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Stocking models of Chinese mitten crab (*Eriocheir japonica sinensis*) in Yangtze lakes

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Abstract

The farming of Chinese mitten crab, a quality aquatic product in China and neighbouring Asian countries, has been developing rapidly in China since last decade. It reached a total yield of 3.4×10^5 tonnes in 2002. Due to the successive over-stocking year after year, many lakes in the mid-lower Yangtze Basin, the main farming area, are under deterioration, leading to a reduction of crab yield and quality, and, subsequently, a loss of farming profits. Aiming at a normal development of crab culture and the sustainable use of lakes, an annual investigation dealing with lake environmental factors in relation to stocked crab populations was carried out at 20 farms in 4 lakes. The results show that the submersed macrophyte biomass (B_{Mac}) is the key factor affecting annual crab yield (CY). Using the ratio of Secchi depth to mean depth (Z_{SD}/Z_M), an easily measured parameter closely correlated to B_{Mac}, as driving variable, 10 regression models of maximal crab yields were generated (r^2 ranging 0.49–0.81). Based on the theory of MSY (Maximum Sustainable Yield), in combination with body-weight (BW) and recapture rate (RR) of adult crabs, a general optimal stocking model was eventually formulated. All models are simple and easy to operate. Comments on their applications and prospects are given in brief.

Keywords: Yangtze lakes; Chinese mitten crab culture; Maximal yield models; Optimal-stocking model

1. Introduction

Chinese mitten crab, *Eriocheir japonica sinensis* (H. Milne Edwards, 1854) (formerly as *E. sinensis*, see Tang et al., 2003), is a catadromous crustacean with a life-span about 2 years (Pan, 2002). It grows in freshwater habitats until maturity and then migrates into saline waters to spawn. When living in freshwater, it is an omnivore feeding on zoobenthos, periphyton, vegetative material etc. (Pan, 2002) and having the habit of burrowing or, sometimes, foraging for food among macrophytes. Although it is regarded as an invader causing great ecological and economic loss in European and American countries (Rudnick et al., 2003), the mitten crab has long been a fashionable table delicacy in autumn in China, Japan and other Asian countries. For many years, its market price has been continuously rising owing to the imbalance between supply and demand. Farming of the mitten crab in China has thus rapidly developed since the

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1980s, and currently practiced throughout the country, especially in the mid-lower Yangtze Basin. Subsequently, the total crab yield in the country has been increasing so rapidly that it attained an amount of 3.4×10^5 tonnes, corresponding to 1.73×10^{10} Yuan, in 2002. It accounted for about 2% of the total product and 16% of the value of Chinese inland aquaculture in that year (Hishamunda and Subasinghe, 2003). Among the various waters, lakes are regarded as the most suitable places for crab farming. In addition to their extensive area with comparatively good water quality, crabs produced therefrom are superior to those from other waters such as fish ponds. In recent years, however, the deterioration of water quality and the exhaustion of natural food resources in many lakes due to successive over-stocking of the crab have resulted in declines in crab sizes and yields (Zhao, 2000; Xu et al., 2003). Hence, the knowledge referring to rational stocking of crabs in lakes is essential not only to the healthy development of crab culture, but also to the protection and sustainable use of lakes. To date, the carrying capacity estimates for lake crab populations have not been reported in China or abroad. Previous researches concerning Chinese mitten crab were mainly concentrated on larval culture, diseases, diets and nutrition etc. (e.g., Li et al., 1991; Mu et al., 1998; Wang et al., 2002; Jin et al., 2003). The present study is conducted for the purpose of devising a scientific method that can be widely used to determine the optimal stocking rate of Chinese mitten crab based on the carrying capacity estimates of lakes.

In inland waters, carrying capacity estimation for fisheries mainly used energy conversion and regression model methods. Energy conversion method has been widely used in monotrophic fish (e.g., Wang and Liang, 1981; Liang and Liu, 1995). However, this method is difficult to be effectively applied to polytrophic Chinese mitten crab, mainly due to the fact that its energy basis is complex and many parameters are difficult to determine. These difficulties can be overcome when regression models are used, for their bases are the regressions between yields and environmental conditions; they require fewer parameters and are easier to apply. For several decades, such models have made great contributions to predict the production of fish with all kinds of diets or total fish production. Their *x*-variables range from physical, chemical and biological or their combination, e.g., the morpho-edaphic index (MEI, ratio of total dissolved solids in mg L^{-1} and mean depth in m) (Ryder et al., 1974; Rempel and Colby, 1991), primary production and phytoplankton standing crop (Liang et al., 1981; Liang and Liu, 1995; Nissanka et al., 2000), zoobenthos standing crop (Matuszek, 1978; Liang and Liu, 1995).

Our research was carried out during December, 2001–March, 2003 in 20 crab culture regions of four lakes in the middle Yangtze Basin. Based on an annual

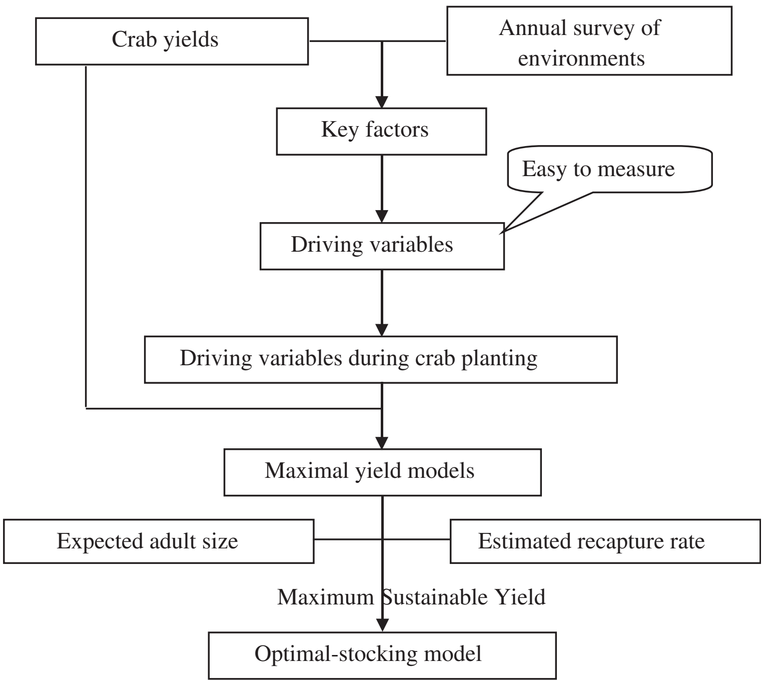

Fig. 1. Approach to estimate carrying capacity and to generate optimal-stocking model of Chinese mitten crab.

investigation of biotic and abiotic environmental factors, we first determined the key factors affecting crab yield, and subsequently identified the appropriate driving variables to generate maximal yield models. Finally, an optimal-stocking model was generated using MSY (Maximum Sustainable Yield) theory as reference. For details of our approach, see Fig. 1.

2. Lakes and methods

The four research lakes, Baoan Lake, Niushan Lake, Lu Lake and Western Liangzi Lake, are all located in the middle Yangtze Basin, Hubei Province, China (114°08′–48′ E, 30°07′–23′ N). Networks or dikes subdivided the waters into 20 regions in total (Fig. 2), with areas ranging from 145 to 6667 ha, with average depths of 2–4 m.

Commercial crab culture has been intensively carried out in these waters since 2000–2001, managed by different fish farms. Generally, there was no supplementary diet. The stocking and catch data of the crab in 2001/2002 were obtained from the records of local fish farms (Table 1). Crab juveniles stocked were mainly yearlings weighing 10 (5–15) g ind^{-1}, and released directly into the waters during December, 2001–May, 2002. In Region 17, 1653 ind ha^{-1} youngs-of-the-year of about 0.05 g ind^{-1} were also stocked in autumn, 2001. When calculating the stocking and recapture rates of this region, we converted the number of youngs-of-the-year

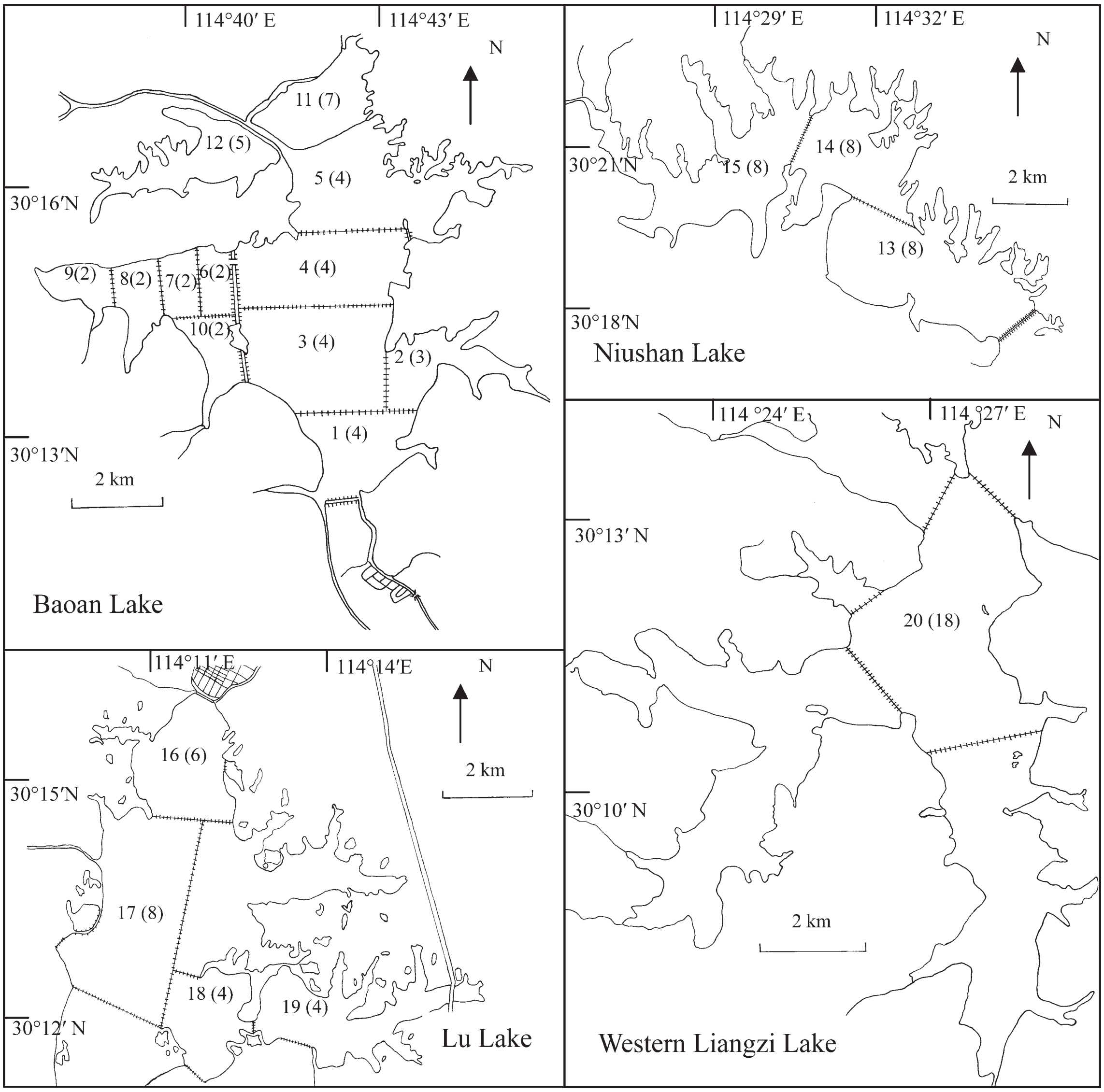

Fig. 2. Regions in four lakes. The number in the front is region-code and the number in parenthesis denotes the number of sampling sites.

Table 1
Stocking populations of Chinese mitten crab and main environmental parameters (annual means) in research regions

Lake	Region*	Crab culture (2001/2002)				Environments (2001 Dec.–2002 Dec.)																
		SR	BW	CY	RR	Area	Z_M	Z_{SD}	T	Cond	pH	NH_3–N	TN	TP	Chl *a*	B_{Mac}	D_{Gas}	B_{Gas}	D_{Oli}	B_{Oli}	D_{Ins}	B_{Ins}
Baoan Lake	Baoankou (1)	1650	147	62	26	363	2.10	1.69	17.6	0.376	7.92	0.171	0.441	0.011	3.91	3800	412	94.7	44	0.46	182	0.28
	Huangfengkou (2)	2390	125	88	29	188	1.97	1.94	17.8	0.885	7.94	0.083	0.257	0.015	1.11	2310	184	43.7	32	0.48	344	1.89
	Changlingzhou (3)	1820	125	82	36	880	2.34	2.13	17.3	0.457	8.06	0.136	0.257	0.009	1.49	2240	292	83.7	20	0.21	119	0.42
	Zhuzhou (4)	1700	120	70	34	645	2.57	1.65	17.3	0.355	8.03	0.141	0.188	0.013	4.28	1010	56	10.6	4	0.06	244	3.95
	Longwangtou (5)	960	120	38	33	625	2.45	1.66	17.3	0.374	7.96	0.158	0.230	0.017	4.27	240	43	18.9	21	0.38	313	1.88
	Lianhuazhou (6)	2390	150	38	11	157	2.69	1.81	18.2	0.252	8.10	0.177	0.241	0.015	2.47	80	12	0.21	28	0.12	704	1.97
	Outang (7)	2760	150	111	27	145	2.63	2.00	18.3	0.236	8.18	0.143	0.180	0.013	3.99	2740	800	18.1	32	0.21	1512	2.91
	Shuimiao (8)	2550	125	105	33	157	2.34	2.44	18.3	0.213	8.38	0.137	0.194	0.011	2.22	9480	664	28.6	4	0.01	1100	1.76
	Changlingtou (9)	2690	125	111	33	149	1.76	2.16	18.8	0.199	8.41	0.154	0.268	0.016	1.98	6800	156	9.07	16	0.60	240	0.59
	Tongshawan (10)	2090	160	78	23	191	2.12	1.70	18.6	0.253	8.08	0.219	0.205	0.016	2.04	2430	188	11.6	52	0.43	1220	4.15
	Biandantang (11)	1290	111	57	40	333	2.13	1.43	17.3	0.193	8.07	0.214	0.270	0.018	4.46	440	58	3.52	29	0.79	266	0.50
	Xiaosihai (12)	2000	ND	47	ND	150	1.75	1.26	16.9	0.321	7.90	0.152	0.190	0.032	2.04	1510	21	43.0	73	0.86	381	0.29
Niushan Lake	Dongpian (13)	1140	157	34	19	1750	3.29	2.38	20.5	0.129	8.17	0.110	0.861	0.008	2.75	1070	29	32.8	29	0.63	84	0.14
	Zhongpian (14)	1110	ND	38	ND	1175	3.33	2.45	20.7	0.137	7.85	0.107	0.931	0.005	1.80	310	17	7.58	21	0.29	59	0.34
	Xipian (15)	3000	ND	28	ND	1333	3.34	2.26	20.9	0.134	8.03	0.115	0.977	0.005	3.30	1390	47	65.9	15	0.13	79	1.01
Lu Lake	Wuqianmu (16)	1260	152	18	9	571	2.17	0.84	17.9	0.241	7.69	0.330	0.783	0.037	7.05	100	26	40.9	108	2.19	222	1.83
	Yiwanwu (17)	2360	150	16	6	1210	2.40	0.76	17.6	0.195	7.60	0.263	0.530	0.033	4.24	150	4	2.58	75	2.69	321	2.15
	Hongqicha (18)	3100	125	44	11	451	1.93	1.21	17.6	0.168	7.48	0.096	0.254	0.022	5.87	90	52	10.6	40	0.38	442	17.3
	Caimohu (19)	ND	ND	ND	ND	712	1.96	1.04	18.0	0.142	7.82	0.107	0.286	0.020	1.85	50	44	21.9	60	1.34	102	1.23
Western Liangzi Lake (20)		980	169	26**	16**	6667	3.21	2.12	21.0	0.110	7.82	0.130	0.438	0.013	2.37	1120	60	70.7	24	0.86	84	0.06
	Mean	1960	138	59	25	563	2.42	1.75	18.4	0.269	7.97	0.157	0.399	0.016	3.17	1870	158	30.9	36	0.66	401	2.23
	CV	36	13	52	45	26	21	30	7	65	3	38	67	55	49	130	142	91	72	105	103	168

*Region code in the parentheses. **The yield record of this lake somewhat mixed with that of the neighbouring waters, and, thus, the CY and RR were excluded from the later analyses. SR, stocking rate of crab juveniles in ind ha^{-1}; BW, body weight of adult crabs in g ind^{-1}; CY, crab yield in kg ha^{-1}; RR, recapture rate in %; Area, ha; Z_M, mean depth in m; Z_{SD}, Secchi depth in m; T, temperature in °C; Cond, conductivity in mS cm^{-1}; NH_3–N, TN (Total nitrogen), TP (Total phosphorus), mg L^{-1}; Chl *a*, chlorophyll *a* in phytoplankton in μg L^{-1}; B, biomass in g m^{-2}; D, density in ind m^{-2}; $_{Mac}$, submersed macrophytes; $_{Gas}$, gastropods; $_{Oli}$, oligochaetes; $_{Ins}$, insects; ND, no data; CV, coefficient of variation in %.

into their prospective survival number of yearlings according to their survival rates (22.5%) (Zhu and Miao, 2003). In Region 11, 17,000 ind ha^{-1} megalops of about 0.007 g ind^{-1} were released in summer, 2002, but excluded from the calculation, since they were too small to be harvested in 2002. Crab adults were caught with the cage traps in autumn (Sep.–Nov.), 2002. The trap is called "Di Long" in Chinese (literally, "Ground Boxes"), which is an assembled series of rectangular boxes made of nettings, with one-way entrance for each discrete box but no exit.

The sizes of adult crabs from these regions were measured randomly from 16 regions during catch seasons. Carapace length and width were measured with vernier caliper (GB1214-85) and body weights with steelyard or electronic balance.

Environmental investigations were conducted during December, 2001–March, 2003. The sampling sites were evenly distributed in each region (Fig. 2). Submersed macrophyte biomass (B_{Mac}), water depth (Z_M), transparency (Z_{SD}) and water temperature (T) were measured monthly, while pH, conductivity (Cond), concentration of total nitrogen (TN), ammonium nitrogen (NH_3–N), total phosphorus (TP), chlorophyll-*a* in phytoplankton (Chl *a*) and standing crops of zoobenthos were determined seasonally in December, 2001–January, 2002, April, July, October, 2002 and January, 2003.

With regard to the sampling methods, submersed macrophytes were sampled by scythes 2–4 times at each site, then cleaned, rid of superfluous water and weighed for wet biomass. Zoobenthos were sampled with a modified Peterson sampler (1/16 m^2) and cleaned gently with a 425 μm sieve. Animals were sorted and preserved in 10% formalin for identification, counting and weighting. Z_M and Z_{SD} were measured by sounding lead and Secchi Disc respectively. pH and conductivity were measured in the field with YSI Environmental Monitoring Systems 6600. TN, NH_3–N, TP and Chl *a* were determined according to Chinese Water Analysis Methods Standards (Huang et al., 1999).

STATISTICA6.0 was used for one-way ANOVA, Pearson correlation, simple regression and stepwise multiple regression analyses.

3. Results and discussion

3.1. Crab populations and their environment

The average crab stocking rate (SR) in these waters during winter, 2001-spring, 2002 was 1960 (960–3100) ind ha^{-1}; the average crab yield (CY) in autumn, 2002 was 59 (16–111) kg ha^{-1} and the average recapture rate (RR) was 25% (6–40%) (Table 1). The adult crabs at harvest were mostly two-year old. Among the 512 adult crabs we measured, there were 244 males and 268 females. It conformed to the theoretical sex ratio of 1 : 1 ($\chi^2 = 1.25$, $0.5 > p > 0.25$). The results of ANOVA showed that the carapace length, width and body weights of males (6.8 ± 0.05 cm, 6.1 ± 0.05 cm, 150 ± 3.4 g) were all significantly greater than those of females (6.3 ± 0.04 cm, 5.6 ± 0.04 cm, 106 ± 1.9 g) ($p < 0.001$).

Table 1 also shows the annual data of the environmental parameters. To synchronize other parameters in time scale, the annual means of water depth (Z_M), Secchi depth (Z_{SD}), water temperature (T) and biomass of submersed macrophytes (B_{Mac}) were calculated with the data from those four months when the measurement of other factors were made, though we have successively measured them for thirteen months. According to the parameters, all these waters were meso-eutrophic macrophytic lakes.

3.2. Key factor affecting crab yield and driving variable of the models

Crab yield (CY) was correlated significantly positively with biomass of submersed macrophytes (B_{Mac}), Secchi depth (Z_{SD}), pH, gastropod density (D_{Gas}) and insect density (D_{Ins}), but negatively with total nitrogen (TN), chlorophyll *a* in phytoplankton (Chl *a*, near-significant), oligochaete density (D_{Oli}) and biomass (B_{Oli}) (Table 2 and Fig. 3B–F). However, there were no significant relationship between CY and crab stocking rate (SR) (Fig. 3A). According to the *r*-values, B_{Mac} is the most important factor affecting the variation of CY among these waters. The result of stepwise multiple regressions further indicates that B_{Mac} makes the greatest contribution to explain CY variation (Table 3). Therefore, B_{Mac} can be statistically considered as the key factor affecting crab yields.

In ecological sense, submersed macrophytes constitute an essential component of lake biocommunity. They may affect the life of Chinese mitten crab in many aspects, such as: 1) Submersed plants and their coexisting periphyton provide food for crabs; both of them are food resources of zoobenthos (e.g., gastropods and insects) and, thus, indirectly afford important food for Chinese mitten crab (Dvořák and Best, 1982; Ju and Shu, 1999; Jin et al., 2003; also evident from the positive correlations of B_{Mac}–D_{Gas} and B_{Mac}–D_{Ins} in Table 2). 2) Submersed macrophytes provide crabs with appropriate habitats, especially when molting, crabs may hide inside submersed vegetation to avoid predators or attack from other crabs (Pan, 2002).

Table 2

Pearson correlation coefficients (*r*, upper triangle) and probability levels (*p*, lower triangle) between parameters of crab populations and environment (*n* is 15 for BW and 18 for others)

	CY	BW	SR	Z_M	Z_{SD}	T	Cond	pH	TN	TP	Chl *a*	B_{Mac}	D_{Gas}	B_{Gas}	D_{Oli}	B_{Oli}	D_{Ins}	B_{Ins}
CY		−0.17	0.36	−0.37	**0.47**	−0.16	0.31	**0.68**	**−0.62**	−0.36	−0.45	**0.76**	**0.74**	0.03	**−0.48**	**−0.51**	**0.53**	−0.05
BW	0.57		0.02	0.35	0.05	**0.60**	−0.26	−0.04	0.43	0.00	0.07	−0.07	0.12	0.14	0.44	0.03	0.35	0.16
SR	0.14	0.94		−0.21	−0.05	0.03	−0.01	0.07	−0.26	−0.02	−0.11	0.35	0.33	−0.04	−0.14	−0.17	0.42	0.45
Z_M	0.14	0.22	0.41		**0.56**	**0.80**	−0.38	0.07	**0.66**	**−0.57**	−0.08	−0.24	−0.11	0.11	−0.39	−0.21	−0.17	−0.26
Z_{SD}	**0.05**	0.88	0.84	**0.01**		**0.62**	0.01	**0.68**	0.17	**−0.88**	**−0.56**	**0.49**	0.36	0.23	**−0.79**	**−0.74**	0.09	−0.30
T	0.53	**0.03**	0.90	**<0.001**	**0.004**		**−0.47**	0.14	**0.69**	**−0.54**	−0.28	0.01	−0.13	0.14	−0.30	−0.16	−0.19	−0.24
Cond	0.21	0.36	0.94	0.10	0.96	**0.04**		0.04	−0.36	0.00	−0.24	0.09	0.14	0.26	−0.05	−0.17	0.01	−0.07
pH	**0.002**	0.90	0.79	0.77	**0.001**	0.55	0.88		−0.22	**−0.53**	**−0.47**	**0.70**	**0.49**	−0.04	**−0.59**	**−0.56**	0.36	**−0.46**
TN	**0.007**	0.13	0.30	**0.001**	0.43	**<0.001**	0.12	0.35		−0.17	0.15	−0.28	−0.35	0.21	0.15	0.25	**−0.49**	−0.24
TP	0.14	1.00	0.95	**0.009**	**<0.001**	**0.01**	1.00	**0.02**	0.49		**0.48**	−0.28	−0.30	−0.24	**0.82**	**0.79**	0.01	0.19
Chl *a*	0.06	0.82	0.66	0.74	**0.01**	0.23	0.30	**0.04**	0.52	**0.03**		−0.34	−0.10	−0.14	0.40	0.37	−0.01	**0.45**
B_{Mac}	**<0.001**	0.81	0.15	0.31	**0.03**	0.97	0.71	**<0.001**	0.23	0.24	0.15		**0.68**	0.15	−0.38	−0.34	0.39	−0.17
D_{Gas}	**<0.001**	0.68	0.19	0.65	0.12	0.60	0.54	**0.03**	0.13	0.20	0.66	**0.001**		0.20	−0.26	−0.36	**0.69**	−0.05
B_{Gas}	0.90	0.64	0.87	0.63	0.34	0.55	0.27	0.88	0.39	0.31	0.53	0.52	0.40		0.00	−0.10	−0.33	−0.31
D_{Oli}	**0.04**	0.12	0.57	0.09	**<0.001**	0.20	0.85	**0.01**	0.54	**<0.001**	0.08	0.10	0.27	0.99		**0.81**	−0.04	0.04
B_{Oli}	**0.03**	0.91	0.50	0.37	**<0.001**	0.50	0.48	**0.01**	0.30	**<0.001**	0.11	0.14	0.12	0.66	<0.001		−0.26	−0.11
D_{Ins}	**0.02**	0.22	0.08	0.46	0.71	0.42	0.95	0.12	**0.03**	0.98	0.96	0.09	**0.001**	0.15	0.87	0.27		0.22
B_{Ins}	0.84	0.59	0.06	0.26	0.19	0.31	0.77	**0.04**	0.31	0.43	**0.04**	0.48	0.86	0.19	0.85	0.66	0.35	

Significant correlation ($p<0.05$) in bold. CY, crab yield; BW, body weights of adult crabs; SR, stocking rate of crab juveniles; Z_M, mean depth; Z_{SD}, Secchi depth; T, temperature; Cond, conductivity; TN, total nitrogen; TP, total phosphorus; Chl *a*, chlorophyll *a* in phytoplankton; *B*, biomass; *D*, density; $_{Mac}$, submersed macrophytes; $_{Gas}$, gastropods; $_{Oli}$, oligochaetes; $_{Ins}$, insects.

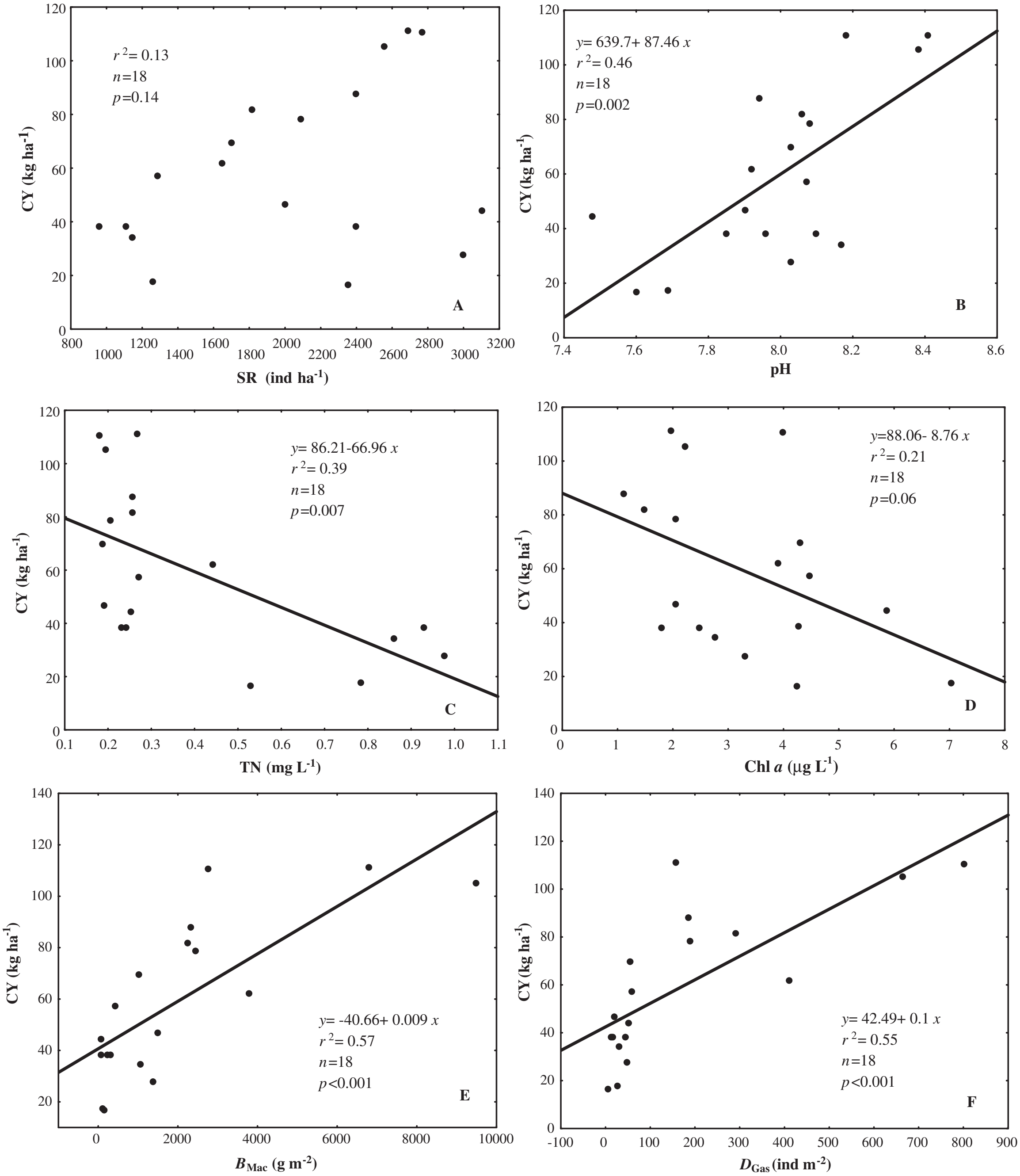

Fig. 3. Relationship between crab yield (CY) and stocking rate of crab juveniles (SR) (A), annual mean of pH (B), total nitrogen (TN) (C), chlorophyll *a* in phytoplankton (Chl *a*) (D), submersed macrophyte biomass (B_{Mac}) (E) and gastropod density (D_{Gas}) (F).

3) Submersed macrophytes also improve water quality and so crab quality. They regulate pH through metabolism and reduce phytoplankton densities (Chl *a*) to enhance water clarity (Z_{SD}) through a variety of mechanisms, such as shading, reduction of nutrient availability (e.g., TN and TP) and reduction of resuspension (Scheffer, 1998; also evident from the positive correlations of B_{Mac}–Z_{SD}, B_{Mac}–pH and negative correlations of B_{Mac}–TN, B_{Mac}–TP, B_{Mac}–Chl *a* in Table 2).

Although B_{Mac} is the key factor for the growth of Chinese mitten crab, it is an imperfect driving variable mainly due to the fact that B_{Mac} is difficult to be

Table 3
Stepwise multiple regression analyses using the data in Table 1

y-variable = CY, $n=18$					
Step	F	r^2	p	x-variable	Model
1	14.11	0.57	0.003	B_{Mac}	$y=46.22+0.009x$
2	9.24	0.77	0.01	TN	$y=78.59+0.007x_1-90.5x_2$

CY, crab yield in kg ha^{-1}; B_{Mac}, submersed macrophyte biomass in g m^{-2}; TN, total nitrogen in mg L^{-1}.

accurately measured. Aquatic plants are usually clumped in distribution so that many samples are needed. Various sampling equipments (e.g., scythes and clamps) could cause systematic errors. Water content in aquatic plants is rather high, so that great errors will occur in the determination of wet weight, and dry weight measurements are troublesome (Chapman, 1976). Inconsistent removal of roots, epiphytes and animals during samplings can affect the final results as well. Furthermore, the lack of necessary equipment and professionals in most farms aggravates the difficulties of B_{Mac} measurements. Therefore, we need to contrive a parameter that can be easily and accurately measured to act as the driving variable instead of B_{Mac}.

In our recent paper (Wang et al., 2005), we established a linear model based on the relationship between Z_{SD}/Z_M and B_{Mac} that yielded a high r^2 of 0.81. In the shallow lakes, Z_{SD}/Z_M can reflect the change of B_{Mac} in time; once macrophytes deteriorate, the rapid propagation of phytoplankton will immediately reduce the water clarity (see also Scheffer, 1998). In comparison with B_{Mac}, Z_{SD}/Z_M is easier to be accurately measured. In the regions of the present study, CV (coefficient of variation) of Z_{SD}/Z_M is only 28%, far lower than that of B_{Mac}, 130%. Moreover, for measuring Z_{SD}/Z_M, Secchi disk and sounding lead are enough, which can be easily obtained and operated by most farms, so that Z_{SD}/Z_M may be an ideal driving variable. After analyzing the simple correlation between CY and Z_{SD}/Z_M, we found that Z_{SD}/Z_M can statistically explain 71% of the CY variation. It is a great enhancement as compared to that of B_{Mac}, 57%. It further indicates that Z_{SD}/Z_M is a good driving variable for the generation of crab yield models.

3.3. Maximal yield models

In order to make our models more practical, we used mean Z_{SD}/Z_M during crab planting period (Dec.–May) as the driving variables instead of the annual mean. In February, neither field investigation nor crab stocking was conducted due to the holidays of Chinese New Year, so that our data for that period were actually obtained from four months. Accordingly, four regression models were generated (Table 4, Eqs. (1) (2) (3) (4)). For fear that the Z_{SD}/Z_M in a single month is not representative enough, six additional models were further generated based on mean data of Z_{SD}/Z_M of two months, three months and four months (Eq. (6)–(7), (8)–(9) and (10) in Table 4).

According to the equation from Håkanson and Boulion (2002), $r_r^2=1-0.66\ CV^2$ (where, CV is the coefficient of variation of y-variable), the theoretically highest

Table 4
Maximal yield models of Chinese mitten crab ($n=18$, $p<0.001$)

$CY_{Max}=b_0+b_1Z_{SD}/Z_M$				
No.	b_0 (±SE)	b_1 (±SE)	r^2	Time scale of Z_{SD}/Z_M
(1)	−21.37 (±18.07)	81.16 (±17.49)	0.61	Dec.–Jan. (one month)
(2)	−1.22 (±18.50)	63.9 (±17.57)	0.49	Mar. (one month)
(3)	−7.5 (±14.12)	94.56 (±18.84)	0.64	Apr. (one month)
(4)	−24.58 (±15.41)	104.31(±18.38)	0.70	May (one month)
(5)	−25.17 (±16.17)	85.26 (±15.71)	0.65	Dec.–Mar. (two months)
(6)	−16.01 (±12.77)	91.29 (±14.70)	0.71	Mar.–Apr. (two months)
(7)	−23.21 (±12.91)	109.26 (±16.34)	0.74	Apr.–May (two months)
(8)	−32.37 (±12.91)	103.18 (±13.98)	0.77	Dec.–Apr. (three months)
(9)	−24.72 (±12.63)	102.52 (±14.74)	0.75	Mar.–May (three months)
(10)	−36.60 (±12.13)	110.69 (±13.49)	0.81	Dec.–May (four months)

CY_{Max}, maximal crab yield in kg ha^{-1}; Z_{SD}/Z_M, ratio of Secchi depth to water depth.

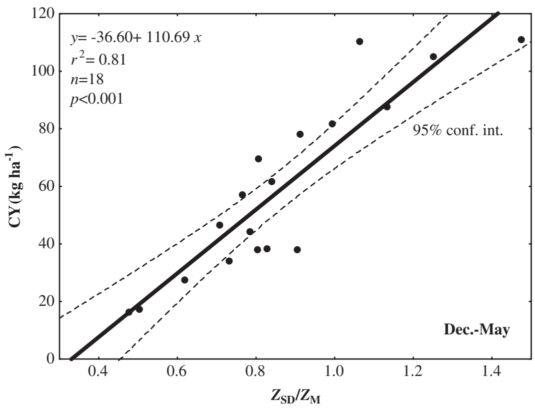

Fig. 4. Relationship between crab yield (CY) and mean ratio of Secchi depth to water depth (Z_{SD}/Z_M) of December–May.

reference r^2 for CY is 0.81. From Table 4, we may find out that all the r^2 of the models are high enough, especially that of Eq. (10) reaches the theoretically highest reference r^2 (Fig. 4).

It should be pointed out that the stocking rates of crab juveniles (SR) make little contribution to explain CY variation (Tables 1 and 2 and Fig. 3A). It means that crab juveniles have been over-stocked frequently so that stocking rate is no longer a factor closely correlated to crab yields. During the investigation, we found that great deterioration of submersed macrophytes occurred in almost all of the waters. The average B_{Mac} of the investigated regions declined from 3813 to 975 g m^{-2} during March, 2002–March, 2003, showing a 74% reduction. No other herbivore was stocked, and no great water level fluctuations appeared in these waters. Thus, the over-stocking of crabs should be responsible for the great vegetation deterioration. As the stocking is already over maximal, the above yield models can be regarded as the maximal yield models of the year.

3.4. Optimal-stocking model

For maximal sustainable production of Chinese mitten crab, we have to know the maximal sustainable production of their resources. According to the theory of MSY, when standing crop of a population reaches half of the carrying capacity, the instantaneous rate of increase reaches its maximal value (Larkin, 1977). Due to the fact that non-respiratory losses of submersed macrophytes are relatively small, their annual net production can be approximated as the maximal seasonal biomass (Håkanson and Boulion, 2002). Hence, we may assume that utilizing 50% of the production of the macrophytic community could achieve the maximal sustainable yield of crabs. In the maximal yield models, the maximal crab yields of a given year could result in resource exhaustion. Therefore, for maximal sustainable productions of Chinese mitten crab, the yield should keep at 50% of the maximal yield of the year. Accordingly, the optimal stocking rates ($\mathrm{SR_{Opt}}$, ind $\mathrm{ha^{-1}}$) can be estimated as follows:

$$\mathrm{SR_{Opt}} = (1000\mathrm{CY_{Max}} \times 50\%)/(\mathrm{BW}\cdot\mathrm{RR}) \qquad (11)$$

Where, $\mathrm{CY_{Max}}$ is the maximal crab yield of the year which can be predicted from models (1)–(10). 1000 is the dimensional adjustment of kg to g. BW is adult crab size (g $\mathrm{ind^{-1}}$) and RR is recapture rate (%).

Till now, we have generated ten maximal yield models and a general optimal-stocking model. In comparison to other inland fishery models, ours have the following characteristics: 1) $Z_{\mathrm{SD}}/Z_{\mathrm{M}}$, the driving variable, is easy to measure and can be conveniently used by producers. Contrarily, the variables in other models, such as standing crops of plankton or zoobenthos (Liang and Liu, 1995; Nissanka et al., 2000), are more difficult to obtain by ordinary users and, thus, have less practicability. 2) The optimal-stocking model is generated based on the driving variable, $Z_{\mathrm{SD}}/Z_{\mathrm{M}}$, during planting season, so that it provides practical references for juvenile stocking. Most other models, however, concentrate on yield predictions and their driving variables were obtained from a certain month (e.g., August) or harvesting time, without much help for animal stocking.

3.5. Applications and prospects

The maximal yield models and optimal-stocking model generated can be widely used in naturally eutrophic lakes in the mid-lower Yangtze Basin, where their morphogenesis, depths, bottoms, climate and even landscapes are similar. If these models are to be used in a water of other type or in other region, it is strongly recommended to calibrate the models according to the characters of local water or reanalyze the key factor.

Moreover, if our maximal yield models are put into practice, the users are recommended to collect Z_{M} and Z_{SD} from several months before crab planting, as it will obviously improve the predictive power of the models (cf. Table 4).

The optimal-stocking model is easily operated; only two additional parameters (BW and RR) are needed after getting $\mathrm{CY_{Max}}$. In the model, BW can be set within 100–200 g $\mathrm{ind^{-1}}$, depending on lake conditions and market demands. Here, we prefer using 150 g $\mathrm{ind^{-1}}$, a size capable of being achieved by farmers and favored by customers. RR is proposed to be 30%, which is calculated by us from the farms with relatively rich resources.

Based on the maximal yield estimates and using 150 g $\mathrm{ind^{-1}}$ for BW and 30% for RR, respectively, we calculated the optimal stocking rates of all research waters. The results show that the optimal stocking rates are 700 ± 60 ind $\mathrm{ha^{-1}}$.

Although our models have the advantages of simplicity and practicality, further tests are necessary to improve their precision and generality. Independent data set should still be collected to verify and calibrate our models, and a detailed analysis about factors that affect recapture rates is needed as well. We will also carry out a long-term monitoring on crab culture and resource changes in some farming waters so as to check whether producers are able to achieve sustainable development of Chinese mitten crab culture through the application of our models.

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