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Research Article

Establishment of the blue crab *Callinectes sapidus* (Rathbun, 1896) in a Mediterranean hypersaline basin: evidence of ecological plasticity and range expansion

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Abstract

A central aspect of ecology is the understanding of how environmental factors influence species distribution, population structure, and dynamics, ultimately highlighting species' capacity to adapt to environmental shifts. This study investigates the population structure and environmental drivers influencing *Callinectes sapidus* (Rathbun, 1896) within a hypersaline basin (Stagnone di Marsala, Sicily, Italy), highlighting the species' adaptability to Mediterranean hypersaline coastal ecosystems. The presence of both sexes at various developmental stages indicates the full establishment of the population within the Stagnone, confirming that ecological opportunism, high salinity tolerance, and thermal preference enable *C. sapidus* to invade areas encompassing a wide range of environments. Two sampling methods were adopted: baited traps and gillnets. The nets captured larger, more mobile males, while traps were effective for a broader size range and included more female individuals. Population structure varied across different sectors of the basin, with the Center–North area showing the highest abundance, likely due to favorable habitat conditions and limited water exchange with the sea. These results emphasize the ability of *C. sapidus* to complete its life cycle under hypersaline conditions and its preference for stable, sheltered environments. The findings have significant implications for managing *C. sapidus* populations and mitigating their ecological impact. Adaptive management strategies, such as targeted harvesting and monitoring of salinity and temperature, are key to controlling this invasive species and protecting Mediterranean coastal ecosystems.

Key words: Coastal ecosystem, ecological opportunism, invasion success, invasive alien species, population dynamics, sampling methods

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Introduction

Biological invasions are one of the major forces of global environmental change and are currently considered a threat to biodiversity and ecosystem services in terrestrial, freshwater, and marine ecosystems (Hejda et al. 2009; Strayer 2012; Havel et al. 2015; Walsh et al. 2016). The introduction of non-native species is one of the main drivers of biodiversity decline (Carlton 2002; Ricciardi et al. 2017; Haubrock et al. 2020, 2022) and, notwithstanding the growing interest in this issue, continues to accelerate (Seebens et al. 2017). In particular, during the last decade, the establishment of invasive alien species (IAS hereafter)—that is, non-indigenous species having an adverse effect on biological diversity, ecosystem functioning, socio-economic values, and/or human health in invaded regions (Olenin et al. 2011)—has rapidly become a central environmental concern in marine ecosystems (Occhipinti-Ambrogi 2007; Walther et al. 2009; Occhipinti-Ambrogi and Galil 2010; Zenetos 2010; Crocetta et al. 2015). Indeed, IAS can alter the food web structure of recipient ecosystems through predation and competition, ultimately causing negative impacts on native species (Simberloff et al. 2013; Cicala et al. 2020; Andolina et al. 2022a; De Santis et al. 2022; Katsanevakis et al. 2023; Cicala et al. 2023, 2024). Notably, alarm has been raised for the Mediterranean Sea, which is now recognized as one of the areas worldwide most severely affected by biological invasions, both in terms of the number of alien species detected and the rate of introduction (Occhipinti-Ambrogi and Galil 2010; Zenetos 2010; Davidson et al. 2018; Petrosyan et al. 2023).

The study of invasive species has thus far concentrated on understanding the biological traits of potential invaders to predict invasion outcomes at local and larger scales (Whitney and Gabler 2008) and to assess the impacts of invasions on ecosystems (Kolar and Lodge 2002; Rahel 2002). In this scenario, increasing knowledge about IAS, their behavior, and the effects they cause in invaded habitats is of crucial importance. Understanding the patterns and population dynamics of invasions is therefore fundamental for predicting the timing and pathways of population expansion. Optimizing management actions that aim to eradicate or minimize the range expansion of these species is essential to controlling and mitigating their ecological impact (Arim et al. 2006; Davidson et al. 2018; Mancinelli et al. 2021). Accordingly, an essential aspect of invasion biology is understanding how environmental factors influence species distribution and population structure (MacIsaac 1996; Corrales et al. 2020) and how ecological alterations caused by invasive species affect native ecosystems (Nunes et al. 2014).

Among other IAS, the last decade has seen increasing interest in the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 (hereafter blue crab). The species is an omnivorous portunid native to coastal environments of the western Atlantic Ocean from the Gulf of Maine to Argentina (Hines 2007), where it has long been recognized as a keystone species regulating trophic cascades and acting as a benthic–pelagic coupler (Silliman and Bertness 2002; Boudreau and Worm 2012). The blue crab was first recorded in Europe in 1901 along the Atlantic coasts of France, probably introduced via ballast water, and later appeared in the Mediterranean Sea in 1947 in the Aegean Sea (Nehring 2011). Subsequently, it showed progressive expansion in brackish systems throughout the northern coasts of the basin, from Spain to Greece (Nehring 2011; Mancinelli et al. 2017a), leading to its inclusion in the list of the 100 most invasive species in the Mediterranean (Streftaris and Zenetos 2006). The last decade has witnessed a further, almost ubiquitous expansion of the blue crab's distribution (Mancinelli et al. 2021; Castriota et al. 2024), paralleled by growing evidence of its impacts on invaded systems, both at the single-species level (e.g., on the Manila clam *Ruditapes philippinarum*: Chiesa et al. 2025) and at the community scale (Clavero et al. 2022; Gavioli et al. 2025).

The most recent records of the blue crab are from south-Mediterranean environments in Algeria, Malta, and Libya, which are characterized by limited and episodic freshwater inputs and generally high salinities (e.g., Benabdi and Belmahi 2020;

Kara and Chaoui 2021; Corsini-Foka et al. 2021; Deidun et al. 2022). The blue crab is euryhaline and eurythermal, showing a complex biphasic life cycle consisting of marine planktonic larvae followed by benthic postlarvae, with juveniles and adults residing in estuaries, lagoons, and other transitional systems, and only females migrating to marine waters for spawning (Lipcius et al. 2007). Thus, the recent records in south-Mediterranean environments may indicate an adaptation of the blue crab to local high-salinity conditions that allow it to complete its biological cycle. The structure and seasonal dynamics of these populations remain virtually unexplored, since available information is limited to studies conducted in invaded lagoons and estuaries characterized by strong salinity gradients (Kevrekidis et al. 2023; Mancinelli et al. 2024).

The aim of this study was to monitor the population dynamics of the invasive blue crab (*Callinectes sapidus*) as it colonizes a hypersaline Mediterranean coastal ecosystem. In particular, we sought to (i) investigate the spatio-temporal distribution of *C. sapidus* in the study area, (ii) assess its population structure (e.g., size classes, sex ratio), and (iii) examine how species abundance correlates with key environmental variables, namely temperature and salinity.

Methods

Study area

The Stagnone di Marsala (Fig. 1) is a semi-enclosed hypersaline basin located along the northwestern coast of Sicily (37.872580°N, 12.464837°E). This shallow coastal marine area has a surface area of approximately 21 km^2 and an average depth of 1.5 m (Andolina et al. 2022b). Due to limited openings and the absence of freshwater inputs (Sarà et al. 1999; Vizzini et al. 2002), the basin is hypersaline and characterized by salinities and temperatures ranging seasonally between 32.8 and 47.1 PSU and 11.2 and 29.1 °C, respectively (Tomasello et al. 2009; Mazzola et al. 2010). The basin is separated from the sea by a calcarenite platform (Isola Longa) and divided into two main sub-basins (Vizzini et al. 2002). The northern basin is connected to the sea by a narrow and shallow opening named Bocca San Teodoro. This sub-basin covers an area of approximately 400 m^2 and has a depth of 0.3–0.4 m (Vizzini et al. 2013). Conversely, the southern sub-basin is connected to the sea by a larger opening, called Bocca Grande, which is about 1,200 m^2 wide and 1–2 m deep (Vizzini et al. 2013). These different degrees of connection with the sea result in limited water exchange in the central–northern part of the basin, while the southern part is more influenced by seawater influxes in terms of temperature and salinity (La Loggia et al. 2004; Mazzola et al. 2010). The basin is characterized by sandy–muddy bottoms with few rocky patches, mainly emerging in the southern sector. The seabed is mostly colonized by the seagrass *Cymodocea nodosa* (Ucria) Asherson, 1870, often associated with *Caulerpa prolifera* (Forsskål) Lamouroux, 1809, which are unevenly distributed throughout the basin. *Posidonia oceanica* (Linnaeus) Delile, 1813, is also present in the central and southern parts of the northern sub-basin, although in regression (Tomasello et al. 2009).

Sample collection and processing

For the purpose of this study, and considering the hydrodynamic features (La Loggia et al. 2004), four sampling zones were identified within the study area: North (37.901727°N, 12.458296°E), Center–North (37.871882°N, 12.465895°E), Center–South (37.845351°N, 12.457651°E), and South (37.820750°N, 12.454201°E). Within each zone, the number of sites was determined according to habitat heterogeneity. The selected sites were one in the North zone (site A), three in the Center–North (sites B, C, D) and Center–South (sites E, F, G) zones, and two in the South zone (sites H, I) (Fig. 1).

Given the homogeneous habitat features of the North zone, only one site (Site A) was selected, located close to the northern narrow opening. This zone is characterized by a sandy bottom and a depth of approximately 30 cm. Sites B, C, and D in the Center–North zone are the most remote from the open sea and are characterized by muddy bottoms, a depth of about 30 cm, and abundant macrophyte coverage. Especially in summer, the seagrass *C. nodosa* and the red macroalga *Laurencia* sp. are very dense in sites B and C. The southern zones, Center–South and South, present a more heterogeneous bottom. At sites E, F, and G in the Center–South zone, depth is about 45 cm. Macrophytes, mainly represented by *C. prolifera* and *C. nodosa*, are abundant in summer but scarce during other periods of the year. Sites H and I, in the South zone, have sandy bottoms with a depth of approximately 60 cm and a high abundance of *C. prolifera*.

Sampling of the blue crab was carried out from June 2021 to September 2023 using traps (60 × 30 cm, nylon mesh size 15 mm). Sampling frequency was

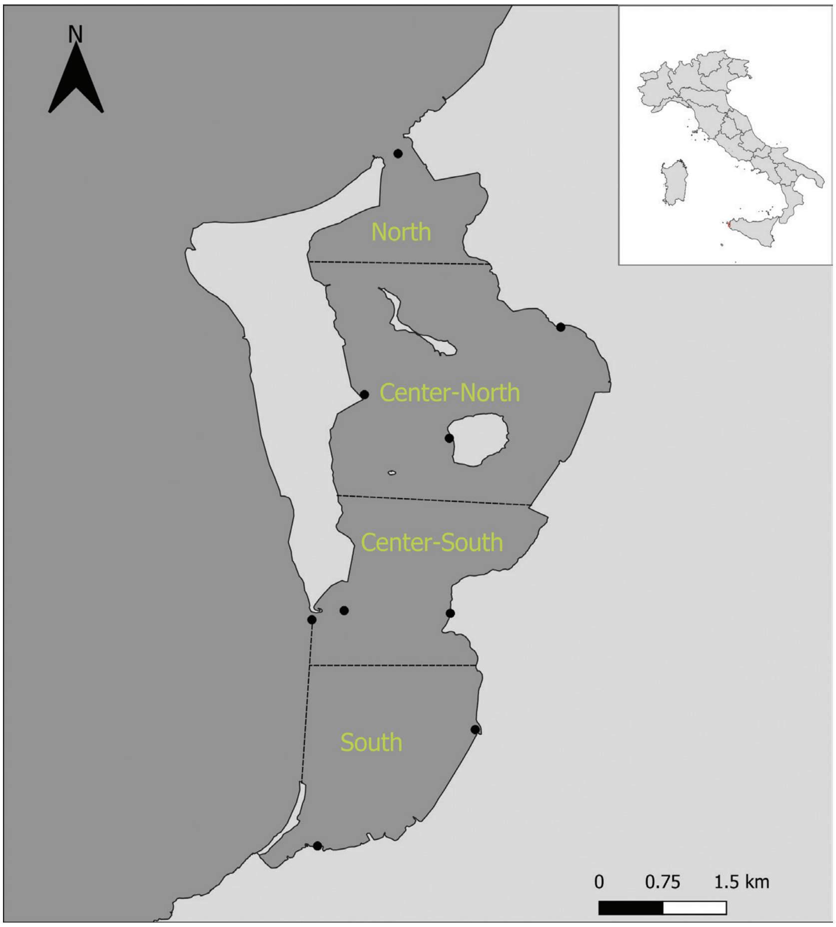

Figure 1. Sampling sites grouped by zones in the study area of the Stagnone di Marsala.

monthly from June 2021 to March 2023 (except in March and September 2022 and January 2023, when sampling was not conducted due to logistical constraints) and then every other month from May to September 2023 (see Suppl. material 1: table S1 for details on the total number of traps used in each season).

Each trap was baited with sardines and chicken discards. Four traps were deployed late in the afternoon at each site and sampling occasion, approximately 70 m apart, left overnight, and retrieved the following morning. Additionally, to increase the chance of capture, from April 2022 to September 2023, crabs were collected in two additional sites in the Center–North zone (sites C and D) and two in the Center–South zone (sites F and G) (Fig. 1). In these additional sites, besides the four traps described above, one gillnet (hereafter net; 50 m long, mesh size 30 mm) was also deployed late in the afternoon and retrieved the following morning.

Environmental parameters such as water temperature and salinity were measured with a multiparameter probe (Hanna® HI98194) at each site and sampling occasion. Captured crabs were placed in individually labeled plastic bags and transferred to the laboratory in refrigerated cool boxes.

Once in the laboratory, identification of *C. sapidus* was based on the presence of two large, obtuse teeth on the frontal margin between the inner orbital teeth (Castriota et al. 2024). All individuals collected had intact lateral spines. Specimens were weighed to the nearest 0.1 g, and carapace length (CL) and carapace width (CW) were measured to the nearest millimeter using a caliper. CW was determined as the distance between the two lateral spines, while CL was measured from the teeth on the frontal margin to the posterior margin of the dorsal carapace. For each specimen, sex was determined by inspecting the shape of the abdomen.

Data analysis

The relative abundance of *C. sapidus* was estimated as catch per unit effort (CPUE) by dividing the number of crabs collected with each fishing gear by the number of fishing gears deployed at each site. CPUE was calculated separately by catch method, hereafter referred to as CPUE by trap and CPUE by net. The monthly CPUE data were averaged by season for each sampling year and zone to summarize the large amount of data and highlight any seasonal trends that could be compared with those reported in the published literature. To assess the spatial distribution of blue crab abundance across the sampling period, distribution maps of CPUE by trap and by net were created using the *ggplot2* package in R v. 3.6.1 (R Core Team 2022).

A univariate permutational analysis of variance (PERMANOVA; PRIMER 6 v.6.1.10 and PERMANOVA+ β20; Anderson et al. 2008) was used to test for differences in blue crab abundance (CPUE) and size (CW) according to the factors Year (2021–2023), Season (summer–spring), Zone (North, Center–North, Center–South, and South), and Sex (female and male), separately for the two catch methods (traps and nets). The PERMANOVA (9,999 permutations) was performed on distance matrices constructed using the Bray–Curtis similarity index applied to log-transformed CPUE data and the Euclidean distance of non-transformed CW data. Spearman's correlation coefficients were used to investigate relationships between CPUE by trap and by net and the environmental variables (temperature and salinity).

Results

Spatio-temporal distribution of *C. sapidus* abundance

Overall, 495 individuals of *C. sapidus* were captured (Suppl. material 1: table S1). A total of 327 specimens were males (66%), and 168 were females (34%), with an overall sex ratio of 1.94:1 (♂:♀). Distribution maps clearly highlight an increasing trend in blue crab abundance over time across all sampling zones (Fig. 2). The peak of catches was recorded during the last sampling period (summer 2023) for both capture methods, with a value of 3.3 CPUE by trap at site B (Center–North zone; Fig. 3a) and a mean value of 10 ± 2.8 CPUE (± SD) by net at site C (Center–North zone; Fig. 3b).

CPUE by trap ranged between 0 and 3.3 ± 0.7 for females, with the highest abundance recorded in summer 2022 in the North zone, while for males, mean CPUE ranged between 0 and 2.4 ± 1.0, with the highest abundance recorded in summer 2023 in the Center–North zone (Fig. 3a). PERMANOVA results based on CPUE by trap indicated a significantly higher abundance of females in the North zone than in all other zones during spring and summer, and in the latter season, a significantly higher abundance of males in the Center–North zone compared to all other zones ($p < 0.05$; Suppl. material 1: table S2c). Furthermore, an increasing trend emerged in overall crab abundance, with CPUE being significantly higher in the last sampling year compared to the first (2023 vs 2021; $p < 0.05$; Suppl. material 1: table S2e). A clear temporal growth pattern also emerged when comparing CPUE in 2022 and 2023 ($p < 0.05$; Suppl. material 1: table S3d).

Overall, nets yielded higher crab catches than traps, with mean CPUE values ranging between 0 and 1 ± 1.4 for females and between 0 and 6.5 ± 7.7 for males, whose peak was recorded in summer 2023 in both central zones (Fig. 3b). The CPUE of males increased significantly in spring and summer compared to winter and was significantly higher than that of females during summer ($p < 0.05$ in all cases; Suppl. material 1: table S3b).

Population structure

The population structure of *C. sapidus* was largely heterogeneous across the sampling zones and seasons (Suppl. material 1: table S1), with carapace width (CW) ranging between 22 and 186 mm (Fig. 4, Suppl. material 1: fig S1). In general, nets captured larger specimens than traps (PERMANOVA, $p < 0.05$). Specifically, the CW of crabs captured by traps ranged between 49 and 153 mm for females and between 34 and 166 mm for males (Fig. 4a; Suppl. material 1: fig S1a). Conversely, the size of crabs captured by nets ranged between 79 and 154 mm CW for females and between 78 and 186 mm CW for males (Fig. 4b; Suppl. material 1: fig S1b). Larger individuals were captured in spring and summer compared to winter (Fig. 4b; Suppl. material 1: table S5b), while sex-based differences were less pronounced.

Spatial variations also occurred among zones, with larger individuals recorded in the Center–North zones (Fig. 4a; Suppl. material 1: table S4b). As observed with nets, size followed seasonal patterns, with generally higher CW values during warmer seasons. Specifically, during spring and summer, a significant increase in CW was observed compared to winter for both females and males, the latter being larger than the former (Suppl. material 1: table S4c, d).

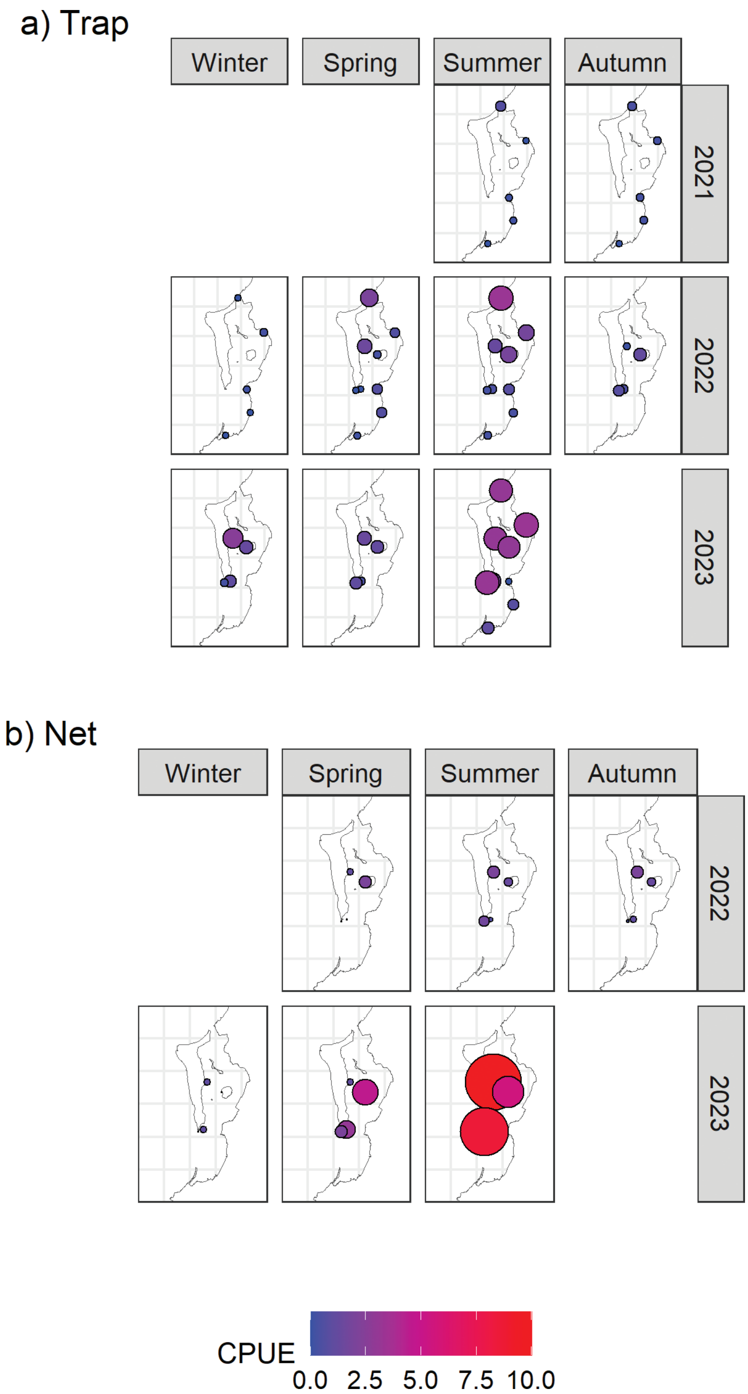

Figure 2. Spatial distribution of mean *C. sapidus* CPUE values by trap (**a**) and by net (**b**) across sampling sites and seasons in the Stagnone di Marsala. CPUE values were averaged by sampling months within each season.

Environmental variables and relationship with *C. sapidus* abundance

Water temperature and salinity showed a clear seasonal pattern (Suppl. material 1: fig S2). The temperature trend was comparable among zones, ranging from 9.1 °C in winter 2023 in the Center–South zone to 35.5 °C in summer 2022 in the Center–North zone (Suppl. material 1: fig S2a). Conversely, salinity was more variable among zones, with the Center–North zone showing the highest values.

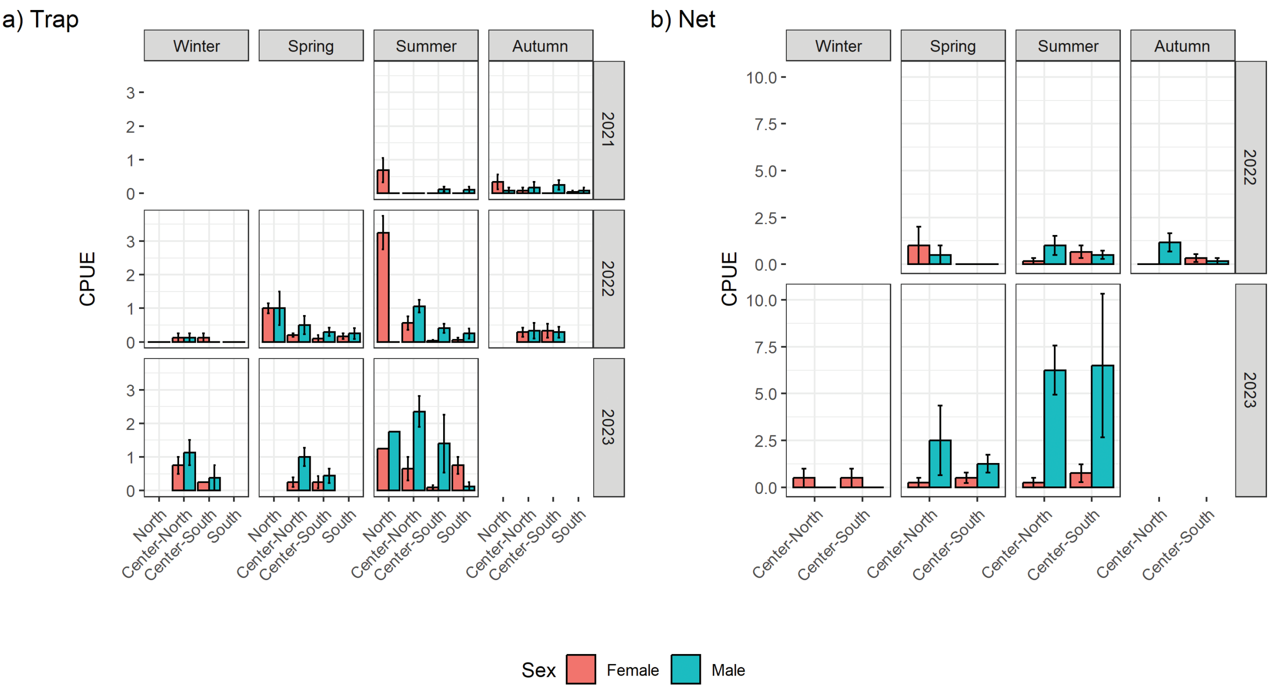

Figure 3. Mean CPUE (± SE) of female (coral bars) and male (cyan bars) specimens of *C. sapidus* caught by trap (**a**) and by net (**b**) in all sampling zones, seasons, and years in the Stagnone di Marsala.

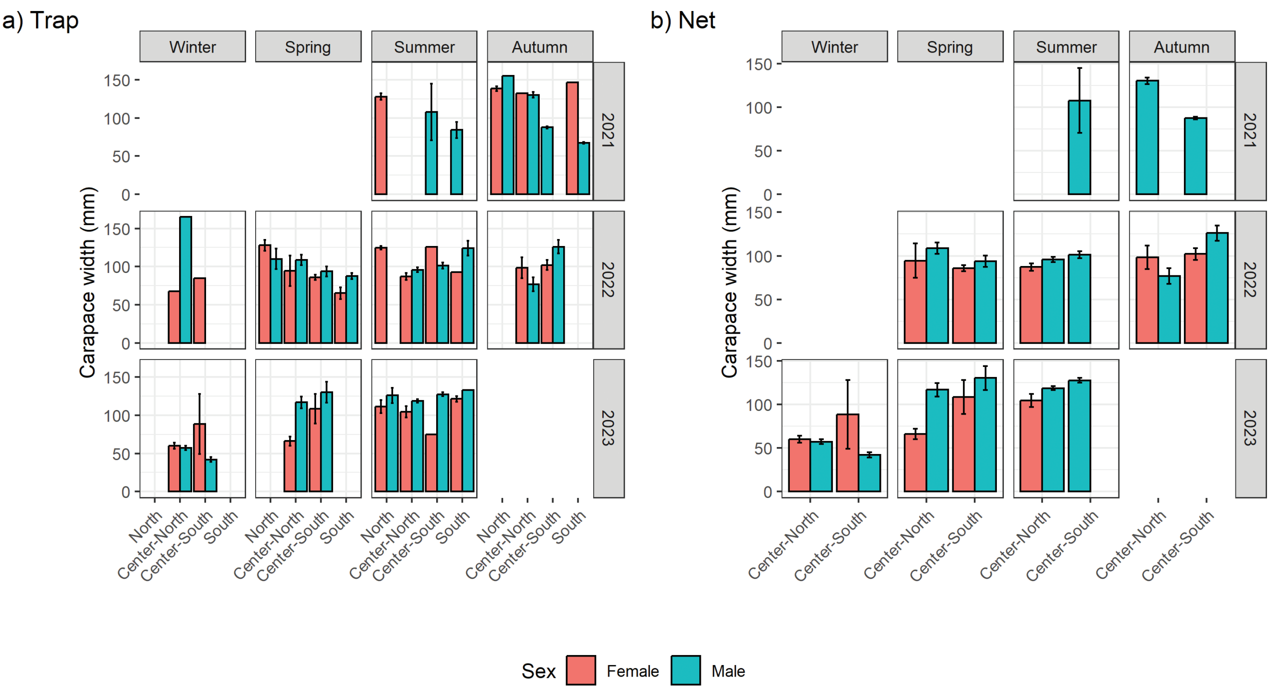

Figure 4. Mean (± SE) carapace width (mm) values of blue crabs caught through traps (**a**) and nets (**b**) in the Stagnone di Marsala. Coral and cyan bars represent females and males, respectively.

Salinity ranged from 29.3 PSU in winter 2022 in the South zone to 52.2 PSU in the Center–North zone in summer 2021 (Suppl. material 1: fig S2b). Overall, blue crab abundance was slightly correlated with both temperature and salinity (Fig. 5), although the relationship was significant only for CPUE by trap and salinity (Spearman's correlation coefficient, $p < 0.05$; Fig. 5b).

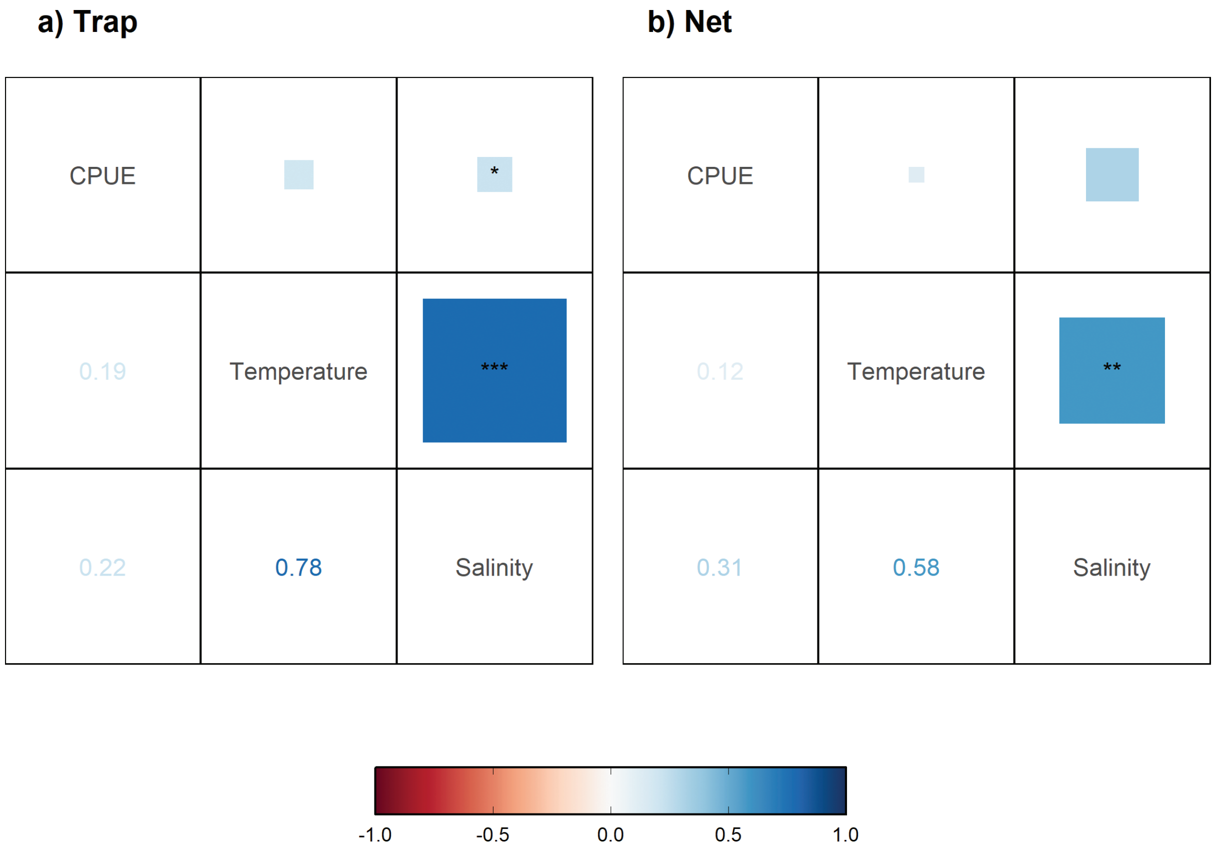

Figure 5. Correlation plots between *C. sapidus* CPUE by trap (**a**) and by net (**b**) and environmental variables (salinity, PSU; temperature, °C). Spearman's correlation coefficient (ρ) values are reported in the lower triangular part, and significance levels are shown in the upper triangular part. Significance levels: ***p < 0.001, **p < 0.01, and *p < 0.05.

Discussion

The observed occurrence, abundance, and spatial and temporal dynamics of the population of *Callinectes sapidus* within the Stagnone di Marsala provide evidence of the invasion success of this non-indigenous species in a Mediterranean hypersaline coastal marine ecosystem. The present study indicates that *C. sapidus* is able to establish in hypersaline waters, confirming its ability to spread in a wide variety of environments (Mancinelli et al. 2013, 2017a, 2024) and showing seasonal and spatial dynamics of its population at a local scale (Hines 2007; Kevrekidis and Antoniadou 2018). The invasion success of *C. sapidus* in Mediterranean coastal ecosystems can be attributed to a combination of biological and ecological traits. Its ecological opportunism, trophic adaptability, strong swimming capacity, and aggressive behavior (Williams 1974; Dulčić et al. 2011) allow it to exploit a wide range of habitats and resources. Most notably, its exceptional tolerance to extreme salinity and temperature conditions enables it to thrive in such environments, thereby facilitating its rapid establishment and expansion.

Spatio-temporal distribution of *C. sapidus* abundance

The abundance of the blue crab varied greatly among seasons, with fluctuations in the different sampling zones ranging from 0 to 3.3 CPUE for traps and from 0 to 10 CPUE for nets, and showing an overall increasing trend from summer

2021 to summer 2023. Similar patterns were observed in studies conducted in other invaded Mediterranean areas. Mancinelli et al. (2024) reported an increasing trend in the blue crab population in the Lesina Lagoon (Adriatic Sea, Italy) during one year of observations (2021). However, the CPUE, calculated as the number of individuals caught per day of netting, remained relatively low, ranging from 0 in December 2021 to 1.76 ± 0.37 individuals per hour in July 2022 (Mancinelli et al. 2024). Clavero et al. (2022) also described the rapid growth trend of the blue crab in coastal wetlands of the Ebro Delta (Spain), showing yearly variation (2011–2020) in its relative abundance.

Seasonal peaks in abundance are not unique to the Stagnone di Marsala, as similar patterns have been reported in other Mediterranean regions—for example, in southern Italian lagoons studied by Mancinelli et al. (2013, 2024) and in sites of the northeastern Aegean Sea, as reported by Kevrekidis and Antoniadou (2018) and Kevrekidis et al. (2023). The spatial pattern of abundance, with a peak in the Center–North zone, may indicate that the blue crab initiated its invasion in the northern area, possibly entering through the northern inlet and gradually expanding southward. It is plausible that the species established more successfully in the central regions (i.e., Center–North and Center–South zones), where environmental factors such as higher temperatures and elevated salinity could provide more favorable conditions for growth, survival, and reproduction. Conversely, the comparatively low abundance in the southern zone of the Stagnone di Marsala might be influenced by greater anthropogenic disturbances, including tourism, boating, and recreational activities, especially during the summer months. However, further research is necessary to confirm this speculation.

Influence of environmental variables

Despite the absence of a significant correlation between temperature and the abundance of the blue crab in the Stagnone di Marsala, peaks in CPUE occurred during the summer season for both sampling methods (traps and nets), when temperatures were at their highest values. It has been observed that in estuaries at higher latitudes, where seawater temperatures drop below 9–10 °C in winter, the blue crab may move into deeper waters, where it overwinters, slowing down all basic activities, from movement to feeding and molting (e.g., Hines 2007; Carrozzo et al. 2014; Kevrekidis et al. 2023; Mancinelli et al. 2024).

Warmer temperatures are known to create optimal conditions for feeding and breeding, which in turn support rapid population growth and the establishment of stable populations in new environments, thereby boosting the invasion success of this IAS (Hänfling et al. 2011; Haubrock et al. 2022). In its native area of Chesapeake Bay, Seitz et al. (2011) demonstrated that *C. sapidus* exhibits a strong affinity for warmer waters, where higher temperatures increase metabolic activity, accelerate growth rates, and enhance reproductive output.

The combination of favorable temperature and tolerance to high salinity during the summer seems to create an ideal setting for *C. sapidus* in the Stagnone di Marsala, enabling the species to thrive in this Mediterranean coastal ecosystem. The Center–North zone of the Stagnone di Marsala, which is the least influenced by the sea and is characterized by consistently high salinity levels, recorded a noticeably higher abundance of *C. sapidus* compared to other zones, especially during the warmer summer months. While this contrasts with findings from some native habitats in the United States, it aligns with those reported from native areas in Mexico. In fact, in Florida (USA), *C. sapidus* mainly occurs in low-salinity estuarine systems and brackish waters (Guillory 2000; Guillory et al. 2001), whereas in the Gulf of Mexico, the presence of *C. sapidus* has been reported in two hypersaline lagoons, Laguna Madre and Corpus Christi Bay (Hawley 1964; Plotnick et al. 1990; Ramach et al. 2009). Notably, in these latter lagoons, salinity levels can be as high as those recorded in the Stagnone di Marsala (more than 40 PSU).

High-salinity conditions play an important role in supporting the establishment of the blue crab in Mediterranean coastal ecosystems. Accordingly, findings from Mancinelli et al. (2024) documented the species' preference for saline coastal habitats in the Lesina Lagoon (Adriatic Sea, SE Italy). Hypersaline basins are often unsuitable for many native species that cannot tolerate high salinity, which in turn reduces competition and creates ecological niches for the blue crab (Ramach et al. 2009). In addition, elevated salinity promotes key biological functions in *C. sapidus*, such as growth, molting, and reproduction (Marchessaux et al. 2024a). Furthermore, Marchessaux et al. (2024b) demonstrated the high salinity range (29–50 PSU) tolerated by the blue crab in Palo and Biguglia lagoons (Corsica, France), showing that salinity had a significant positive effect on the CW of females. This combination of reduced biotic pressure and improved physiological performance helps explain the species' invasive success in hypersaline habitats.

Population structure

Our study has shown that *C. sapidus* has a complex distribution within the studied area. This likely involves seasonally and spatially specific movements for copulation and reproduction linked to temperature and salinity patterns (Hines et al. 1990; Carr et al. 2004; Aguilar et al. 2008), thus generating spatio-temporal variability in population abundance at the local scale.

Variations in size across different zones and seasons within the Stagnone di Marsala basin revealed the species' population structure. The observed spatial and temporal variability in carapace width is consistent with the findings of Mancinelli et al. (2024) in the Lesina Lagoon (Apulia, Italy), who documented considerable variability in the size of *C. sapidus* due to multiple drivers such as genetic factors, seasonal variations, temperature, and food availability. The largest individuals of *C. sapidus* were caught in spring and summer, while the smallest specimens occurred in autumn and winter. This pattern aligns with observations from other Mediterranean studies, including those in the Lesina Lagoon in the Adriatic Sea (Cilenti et al. 2015; Mancinelli et al. 2024), the Monolimni Lagoon in the Aegean Sea (Kevrekidis et al. 2023), and the native area of the Rhode River in Chesapeake Bay, Maryland (Hines 2007).

The non-homogeneous sex ratio, with males captured more frequently than females (sex ratio 1.94:1 (♂:♀)), is consistent with other studies examining *C. sapidus* populations in Mediterranean coastal areas (Mancinelli et al. 2013, 2024; Cilenti et al. 2015). Indeed, males tend to exhibit more active and aggressive behavior, which may contribute to their higher capture rates, particularly within larger size classes (Mancinelli et al. 2013). Male behavior not only makes them more vulnerable to capture in passive fishing gear but also reflects their aggressive nature during foraging and mating seasons. In contrast, the higher occurrence of females in the North zone during the initial phases of data collection could suggest the presence of a potential spawning or nursery area, likely due to favorable conditions such as higher food availability and lower predation levels. These findings further emphasize the role of the environmental complexity of the Stagnone di Marsala in shaping the structure of the blue crab population.

The Center–North zone, which hosted larger *C. sapidus* than the North and South zones, appeared to offer particularly favorable conditions for larger males. This could be due to the presence of extensive seagrass meadows, primarily composed of dense *Cymodocea nodosa* meadows, which provide essential habitat features including shelter, feeding grounds, and breeding sites (Mancinelli et al. 2013, 2017a, b). Accordingly, four ovigerous females were found in the Center–North zone during the summer months, corroborating the suitability of the meadow as a reproductive habitat. These meadows are likely to create an ideal environment for blue crabs to settle, access key resources, and achieve high growth rates. Furthermore, the semi-enclosed nature of the Center–North zone, characterized by limited water exchange with the open sea, may offer a stable and more protected environment, thereby fostering *C. sapidus* establishment. Similar findings have been documented in other Mediterranean semi-enclosed systems, where hypersaline conditions coupled with rich benthic communities create favorable ecological niches for *C. sapidus* (Mancinelli et al. 2024). Furthermore, we found that ovigerous females were present in this zone at high salinity levels during the summer months. This is in accordance with Carr et al. (2004), who showed that ovigerous female blue crabs migrate from low-salinity estuarine regions to high-salinity regions near the ocean to release larvae. In contrast, the lower abundance found in more exposed areas of the Stagnone di Marsala, such as the South zone, suggests avoidance of areas with high hydrodynamic activity, less confinement, and greater human influence.

Implications for management and conservation

The rapid expansion of the blue crab within the Stagnone di Marsala basin raises significant ecological and management considerations that warrant urgent attention. This species holds substantial economic value as a fishery resource in various Mediterranean regions (Frem et al. 2024), as well as in the eastern Atlantic, where established populations support local fisheries and contribute to regional economies in Portugal (Vasconcelos et al. 2019) and Morocco (Gourari et al. 2025). However, its aggressive predatory behavior represents a considerable threat to native species in invaded ecosystems, affecting biodiversity and ecological dynamics (Benabdi and Belmahi 2020). The increasing abundance of *C. sapidus*, particularly in restricted areas (i.e., the central zone of the Stagnone di Marsala), indicates that this area may require targeted management interventions to mitigate the potential negative ecological impacts associated with this IAS, which could lead to changes in the composition of biological communities. To this aim, a more comprehensive assessment of the ecological alterations in the invaded ecosystem is necessary, especially by examining competition processes with native species having similar trophic habits. Future investigations focused on trophic niche characteristics and potential overlap with other species are therefore recommended. The biological characteristics and plasticity of the blue crab—including omnivorous feeding habits, high fecundity, aggressive behavior, high mobility, and large body size—provide attributes for the successful colonization of new areas. It is thus not surprising that its distribution has expanded from western Atlantic waters to transitional and even freshwater environments in the North Sea, the Mediterranean Sea, the Black Sea, and Japan in the Indo-Pacific Ocean (Mancinelli et al. 2021; González-Ortegón et al. 2022; Castriota et al. 2024).

Implementing selective harvesting practices in conjunction with regular monitoring could play a pivotal role in controlling the blue crab population and reducing its negative effects on local ecosystems (Marchessaux et al. 2024b). Contrary to previous findings in the literature, where traps are cited as the most effective fishing gear for catching blue crabs (e.g., Aslan and Polito 2021; Kevrekidis et al. 2023), in our study the use of nets proved more effective. In this context, the combined use of several fishing gears could increase catch efficiency, including the likelihood of capturing different life stages of the crabs. Information gathered from fishermen indicates that blue crabs often damage nets and that untangling them considerably increases the time and labor required during fishing operations. Such practical difficulties, frequently reported in artisanal fisheries (Tsirintanis et al. 2022 and references therein), highlight that despite higher efficiency in terms of catches, the use of nets may present significant operational constraints compared to traps.

The spatial–temporal variability observed in this study further highlights the necessity for adaptive management strategies that consider the complex life cycle and environmental preferences of *C. sapidus*. For instance, focusing fishing activities during peak reproductive months in summer, when larger individuals and gravid females are most abundant, could be an effective approach for supporting population control. However, removing alien species to control invasions often encounters challenges in protected areas such as the Stagnone di Marsala. Conservation objectives in these areas may limit or complicate active interventions (Ferraro 2001). Therefore, effective management requires a context-specific approach and the proactive engagement of governance bodies to balance ecological priorities with conservation mandates (Martínez-Harms et al. 2024). Furthermore, as salinity and temperature are recognized as drivers of *C. sapidus* distribution, future management plans must incorporate potential effects of climate change on the ecosystem. This approach is essential not only for managing the *C. sapidus* population effectively but also for safeguarding the ecological integrity of the basin and its associated habitats. Overall, an integrated management framework balancing ecological health with economic interests will be crucial for addressing the challenges posed by *C. sapidus* in this invaded coastal marine ecosystem.

Conclusion

This study advances understanding of *C. sapidus* population dynamics and its environmental interactions in the Stagnone di Marsala, revealing for the first time the species' remarkable adaptability to hypersaline conditions in this area and its potential for rapid local expansion. Unlike previous studies that focused primarily on estuarine or lower-salinity habitats, our results demonstrate the species' ability to thrive under extreme salinity, highlighting an underappreciated aspect of its ecological plasticity. These findings underscore the importance of continuous monitoring and targeted management strategies that balance conservation objectives with the socio-economic benefits of fisheries. A comprehensive, adaptive approach integrating ecological data with stakeholder engagement is critical to protect native biodiversity while supporting sustainable fishing amid ongoing environmental change.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Range expansion of the blue crab in a Mediterranean hypersaline coastal basin

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