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An Easy-to-Implement Decision Support Tool for the Prioritization of Management Actions: The Case Study of *Procambarus clarkii* in Sicily (Italy)

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Abstract: The frequent introduction and rapid spread of invasive alien species (IAS) along with the limited resources available for their management highlight the need to adopt simple and effective methods for prioritizing management efforts. Here, we propose a technically simple model for prioritizing management actions, using Sicily (southern Italy) as a case study. Despite its invasion being relatively recent and the species not yet widespread, the highly invasive red swamp crayfish *Procambarus clarkii* proved to be able to colonize different habitat types on this Mediterranean island. We adopted a multicriteria analysis method based on geographic information systems (GIS) to identify both the vulnerability of different areas to its invasion, the likelihood of their invasion, and the impact that the occurrence of the red swamp crayfish might have on habitats or species of conservation relevance. The data used in our analysis are routinely available to local administrations and can be easily processed to map the most vulnerable areas for biodiversity protection. The simplicity of the model makes it particularly suitable for local administrative bodies to plan and implement effective invasive species management interventions, optimizing time and costs and allowing the development of concrete nature conservation actions.

Keywords: biological invasions; invasive alien species; management priorities; red swamp crayfish; species distribution model

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1. Introduction

Despite the well-recognized threats caused by biological invasions and the necessity to manage them, 83% of countries at worldwide level do not have specific national legislations or regulations for their prevention and control, and almost half of all countries do not invest in their management (e.g., [1]), Invasive Alien Species (IAS), i.e., those non-native species which have a significant and long-lasting impact on native biota, continue to pose a major threat to global biodiversity [2–4]. IAS outcompete native species through mechanisms such as competition, predation, niche displacement, and parasite spillover (e.g., [5,6]), often leading to the displacement and decline of native populations and sometimes to their local or global extinction [7–9]. Moreover, the occurrence of IAS causes substantial ecological and economic costs, summing up to billions of dollars per year worldwide (e.g., [10–14]). Nevertheless, IAS occurrence, distribution, and impact are far from being easy to assess. In light of the limited resources often available to local administrations, it is crucial to effectively prioritize management actions (e.g., monitoring, control, and eradication) to optimize conservation efforts, costs, and strategies.

Native to northeastern Mexico and southern USA, the red swamp crayfish *Procambarus clarkii* (Girard, 1852) is one of the most widespread invasive crayfish species worldwide and, for its ecological impacts, it is included in the list of IAS of Union Concern attached to the EU Regulation 1143/2014 on IAS for which management is mandatory. Its profound impact on native biota is widely recognized [15–17] due to its biological plasticity and ability to colonize a wide range of environments [18], as well as to its role as a vector of the parasitic oomycete *Aphanomyces astaci* Schikora, 1906 and the fungus *Batrachochytrium dendrobatidis* Longcore, Pessier, and D.K. Nichols (1999) (see [19] and references therein), which are lethal for native crayfish and amphibians, respectively, or as a vector of toxins and heavy metals [20].

In Italy, as well as throughout its non-native distribution range, this crayfish species has undergone a staggering, both natural and human-mediated expansion ([17,18], and references therein). In Sicily, the occurrence of *Procambarus clarkii* is to date reported mostly from isolated water bodies [21–25]. However, the accurate distribution of the species on the island has never been the subject of a dedicated study, so forecasting its future expansion is difficult. In this context, the present study aims to provide a straightforward model for prioritizing management measures for IAS, using *Procambarus clarkii*'s invasion of Sicilian inland waters as a case study. To this end, we developed a multicriteria "Decision Support Tools" (DSTs) based on the updated distribution of *Procambarus clarkii* in the study area to identify threatened, high-priority sites of conservation importance for management efforts. DSTs are designed to assist decision-makers by integrating and analyzing data to support informed, evidence-based choices. The theory behind the implementation of DSTs aims to reduce uncertainty and complexity in environmental management. By offering predictive capabilities and scenario analysis, DST helps stakeholders assess risks, evaluate policy options, and optimize resource management strategies [26].

2. Materials and Methods

The study area covers the entire surface of the Sicilian mainland, i.e., about 25,706 km^2. Small circum-Sicilian islands and archipelagos were not included, as no records of the species are currently available for these areas (but see [27] for the Maltese archipelago).

The Sicilian landscape is predominantly hilly (61% of the surface), with mountain ranges covering 25% and lowlands accounting for the remaining 14%. The average annual rainfall in Sicily ranges between 350 and 1200 mm y^{-1}, and the average annual temperatures range from 8 to 19 °C, apart from the peak of Mount Etna, where average annual temperatures are lower [28]. The climate is typically Mediterranean, with a pronounced seasonality characterized by the alternance of rainy winters and dry, warm summers. Due to its climate, Sicily is characterized by a surface hydrographical network formed by numerous short, torrent-like, temporary streams and a few permanent rivers with a discharge greatly varying between the rainy and the dry periods. A few small, permanent water bodies and thousands of temporary ponds are scattered throughout the island. In addition, several thousands of small reservoirs have been built in the hilly and lowland parts of the islands in the last 70 years, along with about 30 large dam reservoirs built for irrigation, hydroelectrical, and drinking purposes.

2.1. Background—Bibliographic Research and Citizen Science

With the aim of assessing the current state of knowledge about the distribution of *Procambarus clarkii* in Sicily, accurate bibliographic research work was carried out, including both published papers and grey literature. An extensive literature search was also carried out through the databases of SCOPUS (www.scopus.com, last accessed on 24 February 2025) and Google Scholar (https://scholar.google.it/, last accessed on 24 February 2025) using the keywords "*Procambarus clarkii*", "gambero della Luisiana", "gambero della Louisiana", "red swamp crayfish", and "Sicil*". Furthermore, a Citizen Science approach was also used due to the important role it can play as a source of reliable distributional datasets (see [29]). The online naturalistic platforms iNaturalist [30] and Forum Natura Mediterraneo [31] were constantly monitored, as well as the following Facebook groups: (1) Fauna Siciliana—a group founded in 2012 and based on the terrestrial and inland water fauna from Sicily, which currently has more than 22,110 members [32], and (2) *Procambarus clarkii* in Sicilia—a group founded in 2016 with the objective of collecting observations on the presence of *P. clarkii* in Sicily (see [24,33]). For each observation recorded through Citizen Science, the authors carefully checked the uploaded image files, the species identification, and the location provided by the users. Subsequently, the presence of *Procambarus clarkii* at the reported localities was verified through dedicated field sampling sessions.

2.2. Sampling Activities

Procambarus clarkii is known for its pronounced ecological plasticity that allows it to colonize various types of both lotic and lentic water bodies, characterized by a wide range of environmental conditions [18]. For this reason, the water bodies to be monitored were selected in order to have a representative coverage of the different aquatic habitat types in the study area, with a focus on permanent, stagnant, or slow-flowing water bodies. Overall, 87 monitoring sites were selected. These were divided as follows: rivers (n = 34; 39.1%), reservoirs (n = 27; 31.0%), agricultural and natural ponds (n = 16; 18.4%), lakes (n = 4; 4.6%), swamps (n = 5; 5.7%), and man-made channels (n = 1; 1.1%) (Table S1). The selected sites are located within different landscapes, at an altitudinal range from 1 to 1445 m a.s.l. (average altitude of 218 $\pm$ 295 m a.s.l.).

Following Tricarico and Zanetti [34], two methods were concurrently used for sampling *Procambarus clarkii*: active search of signs of species presence and trapping sessions. The sign survey was based on the active, visual search of live crayfish or evidence of their presence, such as burrows, exuviae, and dead individuals or their parts. Two to three operators were involved in this activity along 200 m long transects for each sampled site and each sampling session. For the trapping sessions, collapsible cylindrical funnel traps of different sizes (60 cm/30 cm and 90 cm/40 cm), baited with canned cat food, were set for 48 h along the banks of the investigated water bodies. Each trap was positioned semi-submerged to avoid the death of captured non-target animals, such as pond turtles, water snakes, amphibians, and semi-aquatic birds. The number of traps used simultaneously in each water body varied from 4 to 23, based on the characteristics and accessibility of each water body. For most sites, a single sampling session was carried out; however, trapping was repeated at least twice in those sites where *P. clarkii* was previously recorded, but its occurrence was not confirmed in the frame of a first sampling session. Fieldwork took place between May and October 2023. Collected crayfish were identified according to Scalera et al. [35] and then humanely killed in accordance with national legislation [34].

Latitude and longitude for each locality were determined with a global navigation satellite system (GNSS) receiver. A map showing the sampling sites and *Procambarus clarkii* distribution was produced using QGIS software v. 3.30.2 [36].

2.3. Species Distribution Model

To predict the potential distribution of *Procambarus clarkii* across Sicily using environmental data, we implemented the Maximum Entropy Modelling (MaxEnt) algorithm [37], using as a reference dataset all the worldwide localities available in the public online database GBIF (https://www.gbif.org/, accessed on 12 February 2025) and including novel location sites found in the frame of this work.

At first, all the 19 bioclimatic variables provided by WorldClim (https://www.worldclim.org/, accessed on 12 February 2025), plus the elevation, were considered. However, since some variables were highly correlated (Figure S1), a variance inflation analysis (VIF—[38]) was conducted using the "vif" function included in the "usdm" package [39] to select a set of non-correlated variables, using a threshold of VIF > 10. This process ultimately led us to retain only 11 out of the 20 variables first considered (Table S2). All analyses were performed in R v. 4.1.3 [40].

2.4. Decision Support Tool and Risk Assessment

The study area considered encompasses the entire surface of Sicily, over which a reference grid of square elements with sides of 5 km (25 km^2) was superimposed. This extension was deemed optimal to include the essential elements of a regional-scale ecological analysis. Each reference grid cell is considered a Management Unit (MU).

In order to assess the local vulnerability to invasion, we used a multicriteria "Decision Support Tools" (DST), which is based on the updated distribution of *Procambarus clarkii* in the study area, obtained through a combination of bibliographic review, citizen science and novel samplings, and a set of mixed criteria readily accessible to local administrations and easily processible for mapping vulnerable areas.

Given the limited information available from environmental suitability analyses based on bioclimatic data for an euryecious species such as *Procambarus clarkii* in a relatively homogeneous region, we propose using field-collected data and local geographic information systems to identify areas of highest priority for intervention where monitoring, containment or eradication actions of the red swamp crayfish are feasible and to be prioritized. To this end, we considered the likelihood of colonization of each MU and its sensitivity, with particular reference to (i) the presence of habitats of Union interest according to the EU Directive 92/43/EEC, (ii) the occurrence of Parks, Nature Reserves, and Natura 2000 sites system; and, as a specific indicator of biodiversity sensitivity, (iii) the species richness of amphibians occurring in each MU, considering that for Sicily this information is available and that the red swamp crayfish is known to cause reproductive failure and the extinction of amphibian populations [18,41].

In accordance with the classic concept of risk assessment, here, "risk" is defined as the product of the likelihood of an event occurring and its consequences [42]. In this case, the "event" refers to the colonization of a given MU by *Procambarus clarkii*, while the magnitude of the consequences is described by the severity of the potential impacts on native biota occurring in the MUs. The ecological risk assessment process necessarily involves approximations and simplifications dictated by the lack of all the numerical data needed to make the risk equation arithmetically calculable, i.e., when the available data are mostly qualitative and not quantitative. Therefore, it is necessary to simplify some steps to obtain a qualitative risk estimate, which still provides an important basis for planning management and intervention. The risk assessment can be mathematically expressed with the following formula:

$$R = P \times S \times EF$$

where R is the risk value, P is the probability (as the probability of arrival), S is the severity of the impacts, and EF is an exposure factor (as the availability of suitable habitats). At the limit, if one of the equation's factors is zero, the risk is null.

In the frame of this study, we considered the geographical information provided by the Sicilian Region (https://www.sitr.regione.sicilia.it/geoportale, accessed on 12 February 2025). The analyses were conducted in a GIS environment (QGIS 3.30.2), cross-referencing information obtained from various layers, as described below, with field data originally collected.

2.4.1. Probability of Arrival (P)

This is a probability surrogate derived from the distance to the nearest known colonized point. The distance in meters from the nearest presence point was calculated for each MU using the "Closest point procedure" in QGIS. The values for each square were categorized into four classes, considering the ecological characteristics and dispersal potential of the red swamp crayfish: 1.000 (highest probability, with the nearest known point located within 1 km of the MU); 0.500 (distance between 1 and 5 km); 0.333 (distance between 5 and 10 km); 0.250 (distance greater than 10 km).

Squares registering proximity under one kilometer have the highest probability of being colonized by the species through active dispersal. In fact, it is known that the red swamp crayfish is capable of movements out of water equal to or greater than this distance [18,43]. Proximity was thus used as a surrogate to determine the probability of arrival. In this case, it refers exclusively to active diffusion, meaning diffusion not directly mediated by humans. Human-mediated transport and release into new sites, whether voluntary or involuntary, falls outside any probabilistic assessment, as intentional release factors cannot be identified; accordingly, it is not considered here.

2.4.2. Severity of the Impact (S)

It is a measure of the impact that the red swamp crayfish may exert on a given MU. It is based on (i) the occurrence and extension of habitats listed in Annex I of EU Directive 92/43/EEC (Habitats Directive), (ii) the occurrence of protected areas within the MU, and (iii) the species richness of amphibians with breeding populations occurring within the MU. It is here calculated as 1 + Log10_HN2k + PT + AMP_VAL, where Log10HN2k = Log10 value of the Natura 2000 habitat area (among those selected as suitable) within the MU reference grid cell; PT = binary value (1/0) indicating the presence of protected areas (parks, reserves, SACs/SPAs) within the MU reference grid cell; AMP_VAL = amphibian species diversity value within the MU grid cell. This last value ranges from 0 to 3 and is calculated by dividing the number of present amphibian species by 2, with a maximum of 6 amphibian species occurring per MU.

The Sicilian Region provides geographic information layers related to the land surfaces affected by the presence of habitats listed under the EU "Habitats Directive", occurring both within and outside Natura 2000 sites (https://www.sitr.regione.sicilia.it/geoportale, accessed on 12 February 2025). Based on the available knowledge of the ecology of the red swamp crayfish, different habitat types were included or excluded. For example, river environments with occasional flow were not included as they are considered unsuitable for the species due to the long dry periods that characterize these watercourses. Subsequently, the distribution of habitats was overlaid on the reference grid to assign a unique quantitative value to squares with habitat presence and a neutral value to squares where no habitats of Union interest are recorded. The habitats included in the analyses were the following: 1130 Estuaries; 3120 Oligotrophic waters containing very few minerals generally on sandy soils of the West Mediterranean, with *Isoëtes* spp.; 3130 Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*; 3140 Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.; 3150 Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation; 3260 Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation; 3270 rRivers with muddy banks with *Chenopodion* rubri p.p. and *Bidention* p.p. vegetation, and 3280 Constantly flowing Mediterranean rivers with *Paspalo-Agrostidion* species and hanging curtains of *Salix* and *Populus alba*.

All polygons related to Regional Natural Parks, Natural Reserves, and Natura 2000 network sites were merged into a single layer, which was then overlaid on the reference grid. In this case, the presence of protected areas was assigned a constant numerical value, while MUs that did not overlap with protected areas were given a neutral value. No distinction was made between Parks, Reserves, and Natura 2000 sites, as all categories of protection institutions are established with the intent to safeguard sensitive habitats and species of conservation value.

Data on the amphibian species richness for each MU were obtained from Lo Valvo et al. [44]. Data related to the presence of *Xenopus laevis*, an invasive alien species of Union concern, were removed since it does not represent a species to be protected. The original data available on 10 × 10 km cells were here scaled to the 5 × 5 km reference grid used for this study.

2.4.3. Exposure Factor (EF)

Here, the EF is understood as an estimation of the occurrence of suitable habitats available for the red swamp crayfish in each MU. To assess the presence of suitable habitats for the stable presence of red swamp crayfish, we referred to the presence of aquatic environments. A more detailed ecological analysis was not performed due to the high ecological plasticity of the target species, which can inhabit both lentic and lotic environments across a wide salinity range [17,45]. The EF is calculated as the Log10 value of the freshwater surface area within the MU reference grid cell.

Information layers related both to the occurrence of lentic water bodies (lakes, reservoirs, swamps, and agricultural ponds) and watercourses (rivers and streams) were considered. For the latter, only the main rivers were considered, while smaller branches were excluded as they are likely to periodically dry out completely, making them unsuitable for the stable presence of the species. On the shapefile of the rivers, which is one-dimensional linear, a buffer of 3 m was calculated, thus assigning a standardized surface area useful for obtaining otherwise non-assessable surface data. The surfaces of the basins and rivers were then unified and cropped by intersecting with the reference grid to calculate the water surface occurring in each MU. The values of the water surface were categorized into 10 distribution classes through division into natural intervals (Jenks method) to minimize internal variance. Based on this, a suitable habitats availability map was created as a surrogate for local suitability for the presence of the red swamp crayfish.

2.4.4. "Likelihood of Colonization" Map

The likelihood of colonization of a MU is proportional to the likelihood for the red swamp crayfish to reach the MU itself (P) and to find a suitable habitat for establishing a self-sustaining population (EF). In this frame, it is obvious that both the habitat suitability of a given site for the *Procambarus clarkii* (i.e., the occurrence of lentic to slow-flowing water bodies, "exposure factor"), and its proximity to areas already invaded by the species ("probability of arrival") must be considered: a MU without suitable habitats will not be colonized despite its proximity to thriving populations of the crayfish, or a MU with suitable habitats but far away from the sites hosting populations of the species, and thus hard or impossible to be reached, is unlikely to be invaded in the near future. Conversely, a MU where suitable habitat patches occur and is located in close proximity to areas already inhabited by the species is extremely prone to be invaded, and thus, its susceptibility score is high. Accordingly, a "likelihood of colonization" map was created that, without considering the sensitivity of habitats of conservation interest, combines the data on confirmed presence from the monitoring campaign with information on the potential suitability for the alien species. The map indicates, on a 10-class scale (categorized using the Jenks method), the likelihood of colonization of a given MU by existing populations.

2.4.5. "Sensitivity" Map

The layers previously created for calculating the exposure factor and the severity of the potential impacts were used to produce a sensitivity map for colonization by the red swamp crayfish. The sensitivity of a MU is a measure of its vulnerability to the effects of the occurrence of the invasive species. Those MU-hosting habitats or native species that are known to be potentially damaged by the red swamp crayfish will have a higher sensitivity ranking. In particular, the values assigned to each MU were multiplied together to obtain a value for each square that considers environmental suitability, the presence of protected areas and sensitive habitats, and the presence of vulnerable species. The size of the MU does not allow for highly precise detail regarding individual sensitive sites, but it allows for focusing on the geographic context in which the presence of the red swamp crayfish is likely to cause serious damage to natural ecosystems.

2.4.6. "Risk Assessment" Map

Probability of arrival, severity of the impacts, and exposure factor data were combined for the creation of a risk map, understood as an estimate of the probability that the alien species may reach a given MU, establish there a population, and cause damage to habitats and species of conservation interest. The numerical values obtained were classified according to the Jenks criterion (minimum variance) and reported in six risk categories: very low, low, medium, medium/high, high, and very high.

3. Results

3.1. Distribution of Procambarus clarkii in Sicily

3.1.1. Literature Review

In total, 17 studies concerning the occurrence of *Procambarus clarkii* in Sicily have been published from 2003, when the species was first reported on the island [21], to February 2025. After its first report, the species was observed only in the water bodies located within the "Lago Preola e Gorghi Tondi" Nature Reserve for over a decade until its occurrence was reported at several sites located hundreds of kilometers from the initial release point [25,27,46]. No other occurrence sites were reported in the following years until Longo et al. [47] and Savoca et al. [48–50] anticipated some of the novel sites reported in the present work. Apart from tracking its invasion of the island, research on Sicilian *Procambarus clarkii* populations involved bioacoustics studies [51], parasite spillover [52], its multi-faceted impact on native biota [23,53,54], the occurrence of pollutants in both its edible and non-edible parts [48,50,55], and its possible use as a source of useful biomolecules [47].

3.1.2. Field Surveys

Figure 1 and Table S1 show the performed sampling effort and the location of the surveyed water bodies. We had to exclude seven sites from the original sampling scheme due to their inaccessibility or unsuitability (e.g., drying up of the water body); therefore, the fieldwork took place in a total of 80 sampling sites out of the 87 sites originally selected.

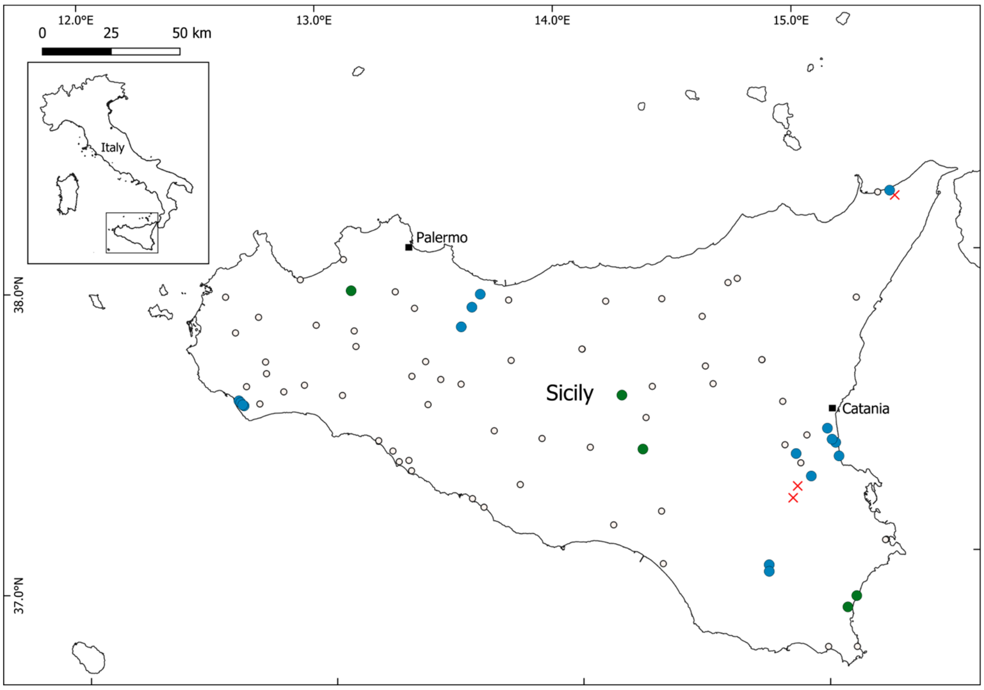

Figure 1. Sampling effort. White dots: sampled sites; green dots: novel sites of occurrence of *Procambarus clarkii*; blue dots: confirmed published sites of occurrence of *P. clarkii*; red cross: not confirmed published occurrence sites.

The occurrence of *Procambarus clarkii* was recorded at 22 sites; among these, 17 were literature sites, and 5 proved to be new occurrence sites for the species (Table 1). The novel occurrence sites are three reservoirs (Poma, Villarosa, and Olivo) and two rivers (Tellaro and Asinaro) (see Table 1).

Table 1. Occurrence sites of *Procambarus clarkii* in Sicily. Geographical coordinates are expressed in terms of decimal degrees (Map Datum: WGS84). Three occurrence localities reported in the literature could not be confirmed in the frame of the present survey.

Location Site	Province	Latitude	Longitude	Habitat	Altitude (m)	Present Survey	Source
Canale Buttaceto	Catania	37.437703	15.047918	Artificial channel	5	Yes (confirmed)	[24]
Fiume Gornalunga	Catania	37.388865	15.078404	River	2	Yes (confirmed)	[27]
Foce Fiume Simeto	Catania	37.400072	15.064382	River	3	Yes (confirmed)	[27]
Pantani di Venetico	Messina	38.212611	15.364333	Pond	5	Yes (confirmed)	[24]
Venetico Superiore *	Messina	38.195686	15.384248	Pond	126	No	[27]
Fiume San Leonardo (upper course)	Palermo	37.842270	13.562021	River	243	Yes (confirmed)	[25]
Fiume San Leonardo (middle course)	Palermo	37.905910	13.609534	River	160	Yes (confirmed)	[22]
Lago Rosamarina	Palermo	37.947632	13.646123	Reservoir	160	Yes (confirmed)	[22]
Fiume Irminio	Ragusa	36.996840	14.778049	River	387	Yes (confirmed)	[24]
Lago Santa Rosalia	Ragusa	36.974803	14.776731	Reservoir	374	Yes (confirmed)	[27]
Fiume San Leonardo (lower course)	Siracusa	37.343166	15.088748	River	3	Yes (confirmed)	[24]
Fiume San Leonardo (upper course) **	Siracusa	37.282435	14.970489	River	18	Yes (confirmed)	[25]
Lentini, stagno agricolo	Siracusa	37.360270	14.913601	Artificial pond	23	Yes (confirmed)	[25]
Torrente Costanzo (middle course)	Siracusa	37.252467	14.912453	River	59	No	[27]

Table 1. *Cont.*

Location Site	Province	Latitude	Longitude	Habitat	Altitude (m)	Present Survey	Source
Torrente Costanzo (upper course) ***	Siracusa	37.214115	14.891158	River	192	No	[27]
Lago di Murana	Trapani	37.626475	12.634279	Swamp	3	Yes (confirmed)	[24]
Lago Preola	Trapani	37.620374	12.641136	Swamp	3	Yes (confirmed)	[56]
Gorgo Medio	Trapani	37.611327	12.651033	Pond	3	Yes (confirmed)	[56]
Gorgo Basso	Trapani	37.609080	12.655051	Pond	2	Yes (confirmed)	[21]
Gorgo Alto	Trapani	37.612475	12.649554	Pond	4	Yes (confirmed)	[55]
Lago di Villarosa	Enna	37.588610	14.211330	Reservoir	384	Yes (new)	Present study
Lago Olivo	Enna	37.405602	14.286552	Reservoir	437	Yes (new)	Present study
Lago Poma	Palermo	37.978040	13.112764	Reservoir	190	Yes (new)	Present study
Fiume Tellaro	Siracusa	36.840100	15.088640	River	9	Yes (new)	Present study
Fiume Asinaro	Siracusa	36.875680	15.127420	River	4	Yes (new)	Present study

* Reported as "Venetico, pozze artificiali" in Vecchioni et al. [25]. ** Reported as "Lentini, canale" in Vecchioni et al. [25]. *** Reported as "Torrente Margi" in Deidun et al. [27].

In the sites where the occurrence of *Procambarus clarkii* was already reported in the literature, the presence of the species was usually confirmed already during a first trapping session, with the following exceptions: at the "Venetico artificial ponds" (province of Messina, 38.195686° N, 15.384248° E, where *P. clarkii* was reported by Deidun et al. [27]) we could not confirm the presence of the species, as no suitable water bodies were found. At the Costanzo stream (province of Siracusa, two sampling points at 37.252467° N, 14.912453° E and 37.257818° N, 14.920217° E), where both *P. clarkii* and the parastacid *Cherax destructor* had been reported by Deidun et al. [27], the sampling activities did not confirm the presence of either of the two alien crayfishes in three different trapping sessions (see also Vecchioni et al. [46]).

The provinces with the higher incidence of sites colonized by *Procambarus clarkii* are Syracuse and Trapani (n = 5 each), followed by Palermo and Catania (n = 4 each), Messina, Ragusa, and Enna (n = 2 each). Conversely, no populations of *P. clarkii* have been detected in the provinces of Agrigento and Caltanissetta to date.

The species was found in the following habitat types: rivers and channels (n = 10; 45.5% of the occurrence sites; 29.4% of the sampled rivers and channels), artificial and natural ponds (n = 5; 22.7% of the occurrence sites; 31.5% of the sampled ponds), reservoirs (n = 5; 22.7% of the occurrence sites; 18.5% of the sampled reservoirs), and swamps (n = 2; 9.1% of the occurrence sites; 40.0% of the targeted swamps).

3.2. Species Distribution Model

The MaxEnt species distribution model (SDM) highlights that the highest probability of occurrence of the red swamp crayfish, inferred from our continuous predictions of habitat suitability transformed into binary predictions, includes the whole surface of Sicily with the sole exception of the highest peaks\parts of the Mount Etna, Nebrodi, Madonie and Sicani mountains (Figure 2A). Out of all the analyzed climate variables, the SDM pointed out that the mean temperature of the driest quarter (Bio9) has the highest permutational importance and contribution (i.e., 33.9% and 19.8%, respectively; see also Table S3), thus playing a significant role in predicting the occurrence of *Procambarus clarkii* (Table S2).

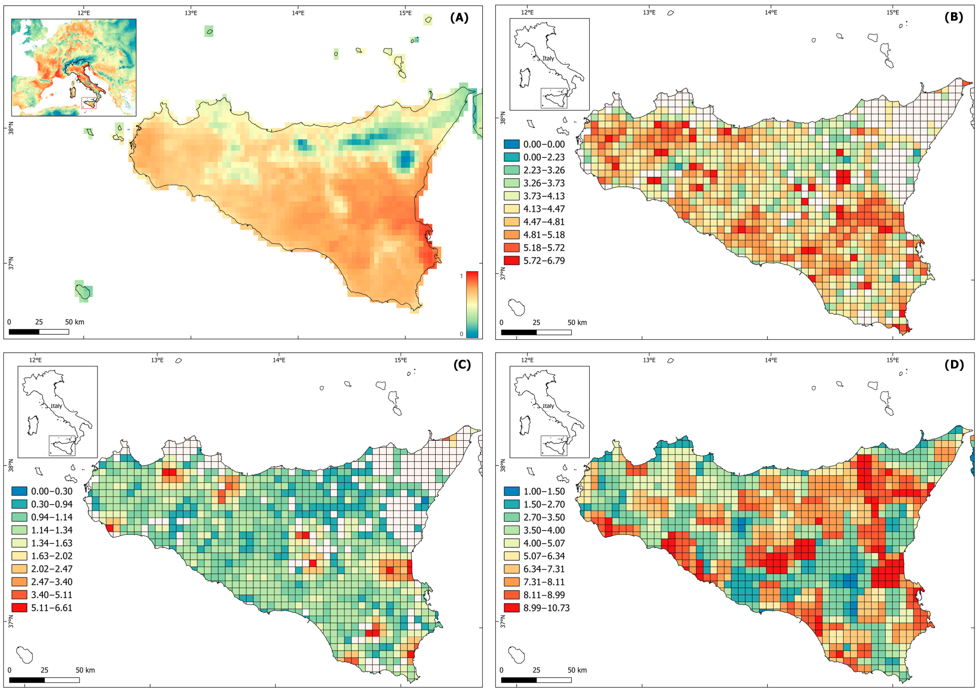

Figure 2. (**A**) MaxEnt species distribution model (SDM) continuous suitability predictions map, based on 19 bioclimatic variables and elevation data; (**B**) Suitable habitats availability map; (**C**): Likelihood of colonization map; (**D**): Sensitivity map. The values reported in (**B**–**D**) are categorized into 10 distribution classes through division into natural intervals (Jenks method) to minimize internal variance.

3.3. Thematic Maps and Risk Analysis

The application of our proposed model allowed for the creation of four thematic maps, each providing valuable insights for the effective management of *Procambarus clarkii*.

The "habitat availability" map (Figure 2B), unlike the "species distribution model map" generated using MaxEnt (Figure 2A), returns null values for much of northeastern Sicily and the Etna region, where climatic factors are suitable for the occurrence of the species, but wetland habitats are absent. In contrast, it shows intermediate values for the Nebrodi Mountains, which, despite being rich in freshwater habitats, show lower suitability values in the MaxEnt model.

The "likelihood of colonization" map (Figure 2C), expressed as the product of suitability and proximity values, predictably highlights higher dispersal potential in grid cells where crayfish presence is known, as well as in adjacent areas. As expected, the probability of dispersal is not uniformly distributed but varies according to the availability of suitable habitats (occurrence of wetlands).

The "sensitivity" map (Figure 2D) reveals relatively high values even in areas distant from known occurrence sites. These areas are not currently under immediate threat, even if they could be subject to human-mediated introductions with severe ecological consequences.

Finally, the "risk assessment" map (Figure 3) shows a strong correlation between known crayfish presence and areas with the highest risk values. It also indicates moderate to high risk across much of central and southern Sicily, where environmental conditions favour crayfish dispersal and where protected areas and ecologically valuable habitats are widespread. Additionally, the risk map reveals that by starting from known occurrence sites, risk values remain high or moderately high, decreasing irregularly depending on the availability of aquatic habitats and the presence of protected areas of varying status.

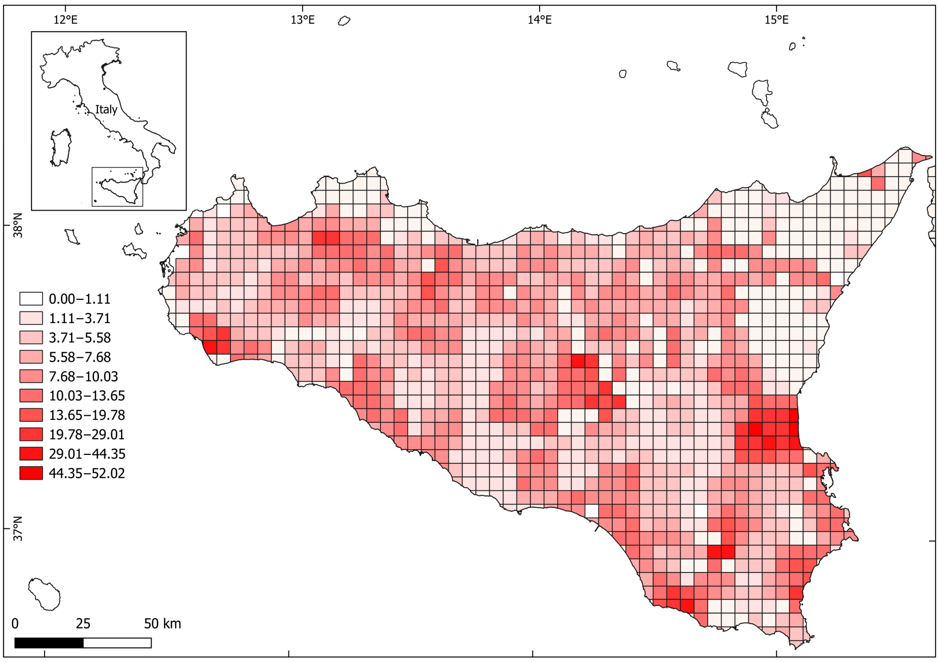

Figure 3. Risk assessment map of *Procambarus clarkii* in the investigated area. The values reported in the map are categorized into 10 distribution classes through division into natural intervals (Jenks method) to minimize internal variance.

4. Discussion

Our study shows how the occurrence and distribution of *Procambarus clarkii* in Sicilian waterbodies includes 22 sites scattered throughout the island. Albeit this picture is obviously an underestimation of the actual distribution of the species, in some areas, the observations clusters are apparent; these are (from Palermo, clockwise) (i) the hydrographical basin of the San Leonardo River, including the Rosamarina reservoir, (ii) the plain of Catania, (iii) the hydrographical basin of River Irminio, including the Santa Rosalia reservoir, and (iv) the Lago Preola–Gorghi Tondi area (Figure 1). In addition to these clusters, where most of the observations were collected, some apparently isolated populations were observed in small rivers (Tellaro, Asinaro) and large, man-made reservoirs (Poma, Olivo, Villarosa).

The presence of *Procambarus clarkii* populations along entire hydrographical basins makes a complete eradication of the species from Sicily technically unfeasible, and its basin-wide control is economically unsustainable. Managers and decision-makers thus need guidance on where and how to direct the limited resources available for the protection of native species and habitats, focusing on areas where invasions might have the greatest ecological impact. In this context, the use of these 'Decision Support Tools' (DST) to optimize resources and prioritize actions is a promising approach. Obviously, the reliability of the results depends on the quality and exhaustiveness of the data used according to the RIRO (*Rubbish in, rubbish out*) principle, i.e., the quality of output from a system is determined by the quality of its input. However, data inaccuracy or unevenness would equally affect decision-making both with or without the use of DST, and the continuous implementation and update of existing datasets related to the distribution of habitats and species is essential. The main merit of the DST here presented is to provide a simple, transparent, and spatially explicit methodology for identifying the priority sites both for their susceptibility and sensitivity to invasion, thus outdoing a purely qualitative "expert-based assessment".

In ecologically homogeneous contexts under similar climatic conditions, conventional species distribution models (SDM) often fail to provide sufficiently detailed information to effectively prioritize management interventions for invasive species. The MaxEnt-based suitability model developed for Sicily (Figure 2A) revealed a substantial homogeneity in the predicted suitability of *Procambarus clarkii*. In contrast, the "suitable habitat availability" map (Figure 2B) incorporating freshwater surface extent produced more refined results, excluding areas that would otherwise appear equally suitable despite lacking inland waters.

Combining the suitable habitat availability map with the map depicting the occurrence of protected areas, threatened habitats, and vulnerable species enabled the creation of a comprehensive 'sensitivity map' (Figure 2D). This tool can support logistical planning and territorial control strategies. Although it does not incorporate probability estimates, it remains valuable in the absence of up-to-date, detailed occurrence data for IAS distribution, serving as a useful resource for prioritizing monitoring efforts. Conversely, invasion probability estimates are incorporated into the 'risk' map (Figure 3), where all information related to the likelihood of colonization in each area is merged with the potential impacts of IAS colonization in that particular MU, thus providing the most complete scenario for decision-making.

One of the key strengths of the present model is its flexibility. In Sicily, the availability of habitat distribution data from the Natura 2000 network allowed us to incorporate both sites located within and outside protected areas. However, such data are not always easily accessible to public administrations, and its inclusion is optional. When available, it provides an additional criterion for prioritizing management interventions. Conversely, the spatial distribution of protected areas and Natura 2000 sites is consistently available across all EU countries, making it a widely applicable dataset. The integration in the DST of biodiversity data linked with taxa potentially impacted by the invasive species, amphibian species richness in our case, further strengthens the model by creating a geographically explicit sensitivity database. In line with the model's flexible nature, amphibian distribution data can be replaced or supplemented with other ecological sensitivity indicators pertinent to the different study areas, such as the presence or distribution of other particularly vulnerable taxa or habitats.

5. Conclusions

The DST described here proved to be easy to implement, requiring only intermediate GIS skills. This makes it suitable for routine use by public administrations responsible for land management. Furthermore, the model can be processed using open-source software, eliminating additional economic burdens. In conclusion, the approach presented here aims to serve as an example of a possible good practice for the management of the environment and its resources in contexts such as real-world conservation, where resources are inevitably limited. We hope that the implementation of this DST might allow for better management of the invasion of the red swamp crayfish in Sicily and elsewhere, but we would also like to stress that the case here presented is just a case study for an approach exportable to a wide range of situations where IAS are involved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments12040111/s1, Figure S1: Correlation matrix between the 19 bioclimatic variables and elevation data showing high correlations; Table S1: List of the sampled Sicilian water bodies. Geographical coordinates are expressed in terms of decimal degrees (Map Datum: WGS84). *: sites where the occurrence of *Procambarus clarkii* was reported in literature, but could not be confirmed in the frame of present survey (see text); Table S2: Model selection through variable inflation (VIF); Table S3: Contributions of the bioclimatic variables in the Maxent models for

Procambarus clarkii based on all worldwide records available on GBIF Variables without any value ("-") were removed because of high cross-correlations (see Figure S1 and Table S2).

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