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Abstract

The signal crayfish (*Pacifastacus leniusculus*) is of great economic value for the Swedish fishing industry. Therefore it is of great importance that knowledge and experience is obtained and applied when creating a sustainable fishing industry. My study shows that the fecundity of the female crayfish is determined by her size, a larger female crayfish gives more offspring than a smaller one. There is a regulation that only allows fishing to a certain extent; this means that you are not allowed to fish crayfish that stretches below the limit of 10 cm. But in order to manage a sustainable fishing these regulations might have to be changed. Since larger female gives more offspring it might be better to let them go and instead catch the smaller ones.

Introduction

The signal crayfish (*Pacifastacus leniusculus*) belongs to the group of crustaceans (*Crustacea*) and are a subgroup of the tribe arthropods (*Arthropoda*) (Fiskeriverket, 2006). The signal crayfish was introduced from North America to Sweden in the 1960s in an attempt to replace the crayfish plague-sensitive noble crayfish (*Astacus astacus*) in those lakes where it was knocked out (Fiskeriverket, 2006). The signal crayfish were found to be more tolerant of crayfish plague than the noble crayfish and today you can find the signal crayfish south of the River Dalälven but not on Öland and Gotland (Fiskeriverket, 2006). The signal crayfish live in shallow water at the shore zone of lakes, ponds and other water bodies (Fiskeriverket, 2006). Often they live in dug burrows or under rocks and other hiding places during the day and go out at night to feed (Fiskeriverket, 2006). The signal crayfish are an omnivore and eat detritus (in the form of fallen leaves), clams, insect larvae, snails, fish eggs and aquatic plants (Fiskeriverket, 2006). Since the signal crayfish is the largest of all invertebrates in our fresh water and since that it is omnivorous, it is very important for the functioning of freshwater ecosystems, for example prevent lakes from growing into bogs (Ackefors, 2005). Studies have shown that signal crayfish which has a more animal based diet grow faster than those having a vegetarian diet (Olsson et al. 2008).

Signal crayfish can be between 5 and 20 years old (Fiskeriverket, 2006) and it grows by replacing its exoskeleton with a new. The males usually become larger than females because they can afford to replace their exoskeleton more times per year, while the females have to put more energy into producing offspring (Ackefors, 2005). When molting, the crayfish becomes less active because its new exoskeleton is softer and thus the crayfish therefore run a greater risk of predation (Nystrom and Rowan, 1990).

Typical predators of crayfish include perch, pike (Nystrom and Rowan, 1990) and eel but also mammals such as mink, rats, ferrets, and birds such as ducks, geese, gray herons (Ackefors, 2005). The juveniles runs a risk of being eaten by large freshwater beetles, insect larvae, toads and frogs (Ackefors, 2005).

The white spot in the thumb grip is the best feature of the signal crayfish (Ackefors, 2005). Signal crayfish are lighter in color than the noble crayfish and is smoother on the carapace and claws than the noble crayfish (Ackefors, 2005).

Mating occurs in September-October when the water temperature starts to decrease (Fiskeriverket, 2006). A sexually mature female catches a sexually mature male's attention by lifting claws and the male flips the female over on her back with the help of his claws (Nystrom and Rowan, 1990). He attaches himself on top of the female and puts the spermatophores at the female's genital opening (Nystrom and Rowan, 1990). Shortly after mating, the female lays her eggs by dissolving spermatophores with a secrete which then form a skin in contact with water, she then lays the eggs (Nystrom and Rowan, 1990). Before the eggs are put under the tail, the eggs are stored under the carapace (Fisheries Agency, 2004). The eggs then develop in 6-8 months and hatch in early summer (Nystrom and Rowan 1990). Depending on growth, males sexually mature at 2-5 years and females at 2-6 years (Fiskeriverket, 2006).

The fishing for the signal crayfish are today the kind of freshwater fishing that is the second most important, economically (Fiskeriverket, 2010). The commercial fishing of the signal crayfish are largest in Lake Hjälmaren and Lake Vättern. In Lake Vättern the fishing for crayfish stands for 94 % of the total fished value (Fiskeriverket, 2010). Even recreational fishing of crayfish is widespread and is considered important for the Swedish rural development, it is estimated that the value of the recreational fishery exceeds 300 million per year (Fiskeriverket, 2010).

The fishery of signal crayfish is deemed one of the few freshwater fisheries where there is a potential to develop and expand the fisheries (Fiskeriverket, 2010). The development of the fishery should be done in a sustainable way and there is thus a need for good knowledge on signal crayfish biology and ecology. In this study, the signal crayfish female fecundity (an organism's potential fertility) has been studies in order to confirm or reject the following hypothesis:

• There is a positive correlation between the number of eggs in a female and female's total length.

And to answer the following question:

• Is the size of a female crayfish a good measure of fecundity?
• Are there abiotic factors that control how productive females are?
• What shows different studies and what shows my own?

The question and hypothesis problematize the limits currently used for fishing crayfish. Today, there is a minimum size for catching crayfish at 100 millimeters (Fiskeriverket 2010). If, however, it turns out that the hypothesis is correct, there may be reason to change the measure and instead sort out the big crayfish females because they would give more offspring and thus maintain a high production of crustacean larvae.

Materials and methods

The sexually mature female crayfish from each local and collection period was stored in a freezer and taken out in twos or threes at a time for sampling and measurements. It was important that the crayfish was not completely thawed since the eggs were easier to count when they were semi- thawed.

The total length of the crayfish was measured with a digital caliper (0.1 mm accuracy). The total length was measured from the tip of the tail end to carapace. The width of the tail was measured with a 1 mm- graduated rule. The measurement was carried out at the point where the tail was widest.

A scalpel was used to remove the carapace from the rest of the crayfish body. The length of the carapace was measured with a digital caliper (0.1 mm accuracy).

The eggs was found underneath the carapace, these were cut out as a packet by using the scalpel. During this part it was a great advantage if the internal parts, underneath the carapace, still were frozen. The eggs were then counted one by one with the help of tweezers.

In cases where the crayfish females were fished during spring, they had the eggs under their tail. In those cases the eggs was counted first before the different length measurements.

All data obtained from the survey (total length, length of carapace, tail width and number of eggs) was recorded on a form. All data were then compiled digitally in. A linear regression analysis was conducted in order to see if there was a correlation between number off eggs and length of the females. A t-test was performed in order to see if there was a difference between number off eggs which were carried under the tail and those who were carried underneath the carapace. This was examined to determine if both of the relationships between the total length and egg during carapace and eggs under the tail is a good measure of fecundity.

To investigate whether there was a difference in the number of eggs in the sexually mature females from each local and collection period an ANOVA test was performed. Pearson correlation test was used to examine whether there were correlations between the abiotic factors and the length of the female crayfish and number of eggs they wore. The abiotic factors that were tested against length and number of eggs was substrates (proportion stone ground on the bottom of the lake), temperature, pH, transparency of water, catch per unit effort (CPUE), lake surface size and the total concentration of phosphorus.

The substrate was tested since studies (Nystrom et al., 2006) have shown that there is more habitat for crayfish where rock bottom is abundant (data not found for Lake Erken). The temperature was chosen since it controls the activity of the crayfish. Crustaceans are sensitive to low pH and pH could therefore be interesting to include. Secchi depth is an indicator of how nutritious the lake is and low transparency means that there are a lot of phytoplankton, which in turn means that the lake might be eutrophic. CPUE is interesting to have included in the test because it explains crayfish density in their habitat. A large lake has probably more habitat than a small lake and therefore the lake surface size is interesting. The concentration of total phosphorus was tested for the same reasons as the secchi depth, it is a good indicator of nutritional status in a lake.

Study area

Lake Bunn

The lake is situated 4 km southeast of the town of Gränna and is divided into three major reservoirs (Bunnfiske 2010). Nutritional status of the lake is moderately nutritious and the lake is surrounded mostly by spruce with elements of cropland and deciduous forest (Bunnfiske 2010). The bottom substrate varies between rocky, gravelly or sandy, but it is the rocky substrate that dominates around the lake (Bunnfiske 2010).

Table 1. Compiled data for Lake Bunn (Fiskeriverket, 2010).

Lake Bunn			
Coordinates (X/Y)	6431540/1421490	**Altitude (m)**	197
Region	Jönköpings län	**Lake size (km^2)**	9,73
Municipality	Aneby, Jönköping	**Maximum depth (m)**	20
Watershed	Motala ström	**Mean depth (m)**	6,4
Year of introduction of the signal crayfish	1982	**Caught crayfish / Year (kg)**	Unknown
Transparency (m)	3,93	**CPUE**	6,18
pH	7,9	**Mean temperature (September, °C)**	19,5
Total phosphorous (µg/l)	9	**Fraction of rocky bottom (%)**	46

Lake Erken

The lake is situated in Norrtälje municipality and is the second largest lake in the county after Lake Mälaren (Svanberga 2010). Calcareous soils are surrounding Lake Erken, which contributes to a high pH in the lake (Svanberga 2010). The lake has a large transparency despite being nutritious (National Board of Fisheries 2010). The lake is surrounded by forest and arable land (National Board of Fisheries 2010).

Table 2. Compiled data for Lake Erken (Fiskeriverket, 2010).

Lake Erken			
Coordinates (X/Y)	6640600/1659480	**Altitude (m)**	11
Region	Stockholms län	**Lake size (km^2)**	23,35
Municipality	Norrtälje	**Maximum depth (m)**	20,7
Watershed	Broströmmen	**Mean depth (m)**	9,0
Year of introduction of the signal crayfish	1966	**Caught crayfish / Year (tonnes)**	5-10 (2008)
Transparency (m)	3,8	**CPUE**	4
pH	8,1	**Mean temperature (September, °C)**	14
Total phosphorous (µg/l)	22,4		

Lake Hövern

Lake Hövern is located on the border between Linköping, Söderköpings and Åtvidaberg municipality (Linköping municipality, 2010). Large parts of the beaches are unexploited and are mostly rocky (Linköping Municipality, 2010). The lake has 15 islands (Linköping municipality, 2010), which creates good habitats for crayfish. The lake is surrounded by mostly coniferous forest with some deciduous forest (Linköping Municipality 2010). In some bays the lake has a high nutritional status due to nutrient leaching, but as a whole the lake is likely oligotrophic (Linköping Municipality, 2010).

Table 3. Compiled data for Lake Hövern (Fiskeriverket, 2010).

Lake Hövern			
Coordinates (X/Y)	6472350/1516700	**Altitude (m)**	65
Region	Östergötland	**Lake size (km^2)**	6,5
Municipality	Åtvidaberg	**Maximum depth (m)**	13,5
Watershed	Söderköpingsån	**Mean depth (m)**	6,2
Year of introduction of the signal crayfish	1971	**Caught crayfish / Year (kg)**	>1000
Transparency (m)	1,4	**CPUE**	4,92
pH	7	**Mean temperature (September, °C)**	20
Total phosphorous (µg/l)	21,0	**Fraction of rocky bottom (%)**	40

Lake Läen

Lake Läen is a mesotrophic lake situated in Lessebo municipality. The lake is estimated to be slightly eutrophic due to nutrient runoff from agriculture (Fiskeriverket, 2010). The lake is surrounded by land sensitive to acidification and in the lake's catchment area several rivers are regularly limed (Fiskeriverket, 2010). The surrounding landscape alternates between agricultural land, spruce and mixed forest (Fiskeriverket, 2010). The lake has many islands and even a stone reef which is good habitat for crayfish (Fiskeriverket, 2010).

Table 4. Compiled data for Lake Läen (Fiskeriverket, 2010).

Lake Läen			
Coordinates (X/Y)	6291630/1468240	**Altitude (m)**	167
Region	Kronobergs län	**Lake size (km^2)**	10,6
Municipality	Emmaboda, Lessebo	**Maximum depth (m)**	14,5
Watershed	Ronnebyån	**Mean depth (m)**	3,7
Year of introduction of the signal crayfish	1970's	**Caught crayfish / Year (kg)**	<200
Transparency (m)	1,9	**CPUE**	2,12
pH	7	**Mean temperature (September, °C)**	17,8
Total phosphorous (µg/l)	10,5	**Fraction of rocky bottom (%)**	60

Results

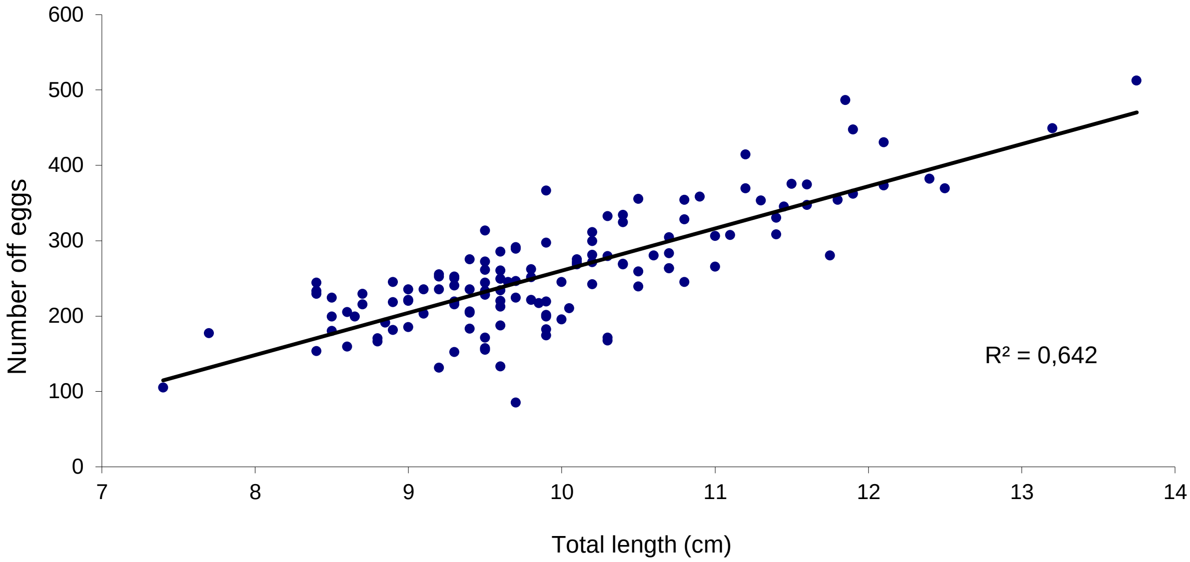

Figure 1. The relationship between size and number of eggs for all female crayfish from all lakes and years (n=129) with eggs underneath carapace (r =0.80, p<0.05).

The total length of a female with eggs underneath carapace explains 64.2 % of the variability in number of eggs (figure 1). There is a significant correlation between total length and number of eggs (p<0.05), the relationship is a compilation of data from seven lakes (figure 2-8). The majority (26 %) of the female crayfish had a total length in the range of 9.5-10.0 cm, length distribution ranged from 7.0-14.0 cm (figure 9). A number of females below 7 cm did not carry any eggs and thus were excluded from the analysis.

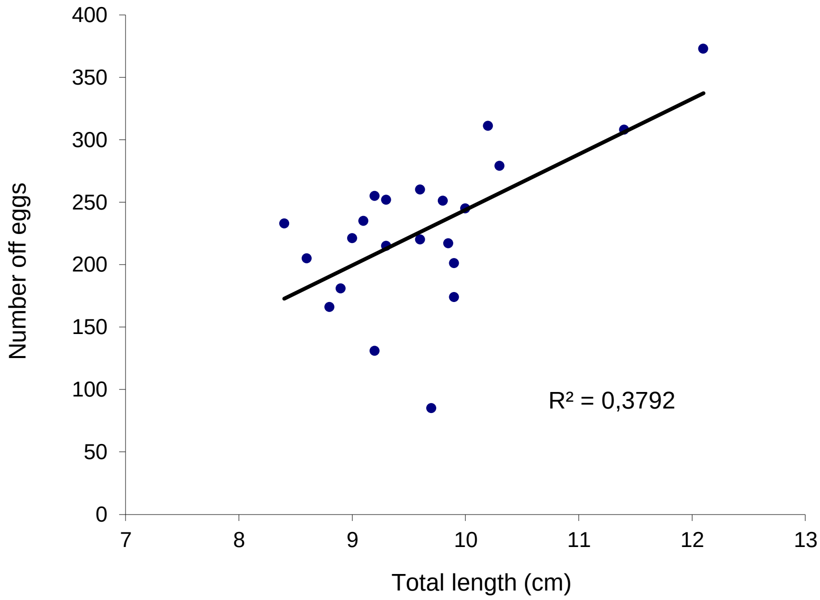

Figure 2. Correlation (r=0.61) between total length and number of eggs for female crayfish (n=22) with eggs underneath carapace for Lake Läen, year 2010.

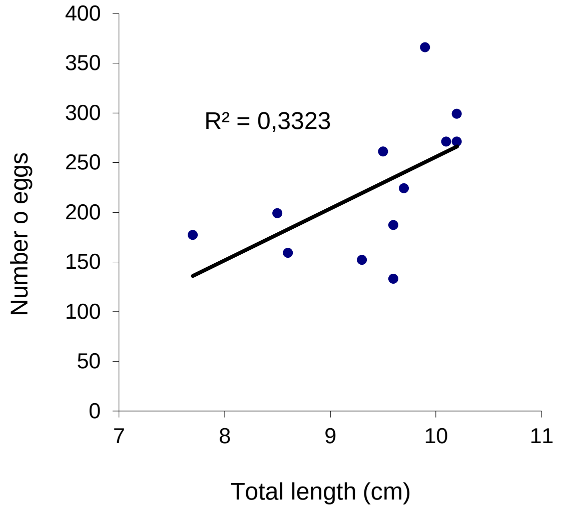

Figure 3. Correlation (r=0.57) between total length and number of eggs for female crayfish (n=12) with eggs underneath carapace for Lake Läen, year 2009.

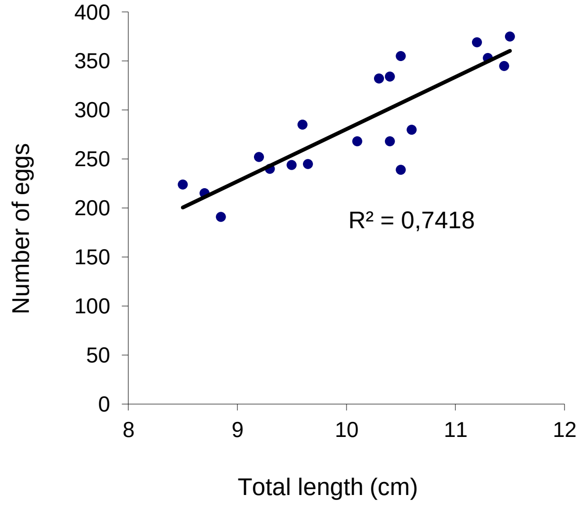

Figure 4. Correlation (r=0.86) between total length and number of eggs for female crayfish (n=19) with eggs underneath carapace for Lake Bunn, year 2010.

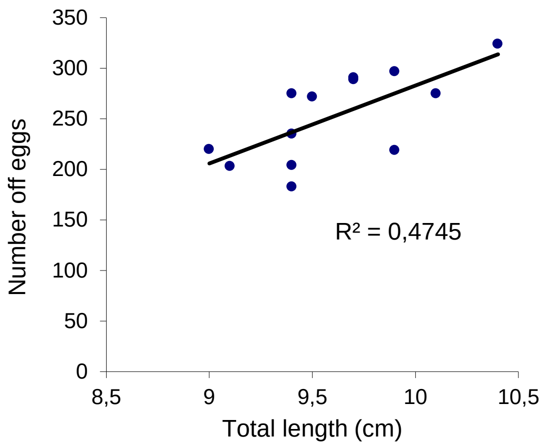

Figure 5. Correlation (r=0.69) between total length and number of eggs for female crayfish (n=13) with eggs underneath carapace for Lake Bunn, year 2009.

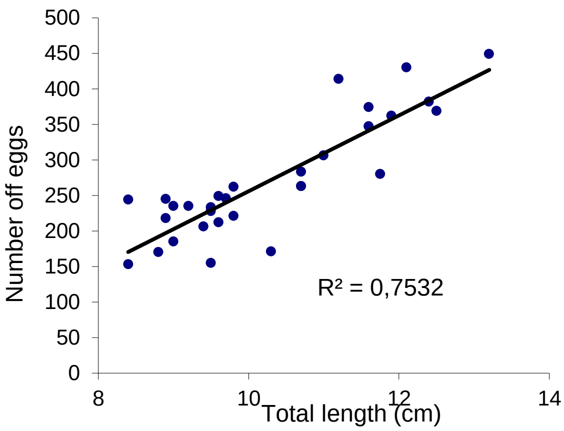

Figure 6. Correlation (r=0.87) between total length and number of eggs for female crayfish (n=31) with eggs underneath carapace for Lake Erken, year 2010.

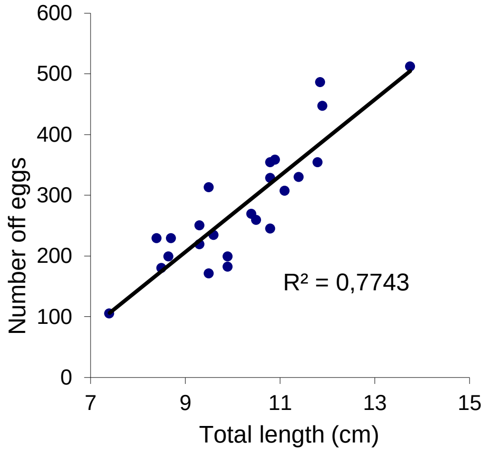

Figure 7. Correlation (r=0.88) between total length and number of eggs for female crayfish (n=24) with eggs underneath carapace for Lake Hövern, year 2010.

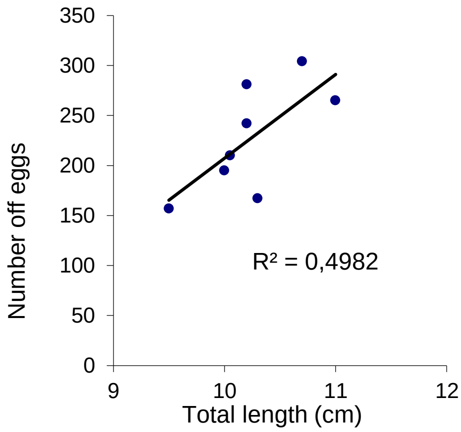

Figure 8. Correlation (r=0.71) between total length and number of eggs for female crayfish (n=8) with eggs underneath carapace for Lake Hövern, year 2009.

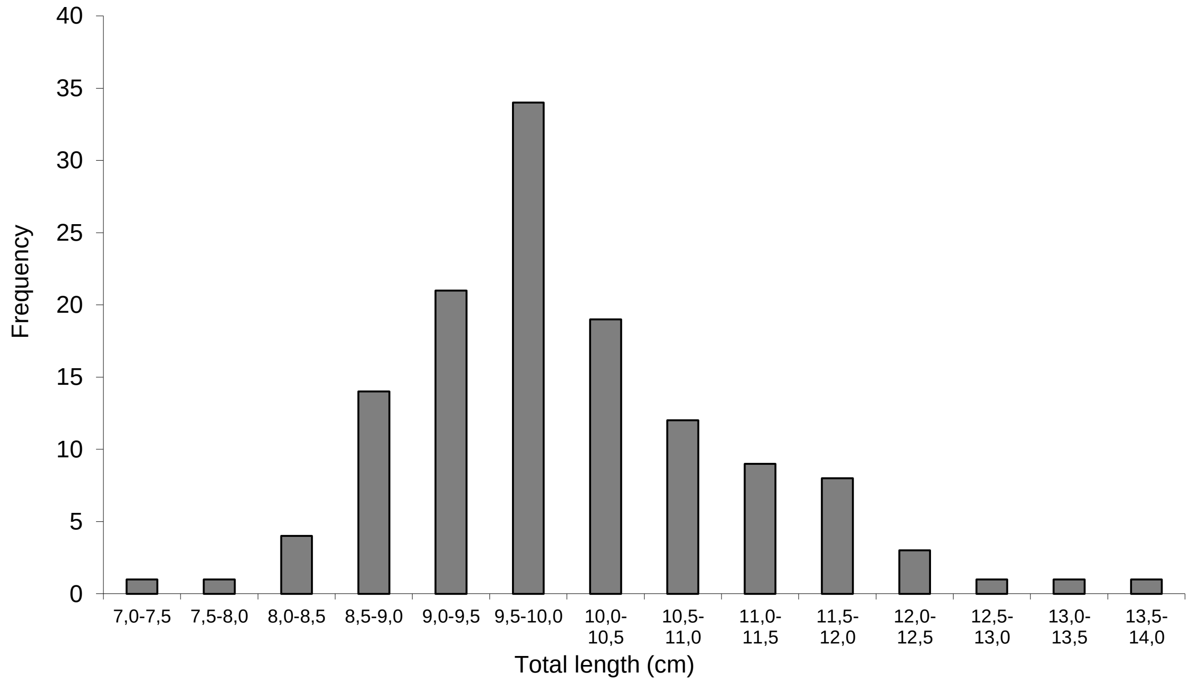

Figure 9. Distribution of total length for n=129 sexually mature female crayfish with eggs underneath carapace.

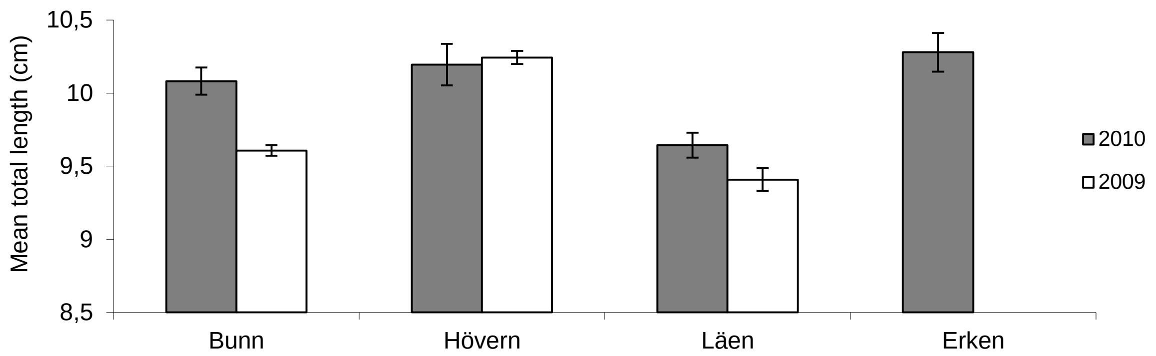

Figure 10. Mean total length for various lakes and years for sexually mature female crayfish (n=129) with eggs underneath carapace.

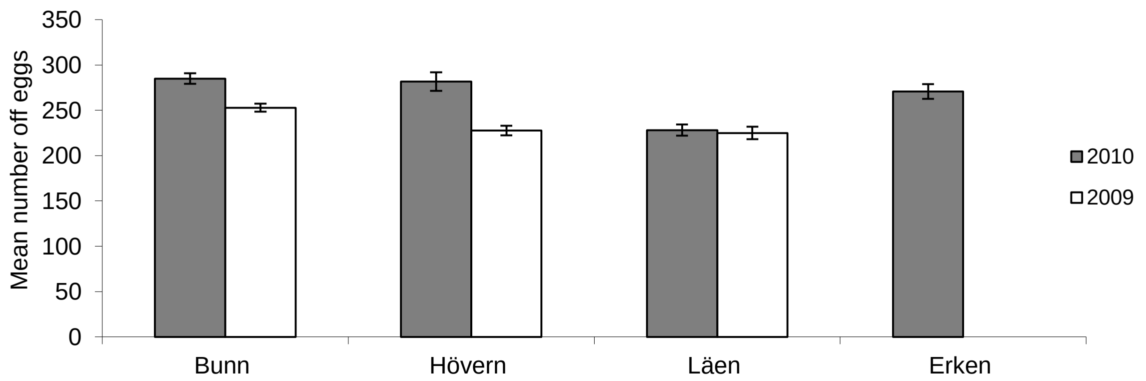

Figure 11. Mean number of eggs for various lakes and years for sexually mature female crayfish (n=129) with eggs underneath carapace.

Mean total length between the different lakes in 2010 did not differ significantly, while there was a significant difference (df=2, F=5.317, p=0.011) in mean length between Lake Hövern 2009 and the other two lakes from 2009 (Lake Bunn and Lake Laen) (Figure 10, table 5).

A significant difference (df=6, F=2.184, p=0.049) were also found in mean number of eggs (Figure 11). The difference is between three groups, the group (1) with the lowest average consists of Lake Hövern 2009, Lake Läen 2009 and 2010. Lake Erken 2010, Lake Hövern 2010 and Lake Bunn 2010 represent the group (2) with the highest mean and Lake Bunn 2009 represents the third group (3) situated between the largest and smallest group (Table 5).

Table 5. Summary of measured data for female crayfish (n=129) with eggs underneath carapace, divided between lakes and years.

Lake	Year	Number of females	Mean total length (cm)	Standard Error	Mean number of eggs	Standard Error
Bunn	2010	19	10,08	0,093	284,94	5,74
Erken	2010	31	10,28	0,13	270,64	8,2
Hövern	2010	24	10,19	0,14	281,62	10,14
Läen	2010	22	9,64	0,085	228,09	6,19
Bunn	2009	13	9,61	0,036	252,84	4,41
Hövern	2009	8	10,24	0,045	227,62	5,38
Läen	2009	12	9,41	0,077	224,91	6,97

There was no significant relationship between total length and number of eggs for female crayfish who carried eggs under the tail (r=0.029, figure 12), the relationship is a compilation of data from two lakes (figure 13-14).

The length distribution of female crayfish that carried eggs under the tail ranged from 7.5 to 12 cm and the majority (22.7%) was in the range 9.5-10 cm (figure 15).

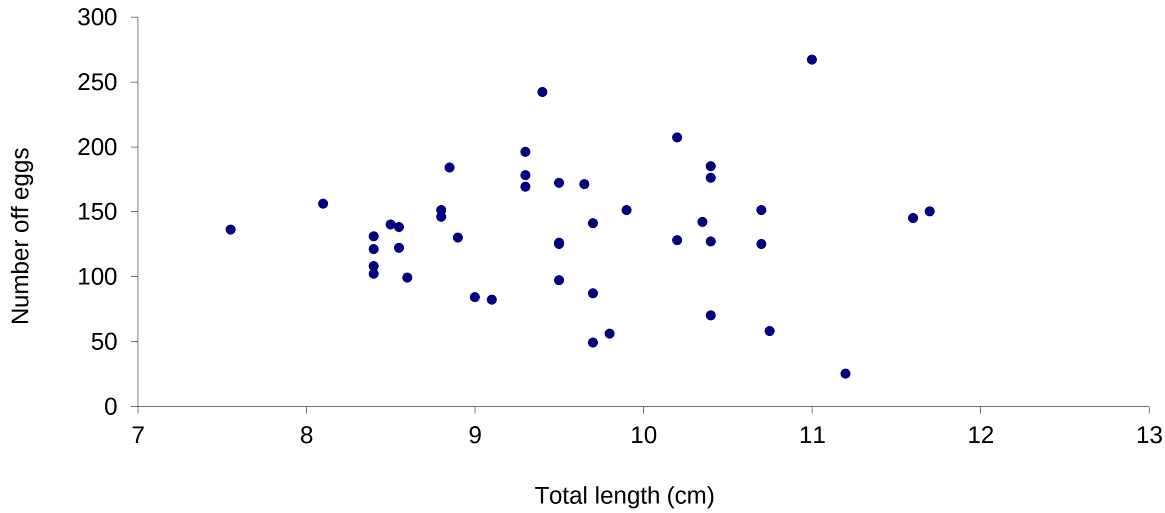

Figure 12. Correlation (r=0.029) between total length and number of eggs for female crayfish (n=44) with eggs under the tail.

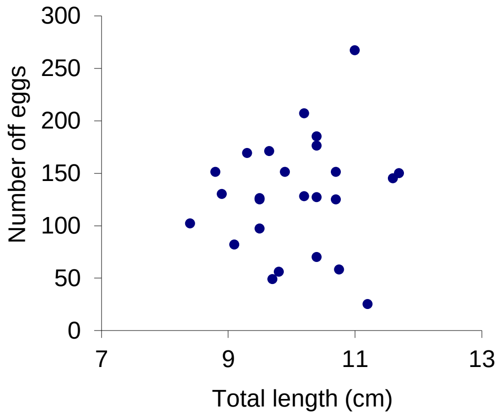

Figure 13. Correlation (r=0.12) between total length and number of eggs for female crayfish (n=25) with eggs under the tail for Lake Erken, year 2010.

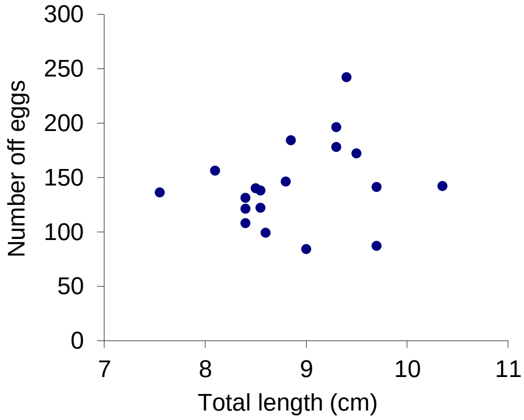

Figure 14. Correlation (r=0.21) between total length and number of eggs for female crayfish (n=19) with eggs under the tail for Lake Hövern, year 2010.

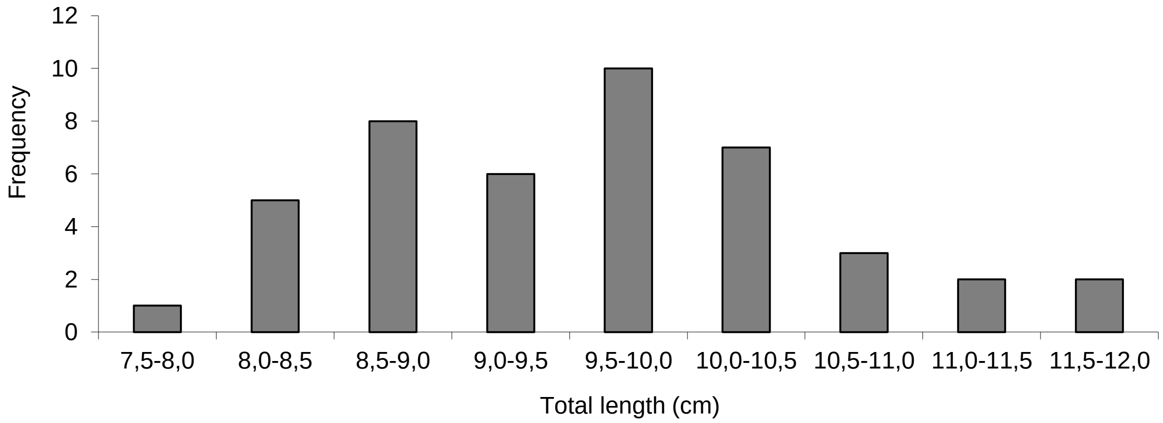

Figure 15. Distribution of total length of 44 sexually mature female crayfish with eggs under the tail.

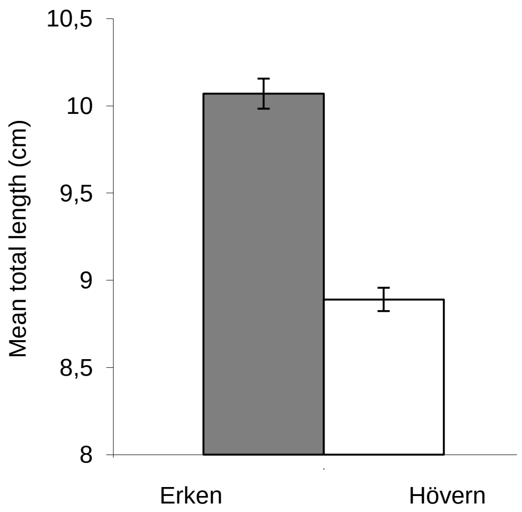

Figure 16. Mean total length of sexually mature female crayfish with eggs under the tail. For Lake Erken and Lake Hövern, year 2010.

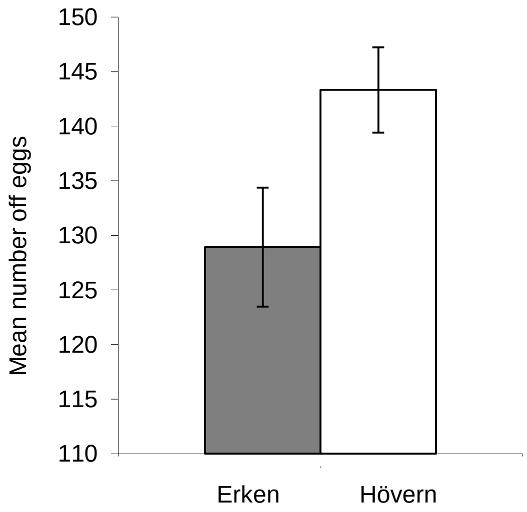

Figure 17. Mean number of eggs of female crayfish with eggs under the tail. For Lake Erken and Lake Hövern, year 2010.

Table 6. Summary of measured data for female crayfish (n=44) with eggs under the tail.

Lake	Year	Number of female crayfish	Mean total length (cm)	Standard Error	Mean number off eggs	Standard Error
Erken	2010	25	10,07	0,086	128,92	5,44
Hövern	2010	19	8,89	0,067	143,32	3,91

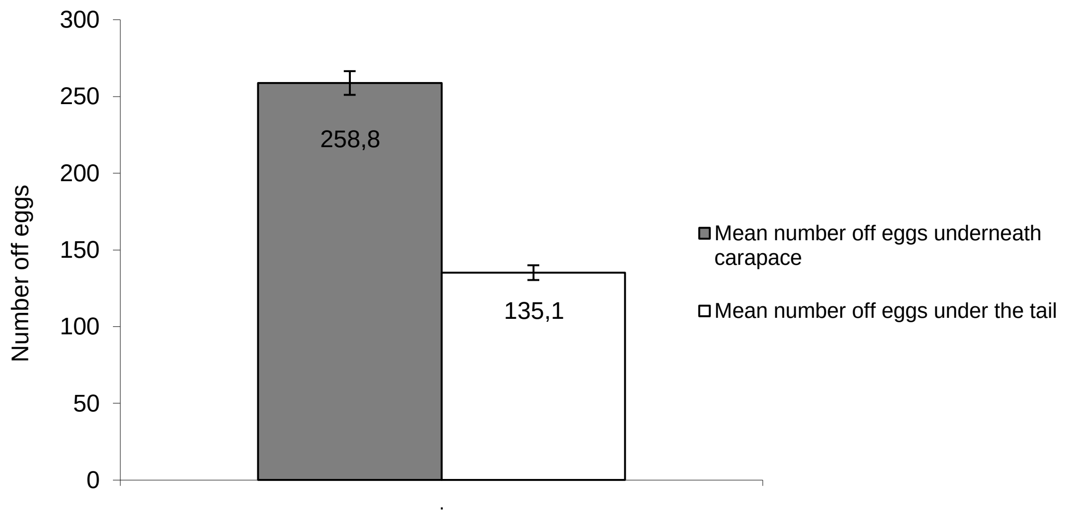

Figure 18. Mean difference between the number of eggs for female crayfish with eggs underneath the carapace (n=129) and number of eggs under the tail (n=44) (p<0.001).

Table 7. Results of Pearson's correlation test for mean length, mean number of eggs and mean number sexually mature crayfish with eggs underneath carapace against abiotic parameters.

		Substrate	Temperature	pH	Transperancy	CPUE	Lake size	Total phosphorous concentration
Mean length	**Pearson correlation**	-0,384	-0,222	0,574	0,396	0,668	0,36	0,712
	Sig. (2-tailed)	0,616	0,778	0,426	0,604	0,332	0,64	0,288
	N	4	4	4	4	4	4	4
Mean number off eggs	**Pearson correlation**	-0,711	0,225	0,468	0,374	0,942	-0,053	0,337
	Sig. (2-tailed)	0,289	0,775	0,532	0,626	0,058	0,947	0,663
	N	4	4	4	4	4	4	4
Mean number of sexually mature crayfish	**Pearson correlation**	0,452	-0,844	0,359	0,159	- 0,273	0,826	0,854
	Sig. (2-tailed)	0,548	0,156	0,641	0,841	0,727	0,174	0,146
	N	4	4	4	4	4	4	4

A singificant difference ($p<0.001$) was found between the means of total length for females with eggs under the tail in Lake Erken and Lake Hövern (Figure 16, Table 6). However, there was no difference between Lake Erken and Lake Hövern of the mean number of eggs (Figure 17, Table 6).

A significant difference ($p <0.001$) were also found in mean number of eggs between the female crayfish who carried the eggs underneath carapace and those who carried the eggs under the tail (Fig. 18). The females who carried the eggs under the tail carried significantly fewer eggs than the females who carried the eggs underneath the carapace (Fig. 18).

Pearson correlation test (Table 7) showed no significant relationships between abiotic factors and the size or how many eggs the female crayfish wore. However, a trend was found between the number of eggs and CPUE (Pearson correlation, df=3, F=0.942, p=0.058).

Discussion

There is a significant positive relationship between the size of a female and how many eggs the female bears when she carries the eggs underneath the carapace, which confirms the hypothesis (figure 1). However, there is no relationship when the female carries the eggs under the tail (figure 12). There was a significant difference in the mean number of eggs from females who carried the eggs underneath carapace and females who carried the eggs under the tail. Females who carried the eggs under the tail had significantly fewer eggs than the females who carried the egg underneath carapace (figure 18). This may be due to that female who carries eggs under the tail runs a greater risk of dropping eggs (Abrahamsson, 1971) and this may explain why the smaller females in Lake Hövern (figure 16) carries more eggs than the larger females in Lake Erken (figure 17). It can thus be due to chance. It may also be due to the larger females in Lake Erken interact more with each other due to a higher density (CPUE tables 2 and 3) and therefore lose more eggs. The size explains thus fecundity better for female crayfish with eggs underneath the carapace than females with eggs under the tail.

Previous studies (Abrahamsson, 1970, 1971; Muck et al. 2002) confirm that there is a positive correlation between size and fecundity, even for the crayfish females with eggs under the tail. However, one should remember that there are many other factors affecting fecundity, such as nutritional status, pH, temperature, competition and predation. A large female crayfish that lives in an oligotrophic lake probably have decreased fecundity than a female crayfish living in a eutrophic lake, due less food availability. A low pH would probably also reduce the fecundity of a large female due to a low pH values degrades the calcium rich exoskeleton, which contributes to stress. A low temperature may inactivate the crayfish which in return reduces its growth and fecundity, while a too high temperature can cause stress and thus reducing the survival (Hammond et al. 2006). Predation on female crayfish might also reduce their fecundity, for example if a female crayfish would be injured during interaction with a predator, she perhaps adds more energy to heal her wounds than to produce eggs. During the performed correlation test no significant correlations for the abiotic parameters were detected (table 7). A trend (p=0.058) was however found between the mean number of eggs underneath the carapace and CPUE. The greater the CPUE, the more egg were carried. Since the catch per unit effort is a measure of crayfish density this result can be explained by the intraspecific competition between the crayfish in lakes with high densities. Competition might enhance the crustaceans females to produce more eggs because larval survival decreases at high intraspecific competition.

The majority (26 %) of the measured female crayfish with eggs underneath the carapace had a total length in the range of 9.5-10.0 cm. The distribution of size (figure 9) looks likely the same in a general lake, thus most caught crayfish are released back to the lake since the minimum size is 100 millimeters. But perhaps there are reasons to change the size limits, large female crayfish not only produce more eggs but also brings some advantages to their offspring. Studies (Muck et al. 2002) of an american freshwater crayfish (*Orconectes luteus*) have shown that the eggs carried by large females grew faster and became larger than the eggs carried by smaller females. This crayfish is in many ways similar to the signal crayfish and one can therefore assume that similar patterns apply to the signal crayfish. This means that a large female would not only produce more eggs during favorable conditions, but also the offspring would have a better chance to survive than the offspring of a smaller female.

To be able to fish on strong and sustainable stocks of signal crayfish it might be necessary to avoid fishing the largest females, and instead fish females in a range from 9-11 cm. According to the distribution (figure 9) the range of 9-11 cm accommodate 66 % of the crayfish I examined which means that it would even be possible to fish more than is done today (10-14 cm, 42 %). The only question is whether it is practical to fish in this size range, it will no longer be possible to sort out the crayfish of different mesh sizes on the cages since it concerns a range and not today's minimum dimensions. Fishermen must measure and sort the crayfish manually, which costs time, energy and money.

In order to create incentives for fishermen to sort crayfish manually, one could introduce some kind of grant or subsidy for these fishermen. Financial assistance may also be needed since the biggest crayfish will be sorted out, it is not unlikely that the catch weight will decrease, which in makes it economically difficult to survive as a crayfish fishermen. But in terms of the number of crayfish is not certain that the catch will decrease. If one lets the big females live, they might give the offspring good survival benefits, which will lead to a strong population of signal crayfish.

At the possible introduction of an interval measurements (9-11 cm) on crayfish fishing, it may be interesting to investigate how many of crustacean larvae that reach a size of 11 cm, i.e. how many of the fry survive from being caught when they are between 9-11 cm. If one know this, it is easier to predict whether the fisheries are sustainable or not. If many female crayfish above 11 cm survive the fishing pressure is probably not too great and the surviving crayfish females produce a lot of offspring. If, however, only a few female crayfish are longer than 11 cm, the fishing might not be sustainable.

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