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Research Article

Modeling the Population Dynamics of the Red Swamp Crayfish (*Procambarus clarkii*) in Doñana: Application to the Harvesting Strategies

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Abstract: The aim of this work is to propose an alternative management and control strategy of crayfishing *Procambarus clarkii* in the Doñana area. A simulation model was developed (Stella 8.0) to evaluate the effects of different fishing effort on crayfish populations during certain times of the year. Then different management options were simulated: Strategy 0: No fishing activity, Strategy 1: Obtaining the maximum yield of crayfish following the current fishing effort regulations, and Strategy 2: Obtaining the maximum yield of crayfish by restricting the fishing effort to the period of the greatest production. The model explained 73.68% of the variance in population biomass. A review and resetting of the crayfishing regulations in this area according to the periods proposed in Strategy 2, was recommended. This management proposal in the developed model was the one that ensures sustainable yields at the same time that preserves biodiversity by restricting the harvesting of crayfish to rice fields and channels from April to September.

Keywords: Crayfishing management; Simulation model; Brazo del Este; Doñana area; *Procambarus clarkii*

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Introduction

Background and justification

The first introduction of the red swamp crayfish (*Procambarus clarkia)* Girard, 1852, native to the southeastern region of the United States) in Europe was conducted in Spain in 1973 at two aquaculture factories located in Sevilla and Badajoz. The introduction aimed to improve the economies of these impoverished regions through the trade of this food resource for human consumption (Habsburgo–Lorena, 1983). Since its introduction, this exotic species has spread throughout the European Mediterranean region in just 40 years (Geiger et al., 2005). This range expansion was due to both the crayfish's significant colonizing ability and to numerous introductions and translocations by Spanish fishermen who realized the economic benefits generated by the red swamp crayfish (Montes et al., 2001). This invasive species has had a negative impact on the biodiversity and ecological functioning of the aquatic ecosystems that it inhabits (Duarte et al., 1990; Angeler et al., 2001:2003; Geiger et al., 2005; Tablado et al., 2010; Marchi et al., 2011a;2011b; Alcorlo and Baltanás, 2013). Indeed, for the Doñana area, García-Llorente et al., (2011) proposed implementing an eradication and prevention program for the management of exotic species such as *P. clarkii.* The introduction of the crayfish in the Lower Guadalquivir marshes has enabled the establishment of an important industry based on fishing, processing, and marketing in local and foreign markets. Currently, Spain is one of the three most important countries in the worldwide trade of this crayfish species, with more than 3000 tons/year (hereafter t/y) n produced in this region, generating annual revenues of $3.3 \cdot 10^6$ €. In this area, there are nine processing factories employing over 400 people. Moreover, there are several hundred fishermen who harvest only crayfish (Montes et al., 2001). Fishing is selectively carried out on wild populations of crayfish inhabiting rice fields, channels, marshes, and river branches and similar habitats (Alcorlo et al., 2008). The placement of the traps used while cray fishing has impacts on the environment (i.e., trampling of submerged vegetation, sediment removal, and disturbance to birds nesting in emergent vegetation) and on other organisms such as amphibians, reptiles, and fish (Geiger et al., 2005). The time of the year and the method of fishing are particularly important, because this activity is carried out in a natural protected area, where it is necessary to reconcile the conservation of the ecosystem and its biodiversity with human wellbeing. Therefore, there is an urgent need to improve the management of the crayfish through a strategy that will guarantee the conservation of the natural area while also facilitating the development of socioeconomic activity. There are alternative ways to control the high density of exotic crayfish populations, such as manual removal, selective fishing by traps, and electric fishing (Holdich et al., 1999). In this regard, the commercial extractive fishing in the Lower Guadalquivir area could be used as an integrative management tool aimed to control crayfish populations, to maintain this socioeconomic activity, and to minimize its impacts on the ecosystem.

The main objective of this work was to evaluate different management strategies to optimize crayfish harvesting as a sustainable and unaggressive activity within the ecosystems of the Lower Guadalquivir region. Data concerning fishing activity and the demography of the crayfish populations monitored during 1999 and 2000 were used to build a simulation model employing different fishery management options (scenarios).

Specifically, our aims were: i) To understand the population dynamics of *P. clarkii* in the study area and ii) To analyze the effect of selective fishing as an effective method to control crayfish populations and to manage the aquatic ecosystems.

Materials and Methods

Study area

This study was carried out in a Natural Protected Area located in the Lower Guadalquivir ('Brazo del Este', SW, Spain) (**Figure 1**). The river bed is composed of silt and clay, and dense patches of common cattail (*Typha* spp.) and reeds (*Phragmites* spp.) grow along the river banks. Other shrub species, such as alkali seepweed (*Suaeda vera*), tamarisk (*Tamarix africana*) and rushes (*Juncus maritimus*), appear together with the helophytic vegetation. The site where the crayfish were captured for this study (37º 08' N, 6º 02' W) is in one of the oldest branches of the Guadalquivir river that empty into the marsh, which was originally a tidal-fluvial system. The area of the water body considered in this study was 796 ha, being completely included within the 'Brazo del Este' Natural Area (BOJA 60, 1989). Moreover, this area is a Special Protection Area for Birds (SPA) and a Ramsar Site (FIR, 2007). The hydroperiod is nearly permanent as it receives runoff from the surrounding rice fields during the dry season (i.e., summer) (Montes et al., 2001). Crayfishing is allowed and regulated within the 'Brazo del Este' Protected Natural Area (BOJA 60, 1996; BOJA 95, 1996) and is carried out using a special trap called a Dutch Trap (mesh size 15 mm in diameter **Figure 2**) that prevents the entrance of waterfowl (FIR, 2007). Regulations allow crayfishing from September 1st to April 15th with 6000 being the maximum number of traps that can be placed in the protected area and a maximum number of 120 traps for each fisherman.

Proposed management strategies for *P. clarkii* harvesting

A simulation model was built to analyze the effects of different levels of fishing effort at different times of the year on the crayfish's population dynamics. The optimum fishing effort was defined as that which contributes to both reducing the impact on the aquatic ecosystems caused by dense populations of *P. clarkii* while ensuring sustainable fishery production. Multiple scenarios with various levels of fishing effort (numbers of fishermen and fishing traps per day) were generated over a period of five years for each of the following management strategies:

Management option (a) Strategy 0*:* No fishing.

Management option (b) Strategy 1: Maximize crayfish production by distributing the fishing effort from September to April, according to the current regulations.

Management option (c) Strategy 2: Maximize fishing production by fitting them fishing effort to the period of the greatest recruitment of crayfish, from September to December.

Figure 1: Image of a Dutch trap.

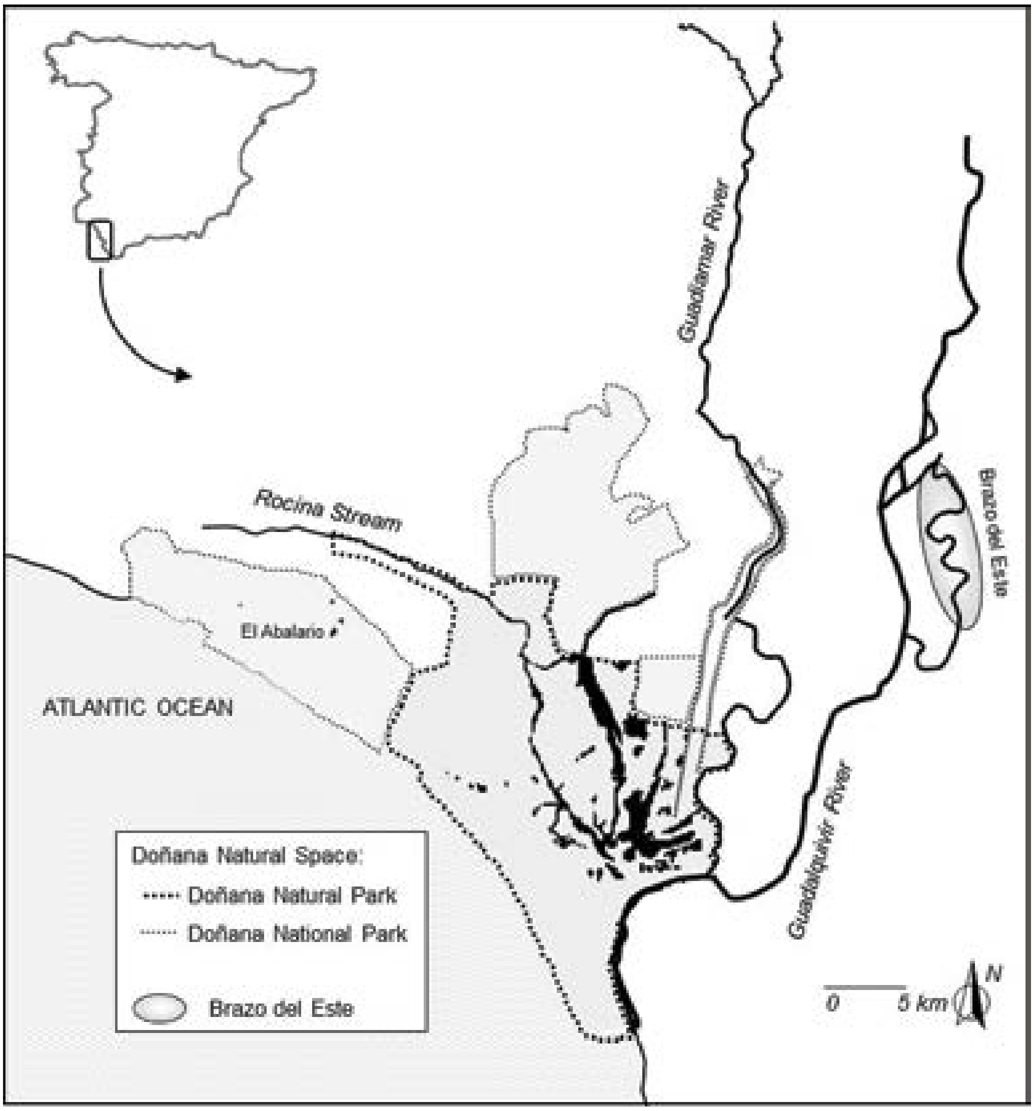
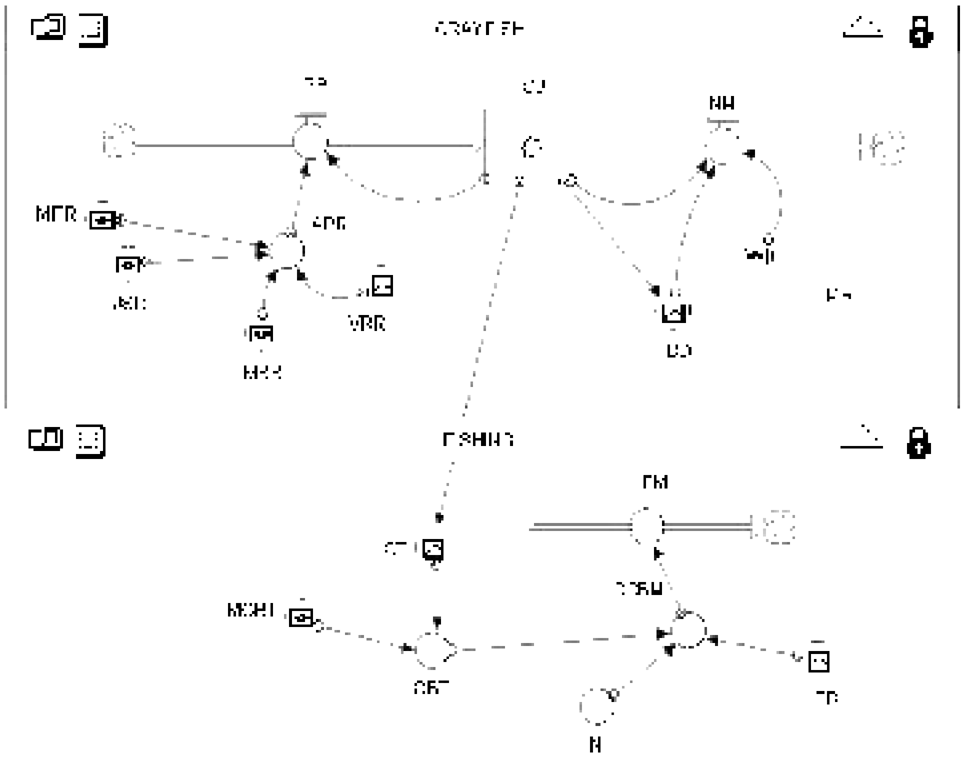


Figure 2: Location of the study area in the Spanish Iberian Peninsula showing the different natural protected areas, the Doñana Natural Space which includes the Doñana Natural and National Parks and the Brazo del Este.



CRAYFISH SUBMODEL.
CB. Crayfish biomass.
PB: Production of biomass.
APR: Actual production rate
MPR: Minimum production rate.
MRR. Maximum reproductive rate.
VRR: Variation in reproductive rate.
JSR: Juvenile survival rate
NM: Natural mortality.
MR: Mortality rate.
DD: Correction factor for Density Dependence.

FISHING SUBMODEL.
FM: Fishing mortality.
FD: Number of fishing days per month.
N: Numbers of trap used per hectare and day.
MCBT: Maximum captured biomass per trap.
CBT: Crayfish biomass per trap.
CT: Coefficient per trap.
CCBM: Captured crayfish biomass per month.

Figure 3: STELLA model linking the population dynamics of *Procambarus clarkii*.

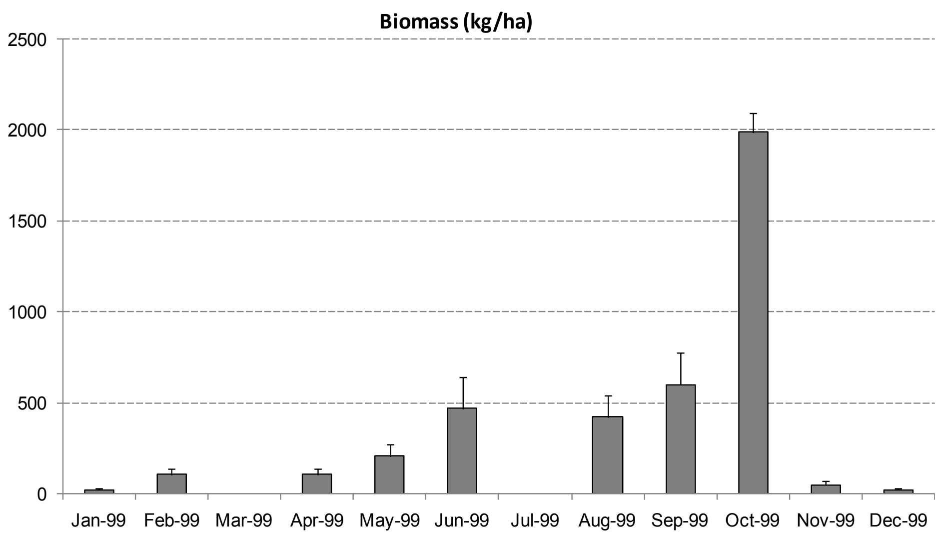


Figure 4: Changes in mean relative abundances of red swamp crayfish ± S.D.

Simulation modeling of crayfish population dynamics and harvesting

The model and the simulations were performed using the STELLA 8.0 software, a high-level programming language (STELLA_c 2003, http://www.hps-inc.com) (Costanza and Voinov, 2001). This software was chosen because is one of the first programs to include a graphical interface, its use is very intuitive, and it is also widely used in simulation modeling. Moreover, it has been used to build several ecological models of crayfish population dynamics and exploitation (Anastacio et al., 1999; Dew, 2001). As stated before, the user-iconographic interface in the finished models produced by STELLA enables one to run simulations quickly and easily without having advanced computer skills.

The relationships among variables and parameters concerning the crayfish population dynamics with harvesting were established in the model represented in **Figure 3**. To account for the temporal variability in the crayfish population dynamics, a monthly simulation time interval was chosen. The data used to model the natural population dynamics of *P. clarkii* (**Figure 4**) were from different sources: intensive monthly sampling conducted at the study area in 1999 and 2000, subsequent studies also based in this area (Alcorlo et al., 2008), and other studies analyzing the birth and natural mortality parameters of *P. clarkii* (**Table 1**).

In this study, the biomass of crayfish was measured at each sampling site. Because the size structure of the crayfish populations varies throughout the year, which is especially relevant to fishing, the biomass of crayfish collected at each sampling site was considered as a proxy of the population size, and the different age classes separately were not considered. The crayfish biomass (kg/ha) was obtained from the relative density of crayfish and monthly mean weight of trapped crayfish (**Table 2**). The relative density of crayfish was estimated from the relative abundance (Catch Per Unit Effort, (CPUE)) correcting for the area of influence of a trap with the α coefficient, which represents the area of influence of a trap ($\alpha = 56.3\ m^2$) according to Acosta and Perry (2000). Crayfish were trapped using Dutch Traps (mesh size 15 mm) baited with fresh fish and remained active for 24 hours.

An exponential growth model for the crayfish population dynamics model was constructed that included an upper limit of crayfish biomass, which caused a dramatic increase in crayfish mortality when the population size approached the carrying capacity of the system (**Figure 5**). The resulting model for the natural population dynamics of *P. clarkii* behaved according to a temporal pattern of 'explosion and collapse' instead of a logistic pattern, because in this case the relationship between population size and relative growth rate was exponential (negative) instead of linear.

Model equations

The variation in crayfish biomass (dCB/dt) expressed in kg/ha was calculated from the balance between the production of biomass (PB) and destruction of biomass due to natural mortality (NM) and fishing (FM).

$$\frac{dCB}{dt} = PB(t) - NM(t) - FM(t) \quad (1)$$

The numerical approximation was done using the Euler integration method based on monthly estimates of the variables and coefficients and applying an integration step (DT in Stella) of 1/30. This basic scheme was connected with an estimate of the Natural Mortality rate (NM) as a second output of the state variable.

The Production of Biomass (PB) was calculated by multiplying Crayfish Biomass (CB) and Real Production Rate (RPR).

$$\mathrm{PB} = \mathrm{CB} \times \mathrm{RPR} \quad (2)$$

The Real Production Rate (RPR) was expressed by the equation:

$$RPR = MPR + MRR \times VRR \times JSR \quad (3)$$

in which MPR is the minimum production rate representing the increase in crayfish biomass as an outcome of its population growth; MRR is the maximum reproductive rate;

VRR is the variation in reproductive rate; and JSR is the juvenile survival rate.

The Natural Mortality (NM) was dependent on the Mortality

Table 1: Summary of population dynamics parameters estimated for *Procambarus clarkii* in different field and laboratory studies.

Parameter	Description	Value	Reference
Maximum Reproductive Rate (MRR) (kg indiv/indiv)	Small females (100 eggs per egg laying)	0.74	Payne, 1996
	Large females (500 eggs per egg laying)	3.74	Payne, 1996
Juvenile Survival Rate (JSR)	Unique stage	0.48	Huner, 1978
	Up to 20 weeks	0.29-0.60	Romaire 1976
Mortality Rate (MR)	Maximum rate in winter	0.1935	Clark et al., 1975
	Minimum rate in winter	0.0327	Clark et al., 1975
	Minimum estimatedin field	0.2541	Anastácio& Marques, 1995
	Maximum estimatedin field	0.72	Anastácio& Marques, 1996
Minimum Reproductive Rate (MPR) (kg indiv/kg population)	Laboratory conditions	0.2	McClain et al., 1992
	Rice fields	0.7	Anastácio et al., 1999

Rate (MR) and a Correction Factor (DD) depending on Crayfish Biomass (CB) (**Figure 5**).

$$NM = MR \times DD \times CB \quad (4)$$

Fishing mortality (FM) was calculated by multiplying crayfish biomass per trap (CBT), the number of fishing days per month (FD), and the number of traps used per hectare per day (N).

$$FM = CBT \times FD \times N \quad (5)$$

Moreover, crayfish biomass per trap (CBT) was dependent on the crayfish biomass (CB) and was calculated as:

$$CBT = MCBT \times CT \quad (6)$$

Where MCBT is the maximum trapped biomass per trap and CT (coefficient per trap) is a coefficient from 0 to 1 depending on crayfish biomass (CB) (**Figure 6**).

Table 2: Individual average monthly weight of crayfish captured at the sampling site.

	'Brazo del Este'	
Date	**Average crayfish weight (g)**	***S.D.***
May 1999	15.48	4.62
June 1999	15.35	4.86
September 1999	15.47	5.19
October 1999	16.27	8.11
November 1999	16.23	8.76
December 1999	10.93	8.34
January 2000	8.08	11.65
February 2000	14.35	10.51
April 2000	13.03	7.94
May 2000	11.83	6.02
June 2000	13.97	9.20
September 2000	9.38	7.31
November 2000	11.44	8.23

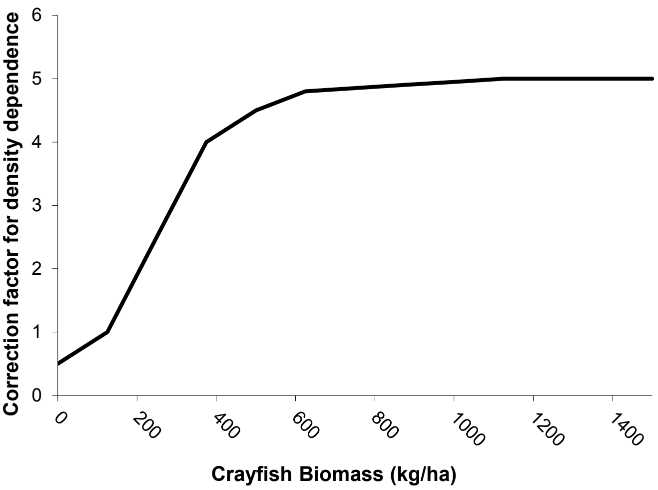


Figure 5: Graphical representation of the function regulating monthly mortality rates in terms of biomass.

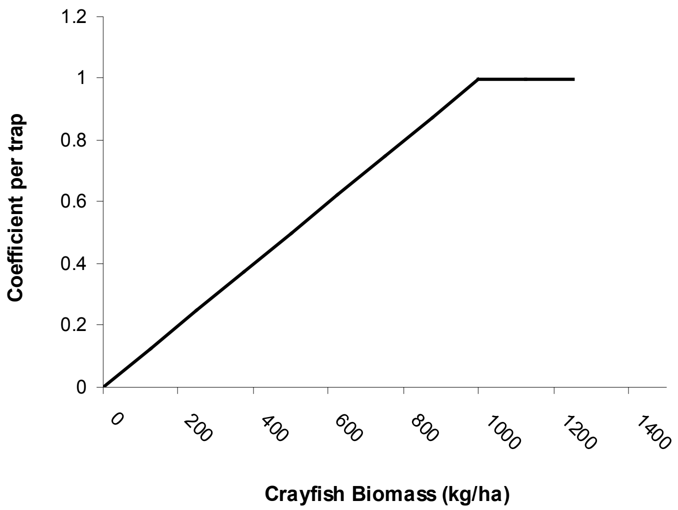


Figure 6: Graphical representation of the function regulating biomass per trap (trap coefficient).

Parameter estimation

The initial crayfish biomass (224 kg/ha) was calculated by averaging all data from the 'Brazo del Este' area.

Minimum production rate (MPR)

This parameter represented the increase in biomass of individuals of *P. clarkii* from their growth rate to define the increase in population biomass (**Table 1**).

Maximum reproductive rate (MRR)

The range of reproductive rates was established from the mean number of eggs found in female *P. clarkii* in the Lower Guadalquivir (Montes et al., 1993; Gutiérrez-Yurrita, 1997; Alcorlo et al., 2008). The sex ratio was 1:1 in the study area (Alcorlo et al., 2008); therefore, differences between females and males were not distinguished in this model.

The mean number of eggs per female was thus divided by two. Considering that crayfish juveniles from 0-1 month of age had a mean weight of 0.11 g and using the mean weight of adults (Alcorlo et al., 2008), the defined values for 'reproductive rate' (expressed as a ratio of biomass) were established between 0.74 and 3.74 (**Table 1**).

Variation in the reproductive rate (VRR)

This parameter defined the effect of temperature on the reproductive rate. The parameter was introduced considering the monthly variation of the temperature and the reproductive cycle of *P. clarkii* in the Lower Guadalquivir, being highest during the months of June and October, slightly lower between these month, and zero between November and April.

Juvenile survival rate (JSR)

The juvenile survival rate for the juvenile stage from 0-20 weeks used in this study was obtained by averaging the values calculated by Romaire (1976) and Huner (1978). These authors defined this rate as the ratio of the number of individuals of a size class and the number of individuals from the previous size class. In our model a mean juvenile survival rate per year of 0.6 was used (**Table 1**); however, values from the entire range of 0.1 to 0.9 were used to calibrate the model.

Real production rate (RPR)

This results from the combination of the above parameters of Minimum Production Rate (MPR) plus the product of Maximum Reproductive Rate (MRR) per the Variation in the Reproductive Rate (VRR) per the Juvenile Survival Rate (JSR) and is expressed as kg of production/kg of population biomass.

Mortality rate (MR)

The values of the monthly mortality rate used in this study ranged from 0.02 to 0.72 (**Table 1**). The *P. clarkii* model was built considering that population mortality was dependent on the population density (**Figure 5**), as this has been observed in several studies (Cano & Ocete, 1994; McClain et al., 1992; Ramalho et al., 2008) and has been introduced in other simulation models similar to ours (Anastácio et al., 1999).

Number of fishing days per month (FD)

The values used in this study were taken from the current legislation. For Strategy 1, the number of fishing days per month were 30, 31, 30, 31, 31, 28, 31 and 15 days in September, October, November, December, January, February, March, and April, respectively, whereas Strategy 2 only considered the corresponding days in September, October, November, and December.

Number of traps per hectare and day (N)

The value of this variable was 7.54 in Strategy 1 from the current regulations, which authorize a total of 6000 traps within 'Brazo del Este' (796 ha). This variable was modified in the scenarios that changed the number of fishing days per month to obtain a fishing effort (number of traps per fishing days) equivalent to the effort under the normal regulations (1700 traps in 227 days in Strategy 1 and 1711 traps in 122 days in Strategy 2).

Crayfish biomass per trap (CBT), crayfish trapped biomass per trap (MCBT) and coefficient per trap (CT)

CBT represented the biomass per trap (kg/trap), which depends on the total biomass of crayfish in the population (CB). If the population was low, the traps contained less biomass. The relationship between the variables (CB and CBT) was defined with the 'coefficient per trap' variable (CT). MCBT, the mean maximum capacity of the traps (saturation of a trap), was defined as an mean value of 0.24 kg/trap according to Alcorlo et al. (2008)

Sensitivity analysis and model calibration

The sensitivity analysis examined the effects of changes in the parameters (coefficients) or external variables on the state variables and was evaluated by the S index ($S = [\delta x/x] / [\delta P/P]$) (Jørgensen, 1988) where δx is the change in the state variable (x) and δP is the change in the Parameter (P). The sensitivity analysis was carried out by varying the values of the parameters up to ± 50%.

Fitting between observed values and predicted values was conducted manually by modifying values of the parameters within the ranges published in the bibliography ('*Estimation of parameters*'). Special attention was payed to the calibration of the most important variables in the sensitivity analysis. The fit evaluation was conducted according slope between observed and predicted values, and the hypothesis of a slope equal to 1 and intercept equal to 0 was tested using a Student's t–test (p <0.05).

Results

Results of sensitivity analysis and calibration

The results of the sensitivity analysis showed that the model was most sensitive to variation Mortality Rate (MR), which was dependent on the crayfish population density (CB). Table summarizes the results obtained with the most relevant parameters. The fitted evaluation between observed and predicted values (**Figure 7**) showed that the model explained 73.68% of the variance (R^2 of the observed values *vs*. predicted values). The slope was not significantly different from 1 (p=0.503), or from 0 (p=0.162).

Simulation results

The evaluation of the results of the three management options that represented qualitatively different situations concerning the crayfish population dynamics were as follows: a) Strategy 0: no fishing, b) Strategy 1: assuming maximum allowable fishing from September 1st to April 15th (227 fishing days), and c) Strategy 2: a new proposed fishing period from September 1st to December 31st (122 fishing days).

Management option (a): Strategy 0

Continuous demographic growth and collapse events (**Figure 8**). The population peaks of greatest intensity occurred in October, which explained the subsequent collapse of the population. The minimum biomass values were approximately 210 kg/ha similar to the initial biomass in the simulation model.

Management option (b): Strategy 1

This option reflected the effect of a fishing effort carried out

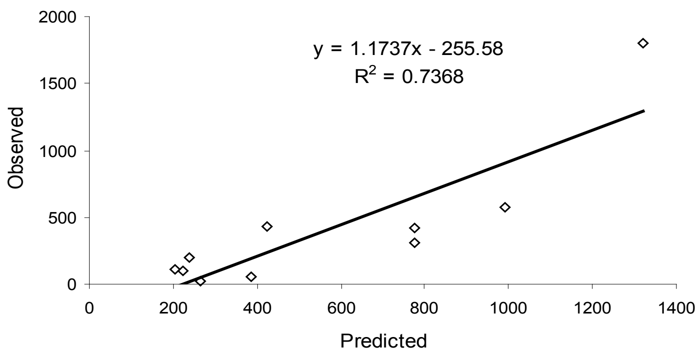


Figure 7: Linear relationship between the observed biomass and the values simulated by the model. The optimal calibration values are: maximum reproductive rate (2.0); juvenile survival rate (0.57); minimum production rate (0.50); mortality rate (0.25).

by 50 fishermen with 120 traps, all within 'Brazo del Este' (796 ha) (**Table 3**); this corresponded to a fishing effort of 1711 traps/ha/year distributed over the total number of allowed fishing days (227 days). This effort provided 168 kg/ha of annual crayfish production. This value was higher than the production values calculated by other authors for our study area; Molina (1984) estimated a 61 kg/ha annual crayfish production in 1981 and 111 kg/ha in 1982. Population explosion events reached 1320 kg/ha of crayfish biomass, with an annual cycle. The minimum values of the population were approximately 200 kg/ha (per month) with an annual population biomass of 6425 kg/ha.

Management option (c): Strategy 2

This option maintained the same fishing effort as in the previous model, 1711b traps/ha/year, but distributed over the new proposed fishing season (122 days) from September 1st to December 31st. This effort provided 230 kg/ha/year of annual crayfish production (**Table 4**), representing an increase in production of 34%. The population dynamics were similar, with 1336 *vs.* 1036 kg/ha and 200 *vs.* 230 kg/ha maximum and minimum values, respectively. The annual population biomass was 6480 kg/ha.

Table 3: Results of the sensitivity analysis. The model is most sensitive to changes in the death rate, which is influenced by the density of the population. In all cases the effect is somewhat less pronounced in the absence of fishing.

Parameter	Value	S index in Crayfish Biomass (CB) parameter	
		Fishing	No fishing
Maximum Reproductive rate (MRR)	1.0 (-50%)	0.359	0.370
	1.5 (-25%)	0.359	0.370
	2.5 (+25%)	0.367	0.378
	3.0 (+50%)	0.523	0.530
	0.250 (-50%)	0.359	0.370
Juvenile Survival Rate	0.375 (-25%)	0.359	0.370
(JSR)	0.625 (+25%)	0.367	0.378
	0.750 (+50%)	0.523	0.530
	0.250 (-50%)	0.525	0.582
Minimum Production Rate	0.375 (-25%)	0.461	0.519
(MPR)	0.625 (+25%)	0.458	0.473
	0.750 (+50%)	0.467	0.481
	0.2 (-50%)	-6.403	-6.016
Mortality Rate	0.3 (-25%)	-1.394	-1.368
(MR)	0.5 (+25%)	-0.653	-0.677
	0.6 (+50%)	-0.585	-0.617

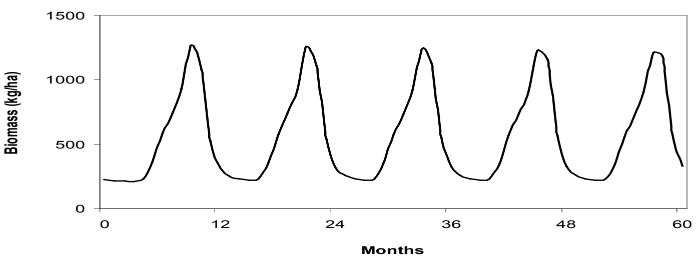


Figure 8: Graphical representation of the simulated population dynamics of *Procambarus clarkii* depending on the settings for no fishing activity (a), modeled for a period of 60 months.

Table 4: Summary of fishery values used in the simulations of the two proposed management strategies. Strategy 1: Distributed fishing effort; Strategy 2: Concentrated fishing effort**.**

	Strategy 0 (no fishing)	Strategy 1		Strategy 2	
		Min.	Max.	Min.	Max.
Total fishing days (days/year)	0	227	227	122	122
Traps/day/ha	0	7.5	74	14.1	125
Traps/year/ha	0	1711	16798	6150	15111
Annual crayfish biomass (kg/ha)	6774	3564	6425	4090	6480
Annual fishing biomass (kg/ha)	0	168	843	230	1036
Annual fishing production (€/ha)	0	151	638	136	499

Discussion

The results from the three proposed scenarios of fishing management (i.e., no fishing and the two fishing strategies) produced different values of annual crayfish production.

Generally, Strategy 2 was more efficient than Strategy 1 in terms of crayfish biomass production, as it provided a higher total harvest than Strategy 1 (6480 *vs.* 6425 kg/ha) with the same fishing effort in half the time. This could be due to the fishing effort being focused on the reproductive season of crayfish in autumn.

In fact, while Strategy 2 assumed 90% of the fishing effort carried out in Strategy 1, it yielded 123% of the respective fishing production while maintaining 115% of the crayfish annual biomass.

Concentrated fishing during the reproductive season may be an optimal strategy. This approach is beneficial because it avoids the overfishing that causes the decline of wild populations (Hein et al., 2007). However, to develop a new sustainable crayfish management plan, it will be necessary to consider the advantages and disadvantages associated with each of the two simulated alternatives and their respective environmental and socioeconomic impacts. This plan should combine the maximization of crayfish production while minimizing the environmental impact from fishing activities. Such an approach combining environmental and recreational preferences with economic factors has been successfully conducted for another exotic crayfish species, i.e., *Pacifastacus leniusculus* in Finland (Kirjavainen & Sipponen, 2004) and Sweden (Gren et al., 2009).

Which option is the most profitable socioeconomically?

The results of the simulations showed that reducing the fishing season from 8 to 4months while maintaining the same fishing effort did not reduce the annual fishing volume. The new fishing period proposed in Strategy 2 (from September 1st to December 31st) included two of the highest fishing production months (September and October), excluding the lower production months (January, February and March). These results support the possibility of reducing the current fishing season since the fishing volume is low during the early months of the year due to the decreased metabolic rate of *P. clarkii*.

For example, during 1999 and 2000 over 75% of the crayfish biomass captured by fishing in Doñana was obtained between July and November (Montes et al., 2001).

Strategy 2 provided 183 tons/year of annual crayfish production. This value can be considered important when it is placed in the context of the Lower Guadalquivir, in which the total production is estimated at 900-1000 tons/year (Montes et al., 2001), thus representing 18.3% of the total production. On the other hand, the time of the year when the fishing is carried out (in relation to the crayfish cycle life) is an important factor to consider in order to obtain captures of crayfish that ensure a threshold value for the abundance of individuals with the minimum marketable size. The size of harvested crayfish affects their market price. For example, medium-sized crayfish (30–40 individuals/kg) cost 0.24–0.30 €/kg, and large-sized crayfish (20–30 individuals/kg) cost 1.05/1.20 €/kg. The latest mean value of the crayfish caught by fishermen was 1.1 €/kg (Martin-López et al., 2011). It is important to highlight that crayfish harvesting in the Lower Guadalquivir River represented 96.5% of the total transaction volume of the foreign trade of products from inland fishing in the Andalucía region during 2010 and 2011, providing gains of 7.73 and 6.93 × 10^6 €/year, respectively, in trade with the United States, France and Finland, the main buyers of Spanish crayfish (Consejería de Agricultura, Pesca y Medio Ambiente, 2013). The annual minimum value of crayfish in markets is usually reached in September and October due to high fishing production in these months and a greater supply of crayfish (**Figure 9**). This means that Strategy 2 would be less advantageous if we only consider economic criteria (**Table 4**). The time of year when fishing is carried out can modulate the population dynamics of crayfish

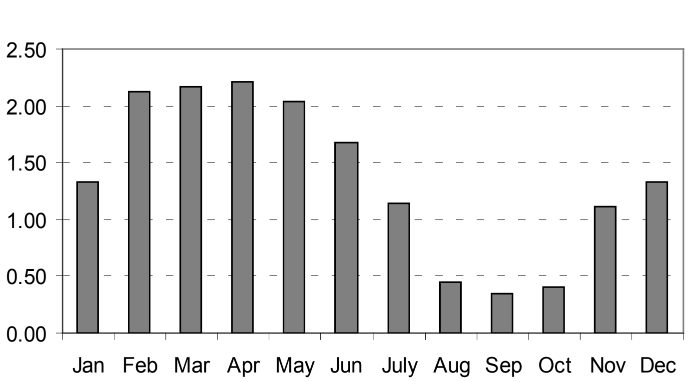


Figure 9: Summary of the mean monthly price of a kg of crayfish estimated from the data of Montes et al. (2001). The chart shows the increase in the CPI between 1999 and 2013 of 47%, according to the Spanish Statistical Institute (our own elaboration).

and their size distribution (e.g., dense populations of smaller individuals *vs.* sparse populations of larger individuals). In fact, Cano & Ocete (2000) observed that the mean size of crayfish from different habitats of the Lower Guadalquivir River (rice fields, channels and marshes) increases in December, which suggests an aging population, while a decrease in the mean size of the crayfish would suggest a shift toward juveniles.

However, the negative influence of the autumn fishing on crayfish size could be countered if fishermen would supplement the fishing effort within 'Brazo del Este' with fishing in channels or rice fields from December to September.

Crayfish populations can have several breeding periods in different seasons of the year according to environmental conditions. These breeding periods can occur in spring (when rice fields are being flooded), in mid–late summer (rice fields are flooded), and late autumn–winter (natural flooding due to heavy rains) (Cano & Ocete, 2000; Alcorlo et al., 2008). The result is that there are always crayfish populations with fishable–sized individuals in the different habitats of the Lower Guadalquivir River.

Which of the two strategies would better reduce the fishing impacts on ecosystems?

The effect of reducing the fishing impact within 'Brazo del Este' was noted some years ago when a closure of the season was implemented between April 15th and September 15th (Asensio, 1991). Fishing activity was regulated in relation to how traps should be set up to minimize the impact on the fauna. In fact, Diaz et al., (2002) showed that if the fishermen set up the trap with a pocket of air in its distal part, the mortality of trapped fish, amphibians and reptiles decreased considerably. For this reason, the main impact from crayfish harvesting becomes the damage done by fishermen walking along the banks and the consequent disruption of the vegetation and wildlife, and the sediment removed due to setting up and removing the traps (Geiger et al., 2005). These impacts, moreover, could cause more or less negative effects on 'Brazo del Este' depending on the hydrological levels of the ecosystem, water quality, effects of drought on vegetation, and extreme hydrological events such as heavy rains or floods. Overall, a reduction from 8 to 4 months of the fishing season would be beneficial to ensure the ecological integrity of this protected natural area; therefore Strategy 2 is the most suitable management option. This strategy follows the restrictions imposed by the regulations developed for controlling the expansion of exotic species (BOJA 152, 2016).

Conclusion

The management of the fishing activity within the 'Brazo del Este' natural protected area should consider the guidelines obtained from results of the simulation and predictive models concerning the effects of fishing activity on the population dynamics of *P. clarkii*. Considering the economic criteria, Strategy 2 seems to present some economic disadvantages in comparison to Strategy 1. However, considering the environmental criteria, Strategy 2 would be the most appropriate. Therefore, a modification of the duration of the open fishing season according to guidelines from Strategy 2 should be recommended. The fishing effort considered in this strategy would provide 183 tons/year of crayfish biomass, which would ensure the development of socioeconomically beneficial fishing activities and long–term sustainable yields from the 'Brazo del Este' area. The reduction of the fishing season within this natural protected area could be augmented with fishing in rice fields between April and September. Indeed, fishing in channels and rice fields could help to control the structural damage caused by crayfish in rice field walls as described in the Doñana area and other Mediterranean wetlands such as the Ebro Delta, as well as on the rice seeds and seedlings. Thus, fishermen could offset the economic losses, if any, from the new regulations on the open fishing season with the economic benefits resulting from fishing in other habitats close to 'Brazo del Este'. Ecological modeling by simulation is useful in managing natural resources such as crayfish as they allow one to 'experience' different management options and to evaluate their results before having to implement them in real ecosystems. Indeed, it may be necessary to build simulation models considering each type of habitat where *P. clarkii* occurs because each habitat will have a different hydroperiod and thus its crayfish populations will show differences in their breeding cycles. Consequently, our methodological approach and results should be considered as a tool to improve the European Non Native Species in Aquaculture Risk Assessment for species not included in Annex IV (e.g. *Procambarus clarkii*), of the EU Alien Species Regulation which is needed.

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