in several freshwater habitats. Knowledge and Management of Aquatic Ecosystems 401: 6. https://doi.org/10.1051/kmae/2011015

Palmas F, Podda C, Frau G, Cau A, Moccia D, Peddio S, Solari P, Pusceddu A, Sabatini A (2019) Invasive crayfish (*Procambarus clarkii*, Girard, 1852) in a managed brackish wetland (Sardinia, Italy): Controlling factors and effects on sedimentary organic matter. Estuarine, Coastal and Shelf Science 231: 106459. https://doi.org/10.1016/j.ecss.2019.106459

Pili AN, Tingley R, Sy EY, Diesmos MLL, Diesmos AC (2020) Niche shifts and environmental non-equilibrium undermine the usefulness of ecological niche models for invasion risk assessments. Scientific Reports 10: 7972. https://doi.org/10.1038/s41598-020-64568-2

Pintar MR, Dorn NJ, Kline JL, Trexler JC (2023) Contrasting invasion histories and effects of three non-native fishes observed with long-term monitoring data. Biological Invasions 25: 3887–3903. https://doi.org/10.1007/s10530-023-03146-9

QGIS Development Team (2018) QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. http://www.R-project.org

Rapinel S, Rossignol N, Gore O, Jambon O, Bouger G, Mansons J, Bonis A (2018) Daily monitoring of shallow and fine-grained water patterns in wet grasslands combining aerial LiDAR data and in situ piezometric measurements. Sustainability 10: 1–16. https://doi.org/10.3390/su10030708

Reisinger L, Tripp N, Atchia A, Bolds S, Cook D, Fralick K, Ganas D, Hayman B (2024) Can intensive trapping to reduce the abundance of an invasive crayfish benefit an imperiled congener? Aquatic Conservation: Marine and Freshwater Ecosystems 34: e4123. https://doi.org/10.1002/aqc.4123

Reynolds J (2011) A review of ecological interactions between crayfish and fish, indigenous and introduced. Knowledge and Management of Aquatic Ecosystems 401: 10. https://doi.org/10.1051/kmae/2011024

Rodríguez CF, Bécares E, Fernández-Aláez M, Fernández-Aláez C (2005) Loss of diversity and degradation of wetlands as a result of introducing exotic crayfish. Biological Invasions 7: 75. https://doi.org/10.1007/s10530-004-9636-7

Sandlund OT, Schei PJ, Viken Å (1999) Invasive Species and Biodiversity Management. Kluwer Academic Publisher, Dordrecht, 431 pp. https://doi.org/10.1007/978-94-011-4523-7

Sandström A, Andersson M, Asp A, Bohman P, Edsman L, Engdahl F, Nyström P, Stenberg M, Hertonsson P, Vrålstad T, Granèli W (2014) Population collapses in introduced non-indigenous crayfish. Biological Invasions 16: 1961–1977. https://doi.org/10.1007/s10530-014-0641-1

Savini D, Occhipinti-Ambrogi A, Marchini A, Tricarico E, Gherardi F, Olenin S, Gollasch S (2010) The top 27 animal alien species introduced into Europe for aquaculture and related activities. Journal of Applied Ichthyology 26: 1–7. https://doi.org/10.1111/j.1439-0426.2010.01503.x

Scalici M, Gherardi F (2007) Structure and dynamics of an invasive population of the red swamp crayfish (*Procambarus clarkii*) in a Mediterranean wetland. Hydrobiologia 583: 309–319. https://doi.org/10.1007/s10750-007-0615-8

Scalici M, Chiesa S, Scuderi S, Celauro D, Gibertini G (2010) Population structure and dynamics of *Procambarus clarkii* (Girard, 1852) in a Mediterranean brackish wetland (Central Italy). Biological Invasions 12: 1415–1425. https://doi.org/10.1007/s10530-009-9557-6

Siesa ME, Padoa-Schioppa E, Ott J, De Bernardi F, Ficetola GF (2014) Assessing the consequences of biological invasions on species with complex life cycles: Impact of the alien crayfish *Procambarus clarkii* on Odonata. Ecological Indicators 46: 70–77. https://doi.org/10.1016/j.ecolind.2014.05.036

Simberloff D, Gibbons L (2004) Now you see them, now you don't! – Population crashes of established introduced species. Biological Invasions 6: 161–172. https://doi.org/10.1023/B:BINV.0000022133.49752.46

Simberloff D, Martin J-L, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilà M (2013) Impacts of biological invasions: what's what and the way forward. Trends in Ecology & Evolution 28: 58–66. https://doi.org/10.1016/j.tree.2012.07.013

Soto I, Ahmed DA, Beidas A, Oficialdegui FJ, Tricarico E, Angeler DG, Amatulli G, Briski E, Datry T, Dohet A, Domisch S, England J, Feio MJ, Forcellini M, Johnson RK, Jones IJ, Larrañaga A, L'Hoste L, Murphy JF, Schäfer RB, Shen LQ, Kouba A, Haubrock PJ (2023) Long-term trends in crayfish invasions across European rivers. Science of the Total Environment 867: 161537. https://doi.org/10.1016/j.scitotenv.2023.161537

Sousa R, Freitas FEP, Mota M, Nogueira AJA, Antunes C (2013) Invasive dynamics of the crayfish *Procambarus clarkii* (Girard, 1852) in the international section of the River Minho (NW of the Iberian Peninsula). Aquatic Conservation: Marine and Freshwater Ecosystems 23: 656–666. https://doi.org/10.1002/aqc.2323

Souty-Grosset C, Anastácio PM, Aquiloni L, Banha F, Choquer J, Chucholl C, Tricarico E (2016) The red swamp crayfish *Procambarus clarkii* in Europe: impacts on aquatic ecosystems and human well-being. Limnologica 58: 78–93. https://doi.org/10.1016/j.limno.2016.03.003

Strayer DL, D'Antonio CM, Essl F, Fowler MS, Geist J, Hilt S, Jarić I, Jöhnk K, Jones CG, Lambin X, Latzka AW, Pergl J, Pyšek P, Robertson P, von Schmalensee M, Stefansson RA, Wright J, Jeschke JM (2017) Boom-bust dynamics in biological invasions: towards an improved application of the concept. Ecology Letters 20: 1337–1350. https://doi.org/10.1111/ele.12822

Tablado Z, Tella JL, Sánchez-Zapata JA, Hiraldo F (2010) The paradox of the long-term positive effects of a North American crayfish on a European community of predators. Conservation Biology 24: 1230–1238. https://doi.org/10.1111/j.1523-1739.2010.01483.x

Tréguier A, Roussel J-M, Bélouard N, Paillisson J-M (2018) Is it a hindrance for an invasive aquatic species to spread across scattered habitat patches? Aquatic Conservation: Marine and Freshwater Ecosystems 28: 610–618. https://doi.org/10.1002/aqc.2887

Twardochleb LA, Olden JD, 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

Wasson K, Fabian RA, Fork S, Stanganelli J, Mize Z, Beheshti K, Jeppesen R, Jones IJ, Zabin CJ, Walker S, Lummis SC, Emery M, Moore JD, Endris C, Jolette D, Byers JE (2020) Multiple factors contribute to the spatially variable and dramatic decline of an invasive snail in an estuary where it was long-established and phenomenally abundant. Biological Invasions 22: 1181–1202. https://doi.org/10.1007/s10530-019-02172-w

Watanabe R, Ohba S (2022) Comparison of the community composition of aquatic insects between wetlands with and without the presence of *Procambarus clarkii*: a case study from Japanese wetlands. Biological Invasions 24: 1033–1047. https://doi.org/10.1007/s10530-021-02700-7

Yuyu W, Wenzhuo T, Bin L, Yayu X, Min G, Xiuyuan L, Guangchun L (2022) Factors determining the abundance of red swamp crayfish (*Procambarus clarkii*) in a large lake connected to the Yangzte River. Journal of Resources and Ecology 13: 61–67. https://doi.org/10.5814/j.issn.1674-764x.2022.01.007

Zhou Y, Harrison MT, Liu K, Xiao L, Zhu J, Wang M, Li H, Yao G, Liu J, Zhu B, Liu Z (2023) Field distribution characteristics and influencing factors of crayfish in rice-crayfish integrative system. Aquaculture 571: 739456. https://doi.org/10.1016/j.aquaculture.2023.739456

Supplementary material 1

Supplementary figures and tables

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Data type: docx

Explanation note: **table S1.** Summary of environmental conditions in ditches. **table S2.** Correlations between environmental variables. **table S3.** Crayfish abundances over years. **table S4.** Models explaining variation of crayfish CPUE. **figure S1.** Length-frequency distributions of red swamp crayfish displaying two size classes (small and large individuals). **figure S2.** Temporal autocorrelation trend of crayfish CPUE.

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