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Investigating invasion patterns of *Callinectes sapidus* and the relation with research effort and climate change in the Mediterranean Sea

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The ecological stability of Mediterranean marine ecosystems is increasingly threatened by invasive alien species (IAS). This study examines the invasion dynamics of *Callinectes sapidus*, a high-risk and readily identifiable IAS across the Adriatic, Ionian, and Central Mediterranean subregions. A comprehensive dataset of published scientific and local ecological knowledge (LEK) records was compiled to analyze spatial and temporal patterns of diffusion. An increase in reported occurrences was found across the entire study area, spreading from south to north. Heterogeneous sampling methods hinder direct comparisons across regions, underscoring the need for standardized reporting protocols. LEK supported the clarification of overall patterns of *C. sapidus* diffusion and enhanced the resolution of temporal and spatial distribution data. The temporal progression of the invasion aligns with phases of arrival, establishment, and expansion. A close association was observed with both research effort and rising sea surface temperatures (SST). This study highlights the importance of integrating climate data and community-based knowledge in IAS monitoring and demonstrates a methodology for assessing climate-linked biological invasions in marine environments.

Keywords Invasive alien species, Species distribution patterns, Local ecological knowledge, Invasion trends, Mediterranean sea, Atlantic blue crab

The Mediterranean Sea is home to the largest proportion of threatened marine habitats in Europe[1]. While the Mediterranean Sea only covers 0.82% of the world's ocean surface area[2], it is considered a global hotspot for bioinvasions[3]. Invasion by alien species is one of the greatest drivers of regional ecological instability[1–8] and contribute to endemic biodiversity loss[4,5].

Invasive alien species (IAS) are defined as populations of non-indigenous species (NIS) which establish and spread[9]. About 1,000 marine NIS have been observed to date in the Mediterranean Sea, more than half considered IAS[9]. The rate of has been introduction rapidly increasing[10]. Common impacts of IAS include the replacement of native species, biodiversity loss, habitat modification, as well as alterations in community structure, socioeconomics, ecosystem function and productivity[9,11,12]. To achieve Sustainable Development Goal (SDG) 14 Life Below Water and SDG 15 Life of Land, it is critical to have a deeper understanding of the dynamics driving the spread of invasive species[1,8,11].

Major IAS present in the Mediterranean Sea were introduced through a variety of mechanisms. The main methods of local IAS introduction include transport through the Suez Canal (referred to as Lessepsian Migration), movement from ports of origin through ballast water, introduction by aquaculture, mariculture or the aquarium trade[13,14]. The variety and frequency of transport mechanisms furthers the difficulty of monitoring the diffusion dynamics of IAS. Marine invaders in the region include various macrophytes such as members of the genus *Caulerpa*, fish like *Pterois miles* and invertebrates including *Rhopilema nomadica*[14]. Another prominent IAS, the Atlantic Blue Crab, *Callinectes sapidus* (Rathbun, 1896) has emerged in recent years as an invader of particularly high risk in the Mediterranean Sea.

C. sapidus was first documented in the Adriatic basin in 1949, likely transported through ballast water during the Second World War[15]. Since 2004 occurrences have been rapidly increasing throughout their invaded range[16–18]. The species demonstrates flexibility to environmental conditions. This resilience might allow them to

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outcompete local species, particularly in areas under increasing levels of environmental stressors[19–21]. Notably *C. sapidus* has a wide tolerance to salinity fluctuations, temperature stress, and pollutants[9].

Ecologically *C. sapidus* is a predator with a trophic position similar to Mediterranean benthivorous fish species[21,22] with a demonstrated preference for sessile and slow-moving benthic organisms, especially fish and mollusks[23,25]. In the Mediterranean they also face low predation pressure[25]. The lack of top-down population control, trophic flexibility and r-strategy of reproduction enables them to be effective invaders[17,18,24,26].

Coastal communities have documented negative economic consequences from the invasion of *C. sapidus*. Extensive damage to fishing nets, reduced catch, higher costs and lower incomes have been reported across the study area[26,27]. In the Venice Lagoon, aquaculture damage in 2023 decreased economic productivity between 56–100%[28]. In the Karavasta Lagoon of Albania fishing productivity was reduced by about 50% in the forty-year period between the late 1970s and 2020[25]. Recent studies have also demonstrated that *C. sapidus* poses a greater risk in future climate scenarios, especially considering projected changes to temperature and salinity conditions[29].

As human and ecological systems are intrinsically linked[30] it is recognized that negative IAS impacts affect local socio-ecology[14]. Due to these concerns, research efforts have rapidly increased since 2004[16]. These efforts have been focused on identifying the presence, ecology and the socio-ecological impacts of the invasion[16]. Importantly as the invasion became studied with greater effort the increase in research interest has led to more observations. Local Ecological Knowledge (LEK) can be an indispensable tool to clarify invasion dynamics, as LEK can provide both long-term perspective of the IAS populations as well as a lived experience of the impacts[31]. Incorporating LEK methodology into research allows for consideration of historical patterns. These approaches lead to more effective methods of monitoring Socio-Ecological Systems (SESs). This collaboration can enrich scientific effort, bridge knowledge gaps and assist in early warning of environmental changes[32,33].

Ecological and invasive species records are spatially autocorrelated in nature[34]. Statistically, this autocorrelation calls for improved and standardized tools for modeling invasions, predicting trajectories and analyzing the dynamics of IAS[35–37] to inform management[38]. Recent research into the distribution of the species has been focused on mapping occurrences and assessing regional risk[16]. Although scientific literature documents observed changes, it frequently lacks the temporal and spatial resolution necessary for detailed invasion dynamics. This is the first report to our knowledge which has analyzed how the narrative of the invasion of *C. sapidus* relates to research effort and climate change in the Adriatic, Ionian and Central Mediterranean.

C. sapidus was considered as a model organism to analyze the spatial and temporal patterns of a readily identifiable and high-risk IAS in the Mediterranean Sea. This study explored how *C. sapidus* presence has changed over time in relation to research effort and sea surface temperature. This approach offers insights into the combined influence of climate change and anthropogenic monitoring on biological invasions. The methodology presented assesses distribution patterns of invasive alien species (IAS) along a unique natural latitudinal gradient from south to north. It was hypothesized that published records of IAS occurrence are related to patterns of research effort, that the species is genuinely spreading and has increased in abundance since the first sighting, and that the observed species diffusion could be related to patterns in climate change. The role of LEK in supplementing ecological datasets is also assessed. These hypotheses are evaluated using segmented regression, generalized least squares (GLS) modeling, kernel density analysis, and SST trend analysis.

Methods

Literature review

A review of *C. sapidus* observations was conducted. Ultimately, a robust dataset from records published in peer-reviewed research was created. The study area focused on the south to north axis from the Central, Ionian and Adriatic Seas subregions of the Mediterranean Sea (46–30° N, 6–25° E). The dataset was employed to investigate the description of the invasion in the study area.

Global biodiversity databases such as GBIF and iNaturalist were excluded from the analysis due to the absence of standardized measures of sampling effort or species abundance. Their inclusion could introduce temporal bias, as platforms like iNaturalist were not available during much of the study period and have exhibited substantial growth in user participation over time[39].

The literature review focused on verified research grade reports which documented the presence and abundance of the species. The search followed methodology from Marrocco et al., 2019[40] and targeted both traditional scientific research and publications utilizing LEK approaches. The initial literature search was conducted through SCOPUS and Google Scholar. The keyword "Callinectes sapidus" was searched from the article title, abstract, and document. The second search added the keyword "Local Ecological Knowledge" to target research utilizing LEK approaches. Next, the review expanded to additional publications cited in the literature. A final search conducted on Google targeted countries in the study area which were not well represented. The standard Google Search was carried out with the keywords "Callinectes sapidus + Country" and "Blue Crab + Country".

Each publication was inspected for the minimum criteria that constituted an occurrence record. These minimum criteria were reported location, timing of observation and the number of individuals present or perceived abundance. Where applicable additional sampling data was also collected. The auxiliary information included method of capture, frequency of sampling and if the observing party were fishermen or scientists. Further records such as personal observations by scientists published in the literature were included as LEK.

Local Ecological Knowledge observations were standardized to an ordinal scale from 0–5 referring to the frequency of encounters during the fishing period[31]. A score of 0 referred to absence, 1 as rare, 2 as occasional, 3 as common, 4 as abundant and 5 as dominant. In cases where no measurement of relative abundance was available the observations were used only for the phase and kernel density analyses. Records which did not report either the number of individuals observed or an abundance metric were omitted from the population growth analysis.

At the end of the literature searches only papers with relevant scientific data were included. The initial 2156 publications were sorted to include those in the target study area with observation records that met the minimum criteria. A total of 77 publications (Supplementary Table) composed the final dataset of 336 unique research grade observations events of over 15,000 individuals over a 58-year period.

Diffusion dynamics- phase analysis

All analyses were conducted using open-source tools in the programs QGIS version 3.42.1 (QGIS Geographic Information System- QGIS Association) and R version 4.3.1 (R Core Team 2024). Statistical significance was evaluated at $\alpha = 0.05$.

Methodologies to analyze invasion dynamics were followed from Perzia et al., 2022[41] and Castriota et al., 2024[16]. To explore the invasion phases, segmented linear regression was applied to the cumulative occurrence data following these approaches[16] which is informed by the general invasion curve framework[42,43]. While recognizing the potential for post-hoc bias in breakpoint selection[34], these analyses provide a descriptive context for evaluating invasion phases consistent with the lag-establishment-expansion model[44]. This approach was used for the purposes of this analysis to qualitatively describe the three phases corresponding to the arrival, establishment, and expansion of the IAS in the entire study area. The slope of the line allowed for consideration of the rate of change in each phase. These phases defined the time intervals used in the Kernel Density and Sea Surface Temperature analyses.

Diffusion dynamics- growth rate and research effort

Cumulative presence records by year were compared to cumulative research publication counts by year. This approach follows the general application of autoregressive models in ecological time series to account for temporal autocorrelation[45,46]. Generalized Least Squares (GLS) models with a first-order autoregressive (AR1) correlation structure were used employing the *nlme* package in R. Separate GLS models were fitted to the natural logarithm of research records and IAS counts as functions of year. This allows for the direct estimation of annual exponential growth rates (β_1) and their standard errors. Doubling times were calculated as $\log(2)/\beta_1$. Growth rates were formally compared using a Z-test Eq. (1).

Equation (1) Z—Score.

$$\begin{aligned} Z = {} & (\beta\_\text{species} - \beta\_\text{research}) \,/ \\ & \sqrt{}(\text{SE\_species2} + \text{SE\_research2})\text{Z} \\ & = (\beta\_\text{species} - \beta\_\text{research}) \,/ \\ & \sqrt{}(\text{SE\_species2} + \text{SE\_research2}) \end{aligned} \tag{1}$$

Confidence intervals for both growth rates and doubling times were computed. Model fit was assessed through residual diagnostics and normality tests (Shapiro–Wilk). Both cumulative presence and publication series were normalized to the [0, 1] for comparison. This analytical framework statistically assessed whether observed increases in *C. sapidus* reflect true biological expansion or are driven by increased research effort.

A three-step calculation allowed for further analysis of research effort by country. For each country in the study area, first the number of publications were compared to the time span of publications (Research Span) Eq. (2)

$$Research\ Span = \frac{(Most\ Recent\ Publication - Oldest\ Publication)}{Total\ Years\ of\ Research} \tag{2}$$

Equation (2) Research span by country.

Second, the amount of coastline for each country was standardized to acquire the proportion in the study area (Relative Area) Eq. (3).

$$Relative\ Area = \frac{Country\ Coastline\ in\ Study\ Area}{Total\ Coastline\ in\ the\ Study\ Area} \tag{3}$$

Equation (3) Relative coastal area by country.

The final calculation used the results from Eq. (2) the Research Span over the quotient from Eq. (3) the Relative Area for each country, in order to calculate the final value of Relative Research Effort by country with Eq. (4).

$$Relative\ Research\ Effort = \frac{Research\ Span}{Relative\ Area} \tag{4}$$

Equation (4) Relative research effort by country.

The final output from Eq. (4) provided a standardized value of research effort by country to the appropriate spatial–temporal scales.

Diffusion dynamics- kernel density

Centers of occurrences were identified following Perzia et al., 2022[41]. The analysis was adapted to use tools available in QGIS. Namely, the Kernel Density Tool was used to identify the highest density and persistent occurrence areas[41]. The Kernel Density Tool was set to a radius of 0.05° and utilized Nearest Neighbor Sampling at 2.00 for each invasion phase.

Mediterranean sea surface temperature- regional and temporal trends

The temperature analyses were conducted using open access remote sensing data from E.U. Copernicus Marine Service Information[47]; https://doi.org/10.48670/moi-00173. The product employed was the Mediterranean Sea—High Resolution L4 Sea Surface Temperature (SST) Reprocessed with a spatial resolution of 0.05° × 0.05°. Data was available beginning 1 Jan 1982 on a daily frequency. To consider trends in environmental pressures driven by climate change from 1982 to 2024, monthly mean SST was utilized for this analysis. This allowed for a high-resolution temperature assessment over a multi-decadal period both at specific invasion hot spots and to analyze trends across the entire study area.

The 14 sampling points were selected to investigate trends of SST in the three Mediterranean subregions and at invasion hot spots identified by the Kernel Density Analysis. The points were grouped by subregion for analysis: Central Mediterranean (4 points; IDs 1, 2, 3, 14), Adriatic Sea (7 points; IDs 5–11), Ionian Sea (3 points; IDs 4, 12, 13). Monthly mean SST were downloaded as CSV files from Copernicus Marine Service. Temperature values were converted from Kelvin to Celsius where necessary, and data were checked for completeness with missing values removed prior to analysis. To assess temperature trends in each region, linear regression analysis and Mann–Kendall tests were employed. The investigation was conducted in R using the *Kendall* package for trend testing and *ggplot2* for visualization.

For the temporal trend analysis, data of monthly sea surface temperatures (SST) from Copernicus Marine Service were downloaded in raster (netCDF) format. These files were processed in R using the *raster*, *ncdf4*, and *lubridate* packages. For each invasion phase, the maximum sea surface temperature experienced at each pixel location was calculated across all time steps within that period. This approach captured long term trends in monthly sea surface temperature which potentially influence *C. sapidus* distribution and survival. The processing maintained the original spatial resolution of the dataset to preserve fine-scale temperature patterns. To quantify sea surface temperature increases from climate change, the difference between maximum temperatures in the expansion phase and maximum temperatures arrival phase was calculated. This comparison highlighted regions experiencing the greatest warming trends since 1982.

Results

Diffusion dynamics- phase analysis

Three invasion phases from 1965 to 2024 were defined following classic invasion theory. The initial arrival phase from 1965 to 1999, establishment phase from 2000 to 2015, and expansion phase from 2016 to 2024. Segmented regression revealed progressively increasing rates of cumulative records overtime. The arrival phase exhibited a slow increase with a slope of 0.28 records per year ($R^2 = 0.87$, $p < 0.001$). The regression model for the establishment phase had a higher slope with an accumulation rate of 6.46 records per year ($R^2 = 0.93$, $p < 0.001$). Finally, the expansion phase demonstrated the most rapid increase in records per year, with a slope of 31.53 ($R^2 = 0.93$, $p < 0.001$) (Fig. 1). The segmented trends should be interpreted with caution, as the post-hoc nature of breakpoint assignment and inherently autocorrelated ecological data does not define biological phase transitions[48]. Importantly, the segments identified in the phase analysis serve as a qualitative descriptive of the accelerating invasion trajectory of *C. sapidus* within the study region. In areas where LEK was utilized, responses of abundance throughout the basin support evidence that individuals were not typically observed and were considered rare before 2000, with increasing frequency to common, abundant, and dominant by 2014. Out of the twelve arrival phase records, eight were LEK reports from fishermen. High degrees of temporal and spatial variability were observed throughout the study area. The majority of occurrences were reported in shallow coastal areas, especially near transitional water systems (Fig. 2).

The initial observations followed a pattern from south to north. Occurrences initiated in 1965 in the Gulf of Gables, Tunisia, Central Mediterranean[49], then in 1970 at the Strait of Messina, Italy, in the Ionian Sea[49,50], and then in 1972 in Ancona, Italy, Adriatic Sea[44]. There is an earlier report from 1949 to 1950 which were collected in the proximity of the Venice Lagoon and are housed in Museo di Storia Naturale di Venezia Giancarlo Ligabue in Venice, Italy[51–53]. However, as the context of the collection was not reported and due to a forty-year gap in observation records this occurrence was attributed to a separate introduction event.

Diffusion dynamics- growth rate and research effort

The application of generalized least squares (GLS) growth models compared occurrence records and research effort. The species accumulated at a growth rate of 0.166 (SE = 0.0498) which corresponds to a doubling time of approximately 4.2 years (95% CI 0.0685–0.2636). At the same time, research effort increased at a slower rate of 0.0886 (SE = 0.0498) corresponding to a doubling time of 7.8 years (95% CI 0.0641–0.1132). The growth rate ratio suggests that species records accumulated nearly twice as fast as research effort (ratio = 1.87). These results indicate that the rate of increase in species growth was not statistically different from the increase in research activity ($p = 0.2717$) (Fig. 3a, Table 1). A regional investigation revealed variability between the Adriatic, Ionian and Central Mediterranean occurrence trends particularly in timing and intensity (Fig. 3b).

The analysis of research effort by country identified that most countries included in the assessment published close to the expected number of reports relative to the time of detection and length of coastline in the study area (Fig. 4). Italy published the most reports and was the only country represented in all three subregions. Libya was indicated as underrepresented. However, it is important to note that the first scientifically published record of

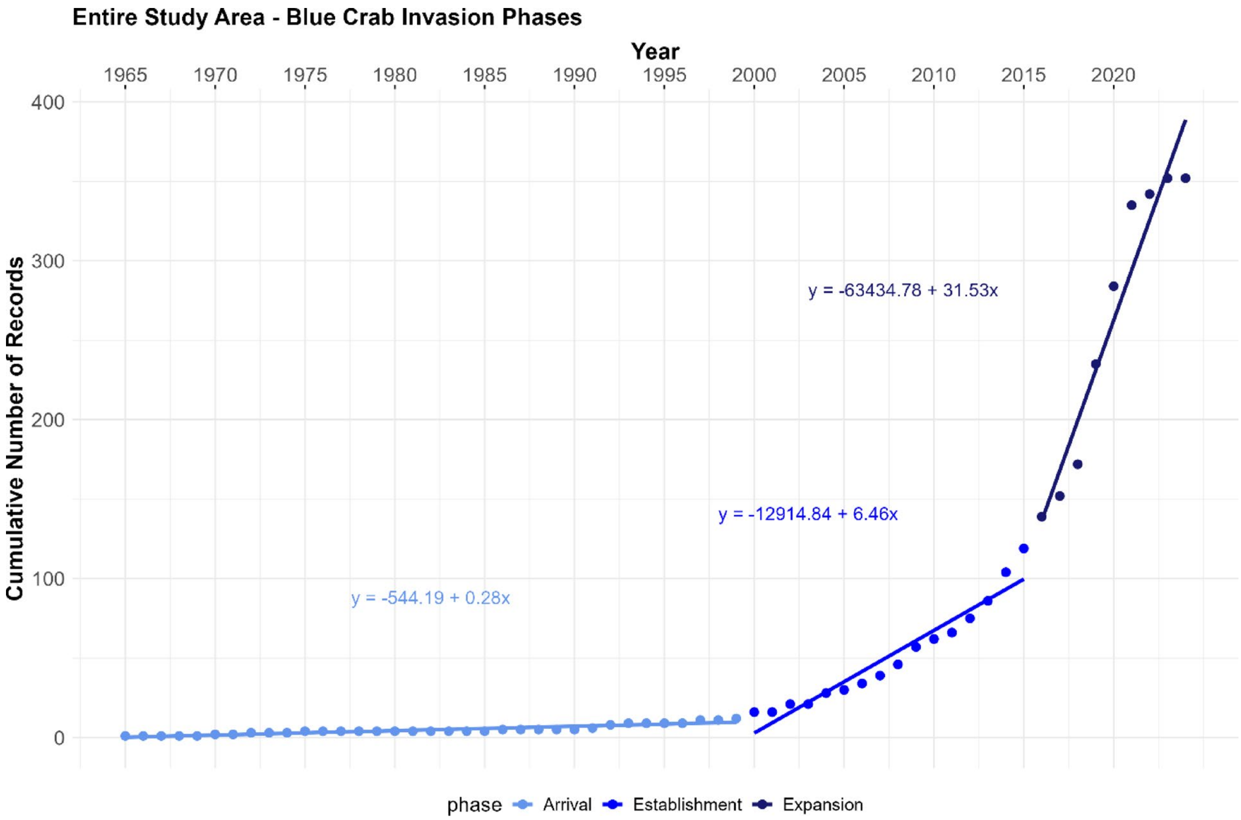

Fig. 1. Cumulative records of *Callinectes sapidus* from 1965 to 2024 in the Adriatic, Ionian, and Central Mediterranean subregions. Linear regression fitted to three inferred invasion phases: arrival (1965–1999), establishment (2000–2015), and expansion (2016–2024) which showed increasing slopes of 0.28, 6.46, and 31.53 records per year, respectively.

the species in Libyan waters was in 2017[54]. It is likely that the establishment phase along this part of the Central Mediterranean coast began in more recent years, following patterns of SST.

Diffusion dynamics- kernel density

The Kernel Density analysis for each phase identified hot spots of observations (Fig. 5a). During the arrival phase, records were the greatest in the Strait of Messina and the Venice Lagoons of Italy. In the establishment phase, observation records increased along the Southern Italian and the Southern Balkan Coasts. Through the expansion phase, populations have continued to spread along coastal areas throughout the study area and expanded spatial distribution.

Mediterranean sea surface temperature- regional and temporal trends

Sea surface temperature (SST) trends across the Central Mediterranean Sea, Ionian Sea, and Adriatic Sea subregions were assessed as a potential climatic driver of the spread. Over the study period, all subregions exhibited statistically significant increases in average annual SST. From south to north the Central Mediterranean Sea showed an annual warming trend of 0.0297 °C per year ($p < 0.001$, $R^2 = 0.007$), the Ionian Sea exhibited a slightly stronger trend of 0.0411 °C per year ($p < 0.001$, $R^2 = 0.014$), while the Adriatic displayed an increase of 0.0381 °C per year ($p < 0.001$, $R^2 = 0.007$). Despite the low R^2 values indicating substantial interannual variability, the Mann–Kendall tests confirmed significant warming trends in all subregions ($p < 0.001$ for all) (Table 2, Fig. 6).

Analysis of seasonal extremes (annual minima and maxima SST) at the selected points provided additional insight. Significant increases to minimum annual SST warming trends were detected in the Central Mediterranean (0.0307 °C per year, $p = 0.0034$, $R^2 = 0.186$) and Ionian (0.0259 °C per year, $p = 0.0011$, $R^2 = 0.226$) regions, while no significant trend was observed in the Adriatic (−0.0109 °C per year, $p = 0.333$, $R^2 = 0.022$). These results indicate since 1982, an observed increase of SST in the winter through the southern and central areas within the study. Additionally, the results identified a higher degree of interannual SST variability in the Adriatic. In contrast, monthly maximum SST trends were not statistically significant in any subregion, ranging from −0.0026 °C per year (Central Med, $p = 0.895$) to 0.0244 °C per year (Ionian, $p = 0.227$).

The temporal trend analysis identified maximum SST in each of the three phases across the study area (Fig. 5b). From 1982 to 1999, the warmest temperatures occurred in the areas off Tunisia, Malta and Sicily (Italy) as well as near the Venice Lagoon (Italy) in the Northern Adriatic. In the establishment phase, warming increased in the Ionian and along coastal regions of Greece and Southern Italy. During the expansion phase warming of surface waters increased above the Northern Ionian Gyre and along the Italian, Montenegrin and

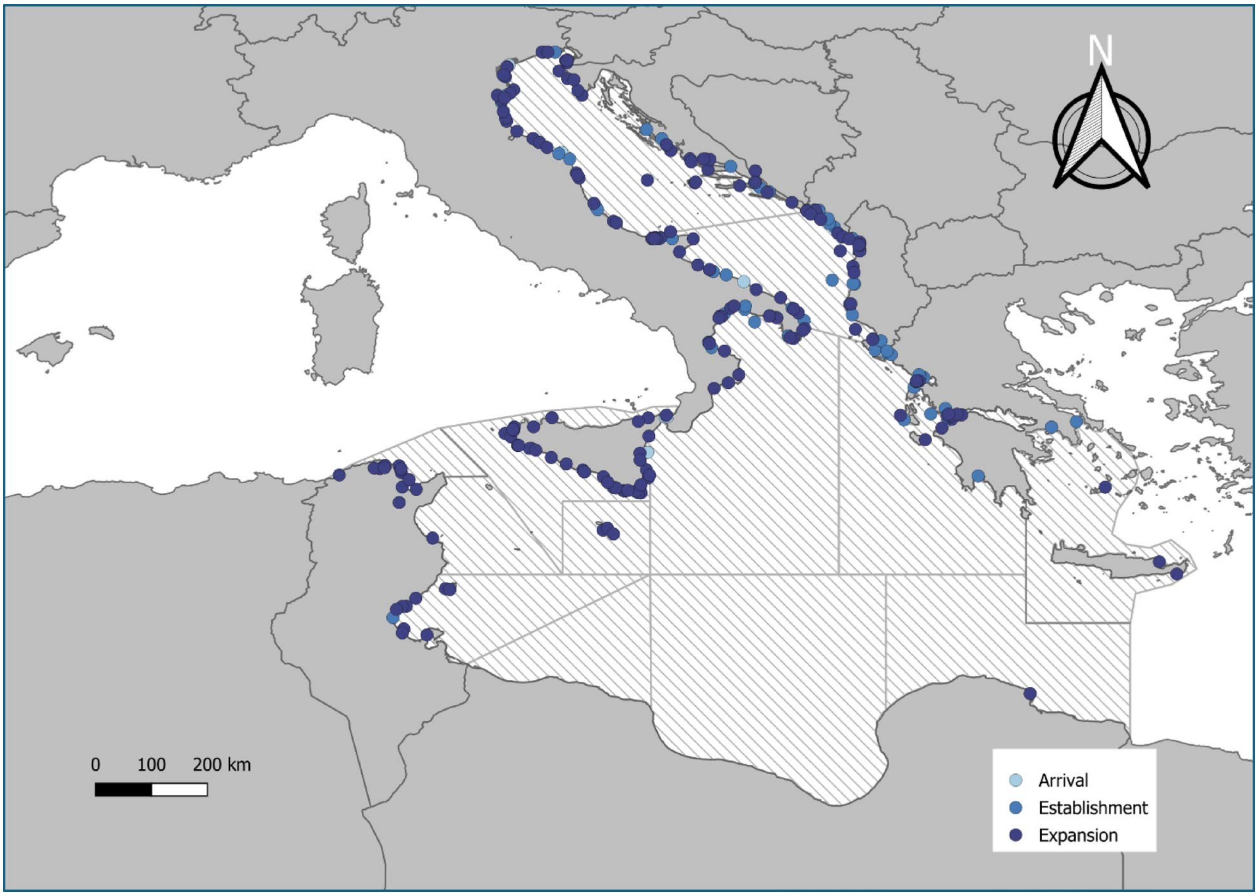

Fig. 2. Total *Callinectes sapidus* occurrence records (1965–2024) included in the analysis, compiled from 77 publications. Data points are color-coded by invasion phase: light blue for arrival, blue for establishment, and dark blue for expansion. More recent records appear in the topmost layer. Map created with QGIS version 3.42.1.

Albanian Coasts of the Adriatic Sea. Overall, the average monthly SST increased from the arrival to expansion phases by up to 3 °C (Fig. 7). *C. sapidus* occurrences were generally reported in areas with a positive increase in temperature, especially in the Ionian and Adriatic Seas. The southern coast of the Central Mediterranean was characterized by a lesser degree of warming and exhibited a slower spread of this IAS.

Discussion

Invasion phases and research effort

The segmented regression models suggest temporal phases consistent with the classic invasion theory (lag, establishment, expansion). The analysis defines an early period of introductions (1965–1999), followed by an establishment phase (2000–2015), and a steep expansion phase (2016–2024). The GLS models suggest a strong relationship between research effort and occurrence records. While observations accelerated at a rate almost double that of research effort, the overall trends of increase were not statistically different from each other. These critical findings indicate that the description of the invasion is strongly related to research effort. It is possible that a rise in reported sightings, indicative of range expansion, may have stimulated interest from the scientific community contributing to the observed growth in publications. This pattern highlights the complex relationship between ecological processes and scientific attention. Both approaches, the regression modeling and GLS models, highlight an accelerating trend in observations consistent with increasing invasion pressure especially since 2016. Additionally considering the 7.8-year rate of research effort, it is likely more publications including observations in recent years will increase. Apparent gaps in distribution, particularly in recently colonized southern areas, may also reflect delayed detection.

Regional and spatial trends

The observed temporal pattern coincides with regional sea surface temperature increases. Significant monthly average warming trends and increases in winter minima temperatures were detected. These findings could suggest that climate change may be facilitating suitable conditions for rapid population expansion. Collectively these results indicate regionally heterogeneous warming patterns. Gyre circulation and deep-water formation events are also driven by climate trends[55]. Throughout the region, changes in interannual circulation possibly facilitate

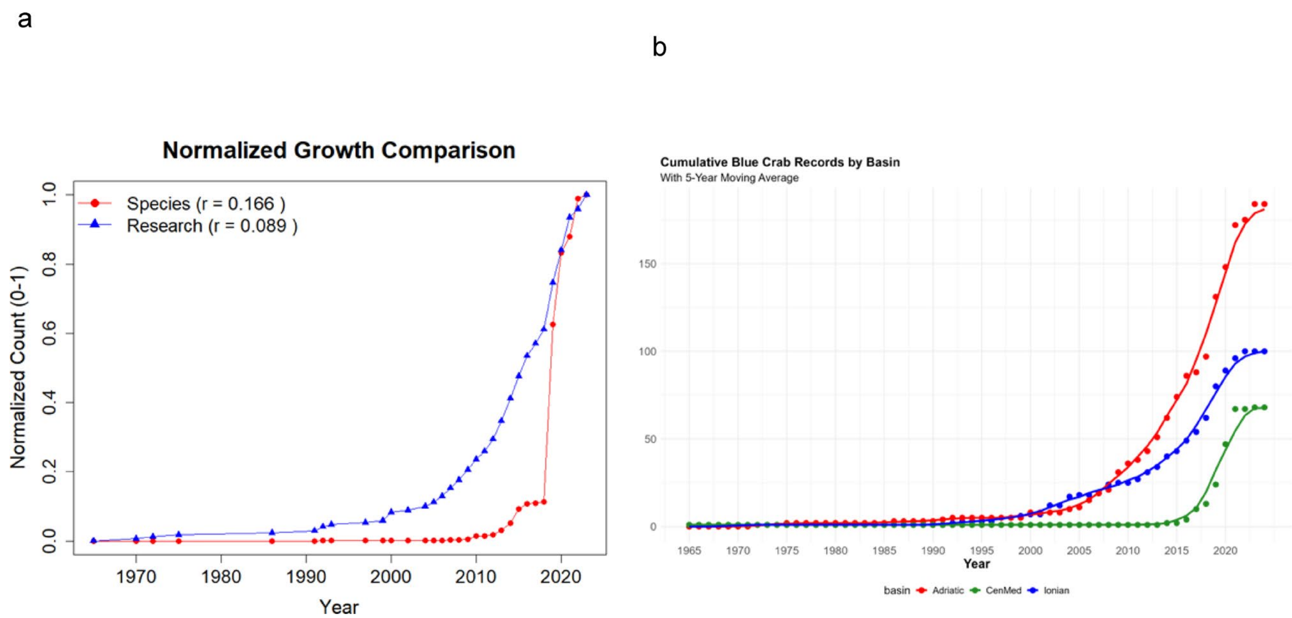

Fig. 3. (**a**) Normalized comparison of cumulative *Callinectes sapidus* occurrence records (red circles) and related research publications (blue triangles), analyzed using a Z test. Although the species occurrence increased at a faster rate (0.166) than research effort (0.089), the difference was not statistically significant. This pattern suggests an ongoing biological invasion, with occurrence records closely linked to research activity. (**b**) Cumulative occurrence records by subregion (Adriatic, Ionian, and Central Mediterranean), highlighting regional variation in invasion dynamics.

Subregion	Annual trend (Δ°C per Year)	Trend significance	*p* value	R^2	MK result	MK *p* value
Central med (ID 1, 2, 3, 14)	0.0297	Significant	< 0.001	0.007	Significant increase	< 0.001
Ionian (ID 4, 12, 13)	0.0411	Significant	< 0.001	0.014	Significant increase	< 0.001
Adriatic (ID 5–11)	0.0381	Significant	< 0.001	0.007	Significant increase	< 0.001

Table 1. Summary of linear regression and Mann Kendall outputs from regional temperature analysis in the study area. Trends are for the entire temporal resolution from 1982 to 2024 using monthly mean sea surface temperature remote sensing data from Copernicus Marine Sea of the Mediterranean Sea—High Resolution L4 Sea Surface Temperature (SST) Data. Analysis was assessed regionally in the Central Mediterranean from four geospatial points, the Ionian from three points, and the Adriatic from seven points.

larval transport with warmer temperatures increasing survivability. Marine heatwaves were documented in the study area in 1994, 2003, from 2013 to 2015 and again in 2019 and 2020[56]. Such shifts in thermal regimes may enhance overwinter survival and facilitate range expansion for *C. sapidus* in the Mediterranean basin.

This pattern may suggest that the slower expansion in southern regions is due to comparatively lower warming trends and differing oceanographic processes, such as gyre circulation and reduced larval connectivity. Libya is likely underrepresented due to the species being observed there for the first time in 2017. The first record of occurrence in Libya was along the east coast at the Umm- Hufayn Lagoon and suggests a more recent arrival[54]. This further supports a south-to-north spatial progression of the invasion and reinforces the role of climate trends in facilitating earlier establishment in the northern subregions, such as the Adriatic and Ionian.

Noteworthy, one observation record was a mass mortality event in 2020. The report of 2760 dead individuals was documented at the Oasi Faunistica di Vendicari in Sicily, Italy. The observing researchers suggested that many environmental factors likely worked synergistically to lead to this die-off which was exacerbated by a three-year drought[57]. The observation occurred inland from the mouth of the Pantano Sichilli, which are brackish ponds without a permanent connection to the sea. The *C. sapidus* individuals were found partially buried in the muddy sediment, exhibiting in situ postering typical of the species. Before this mass mortality event was observed, the species was previously unknown to occur in the lagoon ecosystem of the Vendicari ponds[57]. This suggests that while warming may facilitate expansion, extreme or compounded stressors such as from prolonged drought may exceed species tolerance limits.

LEK contributions to understanding invasion dynamics

In addition to clarifying the dynamics of the IAS invasion, this analysis highlights the critical relationships between fishermen and the scientific community. The majority of LEK methodologies reported in the literature

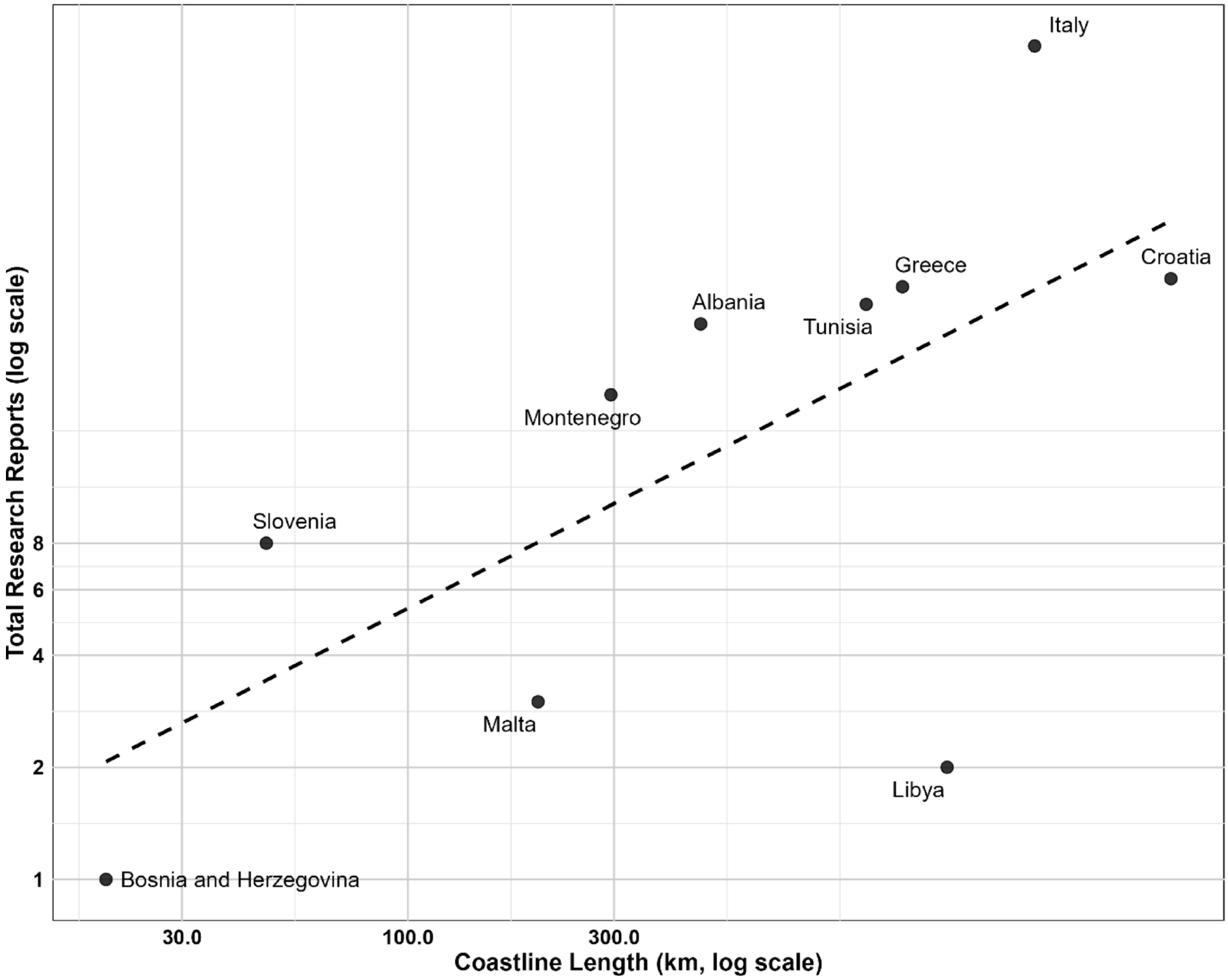

Fig. 4. Relative research effort by country, standardized by the time span of reported records and the length of national coastline within the study area. Most countries align with the expected pattern (dashed line), with the exception of Libya and Malta, which show lower-than-expected research levels, likely due to delayed species introduction.

tapped into the knowledge of fishermen. The initial sightings and early detection of the species were made by fishermen who brought their findings to scientists. Moreover, considering IAS abundance in light of LEK reports standardized the relative abundance records. This allowed for a description of invasion patterns not captured by the variety of sampling efforts employed by traditional scientific analysis. This emphasizes the value of LEK for IAS early detection and management planning.

Protected areas and predator dynamics

Additionally, LEK identified that invasion in nature reserves presents a particular challenge[26]. This is attributed to the fact that fishing for *C. sapidus* is prohibited or restricted in most protected areas. On the other hand, research has shown for other invasive crabs that native predators can control IAS populations in areas with no fishing pressure[58]. Furthermore, predators native to the Mediterranean Sea such as *Octopus vulgaris* have been documented feeding on *C. sapidus*[22,59]. In protected areas native predators may more effectively manage populations and therefore mitigate the impacts of IAS on ecosystem conditions. In either case, it is currently unfeasible to launch an effort to eradicate *C. sapidus* by fishing in nature reserves. These opposing accounts highlight a need for future research efforts to investigate the ecology of the invasion dynamics inside and outside of protected areas. This identifies a potential policy gap between the management of invasive species and the management of protected coastal areas. This is especially critical for invasions occurring at protected sites focused on the preservation of native biodiversity, especially those managed under the Natura 2000 Network, Special Areas of Conservation (SACs), Special Protection Areas (SPAs), and Ramsar Sites.

Conclusion

This analysis of long-term invasion dynamics for *Callinectes sapidus* across the Adriatic–Ionian–Central Mediterranean subregions demonstrate invasion dynamics of *C. sapidus* are likely facilitated by rising sea surface temperatures. These results indicate that urgent actions are needed to mitigate the impacts of the emerging

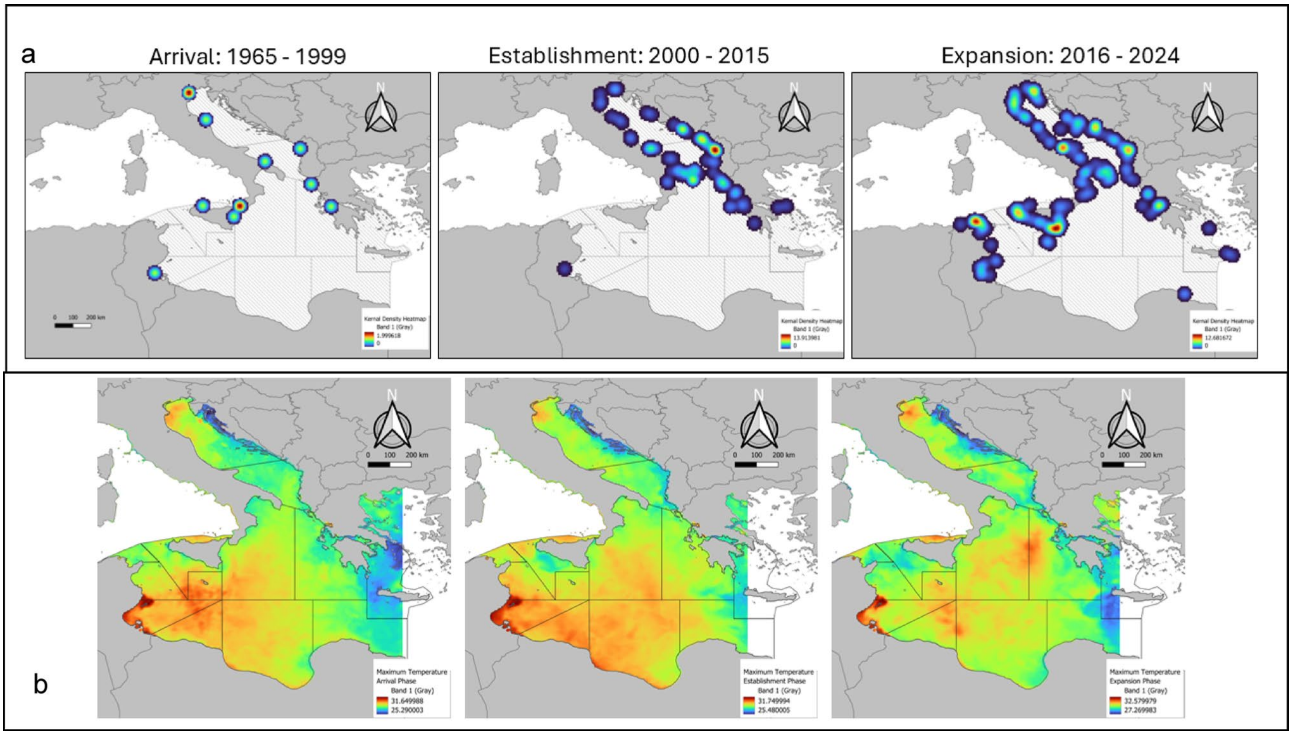

Fig. 5. (**a**) Kernel Density analysis of occurrence records during each invasion phase, generated using QGIS software. Areas with higher record densities are shown in red, while lower densities are depicted in blue for each respective time step. (**b**) Maximum sea surface temperatures across the study area for each phase, with warmer temperatures indicated in red and cooler temperatures in blue. Map created with QGIS version 3.42.1.

Subregion	Min. temp. trend (Δ°C per Year)	Min. temp. p value	Min. temp. R^2	Max. temp. trend (Δ°C per Year)	Max. temp. p value	Max. temp. R^2
Central med (ID 1, 2, 3, 14)	0.0307*	0.0034	0.186	− 0.0026	0.8948	0
Ionian (ID 4, 12, 13)	0.0259*	0.0011	0.226	0.0244	0.2266	0.035
Adriatic (ID 5–11)	− 0.0109	0.3329	0.022	0.0227	0.3661	0.019

Table 2. Results of linear regression analysis showing trends in annual maximum and minimum sea surface temperatures (SST) from 1982 to 2024 across the three Mediterranean subregions (Adriatic, Ionian, and Central Mediterranean). SST values were derived from monthly mean satellite data (Copernicus Marine Service, High Resolution L4 SST).

ecological and socio-economic risks caused by *C. sapidus*. In addition, coordinated regional monitoring efforts, standardized reporting, climate-informed early warning systems, and adaptive management approaches should be developed consistent with science and community-based response to the ongoing spread of this species.

Although *C. sapidus* is not currently listed under the EU Invasive Alien Species (IAS) Regulation (EU 1143/2014), these findings highlight that the ongoing expansion in European waters may continue to present risks both ecologically and socio-economically. Given the demonstrated association with regional climate trends, *C. sapidus* may also serve as a model species for integrating climate-adaptive management approaches into IAS policy. Therefore, it is suggested that *C. sapidus* warrants formal risk screening and consideration for Union Concern listing to ensure coordinated surveillance, impact assessment, and potential early intervention across Member States[59,60].

Past research has identified a high degree of variability in the species distribution and population sizes approaches[16,17,24]. This emphasizes the need for location-specific mitigation in order for site-specific actions to be developed to mitigate negative SES impacts. These targeted approaches include prevention, early detection and rapid response, as well as facilitated eradication and control[61]. Including LEK in invasive species assessments proves to meliorate resolution and should be used in combination with scientific analysis[24,30,39,40]. Local ecological knowledge is especially valuable for early detection and monitoring in data-poor regions.

These results indicate that urgent actions are needed to mitigate the impacts of the emerging ecological and socio-economic risks caused by *C. sapidus*. In addition, coordinated regional monitoring efforts, standardized reporting, climate-informed early warning systems, and adaptive management approaches should be developed in line with science and community-based response to the ongoing spread of this species.

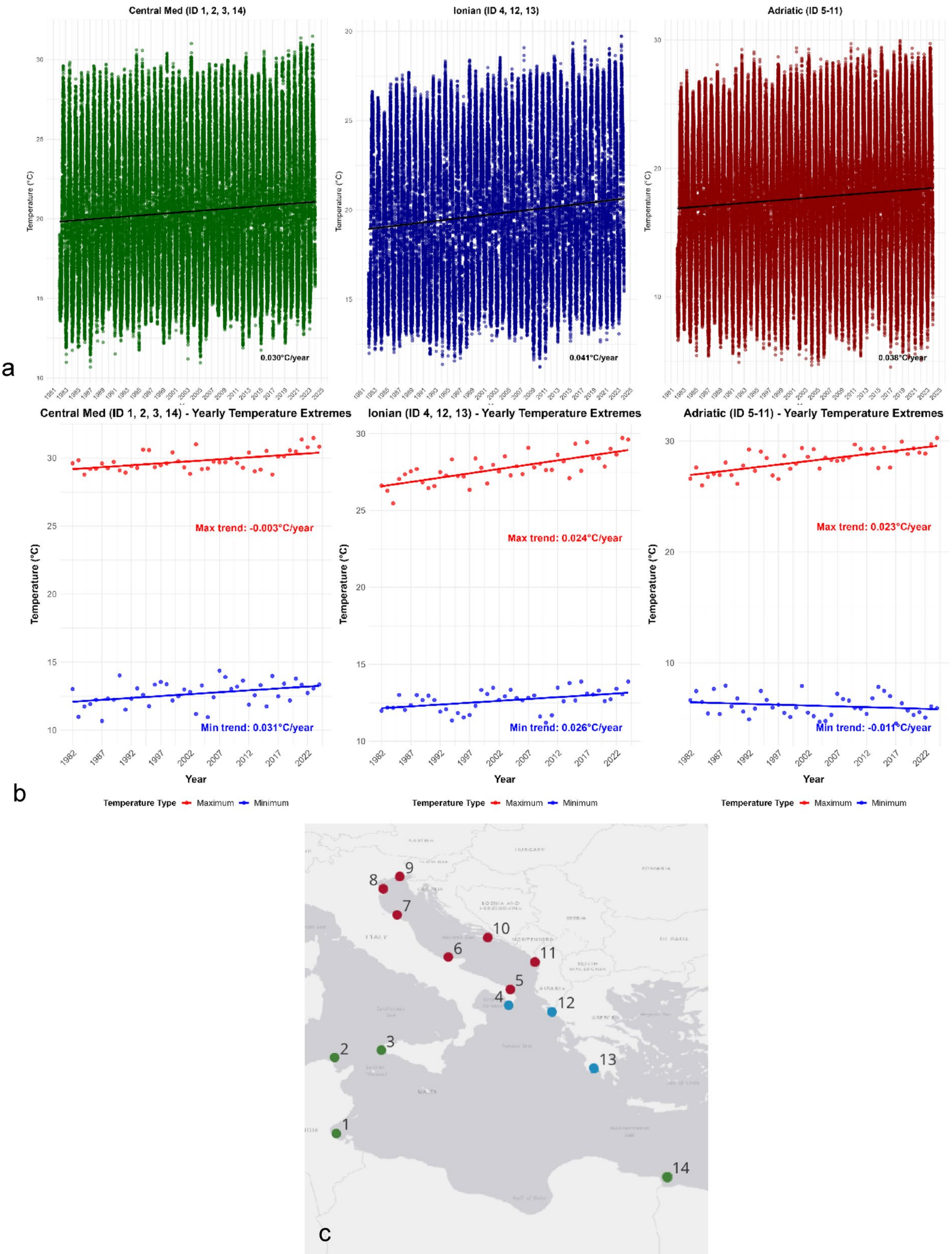

Fig. 6. Values are derived from monthly mean sea surface temperature data obtained from the Copernicus Marine High Resolution L4 Sea Surface Temperature (SST) dataset for the Mediterranean Sea. (**a**) Plots of sea surface temperature analyses reported in Table 1 for each subregion within the study area. (**b**) Plots showing annual minimum and maximum monthly sea surface temperatures for the study area, as reported in Table 2. (**c**) Map of points included in the regional temperature analysis. Map created with QGIS version 3.42.1.

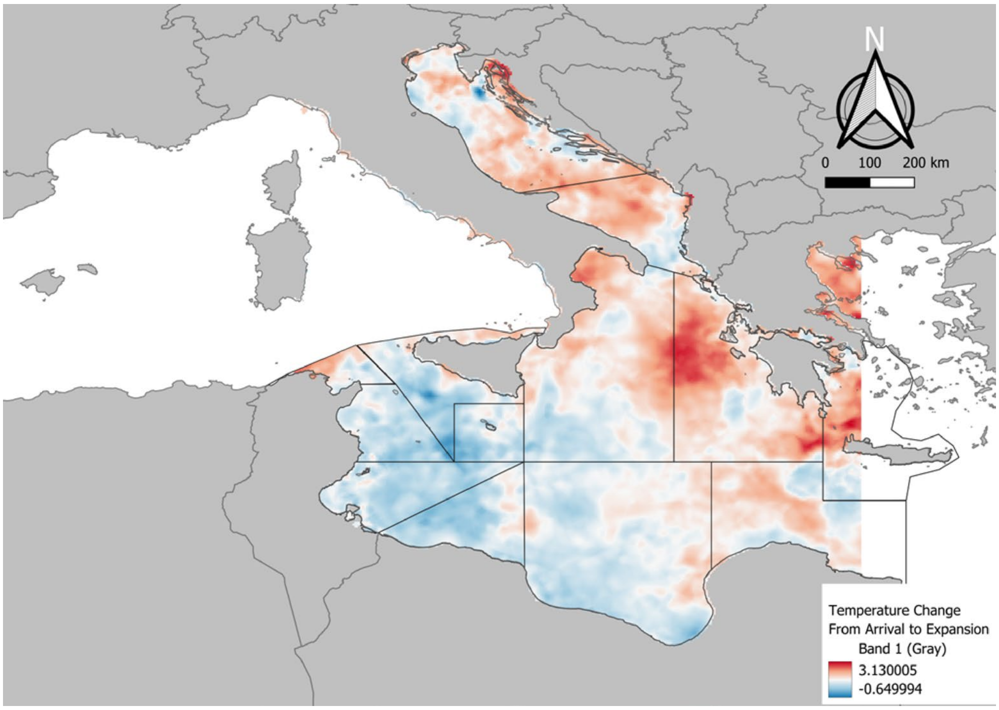

Fig. 7. Values were calculated from maximum sea surface temperature data obtained from the Copernicus Marine High Resolution L4 Sea Surface Temperature (SST) dataset for the Mediterranean Sea during each invasion phase using R. Differences in maximum monthly temperatures between the arrival and expansion phases are reported as changes in degrees Celsius. Map created with QGIS version 3.42.1. Locations with temperature increases are shown in red, decreases in blue, and areas with minimal change in white.

Looking forward, several methodological tools offer promise to improve detection and response efforts. In order to assess population status, it is important to utilize standardized approaches. Challenges to eradicate the species and to standardize the description of the invasion have been identified. There is a wide array of methodologies that can be employed to study non-indigenous species (NIS). Modern techniques including modeling future distribution are also commonly employed to predict future patterns in relation to climate change[62]. Another innovative tool that has been demonstrated as highly effective in documenting species distribution patterns is the use of eDNA[63,64]. This approach allows the early detection of NIS[65] with affordable and readily accessible technology. eDNA approaches have important applications as a tool for conservation and management, allowing local stakeholders to implement prompt mitigation strategies to reduce the extent of ecological impacts on strained ecosystems[65,66]. Research also suggests that eDNA can yield highly comparable results to in situ observation and can be effective at determining species distribution[67]. Use of eDNA is of even greater value for rapid identification of species which are difficult to readily identify[63–66].

This study provides a novel integrated assessment of *Callinectes sapidus* invasion dynamics across the Adriatic–Ionian–Central Mediterranean region by combining scientific records with local ecological knowledge (LEK). The findings reveal a pattern of rapid recent expansion, closely associated with rising sea surface temperatures. Furthermore, these results underscore the importance of understanding how climate trends, scientific effort, and community-based observations interact to shape invasion dynamics. These insights highlight the need for urgent, coordinated responses to mitigate the growing ecological and socio-economic risks posed by this species. Regionally informed standardized monitoring, early warning systems, and adaptive management strategies should be developed in alignment with both scientific evidence and community-based knowledge. Together, these results offer a transferable framework for integrating climate, community, and scientific data to unravel the dynamics of marine invasive species.

Data availability

This study was conducted using E.U. Copernicus Marine Service Information; https://doi.org/10.48670/moi-00173. Data files from the study will be available upon request to the corresponding authors. There was no custom R code produced during the collation and validation of this dataset.

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Author contributions
MP designed and conceived the study. Data and literature collection, preparation of data and analysis was done by MS. Drafting was done by MS and MP, with revisions from FZ and VS. All authors have read and revised the submitted manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information

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