Selection of suitable predatory mites against, *Panonychus citri* (McGregor) (Acari: Tetranychidae) using relative control potential metrics and functional response

Muhammad Asif Qayyoum[1*], Zi-Wei Song[1], Bilal Saeed Khan[2], Muhammad Irfan Akram[3], Muhammad Zeeshan Shabbir[1], Izhar Hussain[4], Bao-Xin Zhang[1], Yuan Zheng[1] and Dun-Song Li[1]

Abstract

Background: Selection of suitable predators for the control of the spider mite, *Panonychus citri* is always a challenge due to the lack of their reliable predicted efficacy. In this laboratory study, biological control potential of *Neoseiulus californicus*, *N. cucumeris* and *Scapulaseius newsami,* against *P. citri* using the "Relative Control Potential" (RCP) metric to compare their efficacies was evaluated. The functional response type was determined at different prey densities (after 24 h).

Results: The type II functional responses were observed from all the tested predators feeding on 3 different life stages of *P. citri*, except *N. cucumeris,* which was fed only on eggs. All predatory mites preferred eggs of *P. citri* with a higher attack rate (1.397) in *N. cucumeris*, followed by *N. californicus* (1.238) and *S. newsami* (0.975). Handling time was also lower in *N. cucumeris* than other mites, with a trend as: for *N. cucumeris*, eggs > adults > immature stages; for *N. californicus*, immature stages > eggs > adults, while for *S. newsami*, eggs > immature stages > adults. The integration of greenhouse abundance and fecundity (%) data resulted in a higher RCP for *N. cucumeris* than other predators.

Conclusion: *Neoseiulus cucumeris* was selected as the most suitable predatory mite for the control of *P. citri* with a higher RCP and potential to maximum reproduction. *S. newsami,* which was used for the first time, gave almost similar results compared to *N. californicus* but with lower efficacy.

Keywords: *Panonychus citri*, Predatory mites, Attack's rate, Handling time, Fecundity, Abundance

Background

Most of the insect pest population is controlled by natural predators as a biological control strategy (Symondson et al. 2002). The selection of a suitable predatory species depends on its generalist characteristics (ability to feed on alternative prey/food sources) and break the pest population during colonization (Messelink et al. 2012). This selection of suitable predators was done by using functional response on prey densities and consumption (Solomon 1949), which allows for the estimation of maximum daily prey consumed or attacked by a predator by determining its stabilizing factor in the predator–prey population (Murdoch and Oaten 1975). The functional response resulted in a linear increase, decelerating increase to a plateau, sigmoid increase, and dome-shaped curves for type I, type II and type III (Trexler et al. 1988) and type IV, respectively based on the number of prey killed by a predator against total available preys (Pervez and Omkar 2005). Functional responses gave the predicted impact

---

*Correspondence: asifqayyoum@gmail.com
[1] Plant Protection Research Institute, Guangdong Academy of Agricultural Sciences, 7 Jinying Road, Tianhe District, Guangzhou 510640, China
Full list of author information is available at the end of the article

Qayyoum *et al. Egyptian Journal of Biological Pest Control* 2021, **31**(1):143

Page 2 of 9

of the predator on the prey densities (Dick et al. 2017). However, comparing two or more predators requires an estimation of their relative control potential (RCP) by using their attack rate as a functional response measure and fecundity as a numerical response measure to choose an efficient predator (Cuthbert et al. 2018).

Panonychus citri (McGregor), a citrus red mite, is a major pest in Asia. (Kennett et al. 1999) including southern China (Li et al. 1997). The motile stages (immature stages) and adults feed on cell content which leads to stippling symptoms. Severe infestation of *P. citri* leads to defoliation, fruit dropping, and dieback (Keetch 1968). Due to extensive chemical control, *P. citri* developed resistance and changes in its behavior against many acaricides (Qayyoum et al. 2021a, b). In addition to chemical control of *P. citri*, management cost is higher and difficult (hilly areas), which also may eliminate the role of its natural enemies. Recently, mainly Phytoseiidae and some other mite families used as biological control agents of different phytophagous mites (Cakmak et al. 2009). Among the phytoseiids, *Neoseiulus californicus* (McGregor) and *N. cucumeris* (Oudemans) are commonly used as an augmented biological control against different mite and insect pests (Mendel and Schausberger 2011). At the same time, *Scapulaseius newsami* (Evans) is commonly observed in the citrus or lemon fields of southern China (Song et al. 2019). *N. californicus* is a selective predator of tetranychid mites with type II functional response, while *N. cucumeris* and *S. newsami* are placed in the generalist phytoseiid mites with type III preferring other prey than spider mites (McMurtry et al. 2013). However, these predatory mites have different lifestyles from each other. For evaluating a predator's effectiveness, the functional response is widely used to predict potential biological control agents. For a better understanding the effectiveness of *N. californicus*, *N. cucumeris,* and *S. newsami*, the functional responses against different life stages of *P. citri* with their relative control potential (RCP) for comparison were evaluated under laboratory studies.

Methods
Mites' cultures
Neoseiulus californicus and *N. cucumeris* were obtained from a laboratory culture rearing on *Tetranychus urticae* Koch. and *Tyrophagus putrescentiae*. *S. newsami* and *P. citri were* collected from citrus/lemon orchards in 2019 and cultured for 6 months before starting the experiment. The predator–prey synchronizations were gained by rearing *N. californicus*, *N. cucumeris,* and *S. newsami* on *P. citri*. The eggs of predators were separated into new leaf (lemon) discs with enough prey mites to get same-aged adult females. All this rearing process was carried

out under controlled conditions with a temperature of 26 ± 1 °C, photoperiod of 16: 8 h (Light: Dark), and relative humidity of 75 ± 1%.

Experimental conditions and methodology
The experiment was performed using a lemon leaf disc (lower leaf surface up) (3.5 cm diameter) by placing it on a water-saturated sponge. All leaf discs were stripped with absorbent paper on their edges to prevent mites from escaping and retain moisture. Mites attached to the absorbent paper were not included in the study data. Each 4 tested units were considered one test group by placing into a plastic box (15 cm × 15 cm × 6.5 cm) and replicated 10 times (10 × 4). All plastic boxes were filled with water just below leaf discs and water was maintained regularly. All experimental procedure was done under controlled conditions as described above. Adult females (> 24 h old) were collected from the stock cultures and isolated from the colony before gaining maturity for uniform age. All collected females were allowed to mate with males for a period of 24 h. After mating, females were starved for 24 h before transferring to the experimental units. Injured or less moved females were excluded from the experiments.

Different densities of *P. citri* eggs were obtained from placing the 10–20 adults female on the lemon leaf discs and removed after 24 h under controlled conditions. The number of eggs was counted as per density by removing excess eggs. Immature densities were obtained by placing more than 50 adult females on the lemon leaf and allowing them to lay eggs for 5–7 h. before removing the adults. For further growth, the lemon leaf with eggs was placed under controlled conditions for further development. As soon as the immature stage (> 90% proto-nymph) was obtained, they were shifted to the experimental unit.

The selection of prey densities against the 3 predators (*N. californicus*, *N. cucumeris,* and *S. newsami*), a pre-consumption of immatures and adults of *P. citri* was carried out. The pre-densities selection test revealed that offering predators more than 200 and less than 4 motile stages of *P. citri* reduced their searching performance and reduced fecundity rate. A maximum of 160 and a lowest of 5 density of each stage was offered to the predator based on the pre-test data, as endorsed by Xiao and Fadamiro (2010).

A functional response experiment was performed using 6 densities (5, 10, 20, 40, 80, and 160) of eggs, immatures, and adults of *P. citri* by offering to a single female of *N. californicus*, *N. cucumeris,* and *S. newsami*. The prey eggs, immatures, and adults consumed by the predators were replaced by new ones during the experiment. Data

Qayyoum et al. Egyptian Journal of Biological Pest Control 2021, **31**(1):143

Page 3 of 9

of prey eaten and eggs laid by all predators were recorded after 24 h.

Statistical analysis

Data from functional responses are analyzed in 2 steps (Juliano 2001). In the first step, maximum likelihood estimates (intercept (P_0), linear (P_1), quadratic (P_2), and cubic (P_3) coefficients) were calculated, using a logistic regression/polynomial function by comparing the proportions of prey eaten to the initial density and resulted in functional response type.

$$N_e/N_0 = \exp(P_0+P_1N_0+P_2N_0^2+P_3N_0^3)/[1 + \exp(P_0+P_1N_0+P_2N_0^2+P_3N_0^3)]$$

where "N_e/N_o" is the prey consumption probability and "intercept (P_0), linear (P_1), quadratic (P_2), and cubic (P_3)" are regression coefficients. A significant functional negative and positive value of P_1, the predator gave functional response types II and III curve, respectively (Juliano 2001).

Since it accounts for prey loss per density, the non-linear least square regression was used in the second step to estimate handling time and attack rate coefficients.

$$N_e = N_0\{1 - \exp[\alpha(T_hN_e - T)]\}$$

where "Ne" stands for the number of prey killed, "N_o" stands for initial prey density, "T_h" stands for the handling time, and "T" stands for the total time given to the predator (24 h). The attack rate "α" and handling time "T_h" parameters were calculated using a nonlinear least-squares regression procedure.

Curve fitting using the polynomial equation and Holling's disc equation was performed using R (RCore-devlopment-team 2019). ANOVA analyzed the prey density-dependent effects on consumption and number of eggs laid by predators, and then the Tukey test was used to compare the results ($P=0.05$). The abundance data of the 3 predatory mites were obtained from a greenhouse augmented biological control experiment by releasing the predatory mites ($n=$ more than 50/plant) at the highest infestation of *P. citri* and other insect pests. Abundance data (Mean $\pm$ SE) from highest (predators released) to almost zero *P. citri* was used. The fecundity (%) of predators (per adult female) was calculated by using the below formula by feeding on different life stages of *P. citri*;

$$\text{Fecundity} = \left(\text{Eggs production}\middle/_{\text{prey consumed}}\right) \times 100$$

The relative control potential (RCP) was calculated to compare their efficacies based on a maximum feeding rate ($1/h$), as a result of their functional response and abundance of predator in greenhouse or fecundity (%) as calculated above. The RCP was calculated as below formula;

$$\text{RCP} = \left(\frac{\text{FR}_{(1/h)}\text{predator} - A}{\text{FR}_{(1/h)}\text{predator} - B}\right) \times \left(\frac{X \text{ predator} - A}{X \text{ predator} - B}\right)$$

where FR is the maximum feeding rate ($1/h$), and "X" is proxies for the responses (a measure of predator greenhouse abundance or fecundity of predator). If the value of RCP$=1$, no difference between the 2 predators; for RCP<1, predicted predator-A less efficient than predator-B, and RCP>1, predator-A is predicted as greater efficacy than predator-B. RCP indicating the predicted increase or decrease relative efficacy of predator-A compared to predator-B (Cuthbert et al. 2018).

Results

The prey's (*Panonychus citri*) survival rate varies depending on predator species, prey life stage, and density. Prey survival was a maximum in their adult stage at the highest density (160 prey) when fed by *N. californicus* and *S. newsami*, while for *N. cucumeris*, prey survival rate was higher at the immature stage (86.1%) (Table 1). Daily consumption rate of *N. cucumeris* was significantly higher than *N. californicus* and *S. newsami*. The prey consumption rate increased with an increase in prey density then decreased after attaining maximum consumption at the density of 80 prey. The daily consumption rate of all tested predators among densities and within the specific densities of all predatory mites were also observed highly significantly (Table 1). The consumption rate of all predatory mites against *P. citri* depended on density, life stage of prey, and interaction, as presented in Table 1. Fecundity rate of female *N. californicus* and *N. cucumeris* was increased with the increase of gradual level of prey density rather than prey consumption, except for *S. newsami* by feeding on immature stages and adults as presented in relationship expression between the rate of oviposition and density of prey (Table 2). Daily eggs laid by a female of *N. californicus* and *S. newsami* depended on prey density only, while *N. cucumeris* number of eggs laid in a day depended on prey-stage and density (Table 2).

The functional responses were observed from all predators fed on the 3 different life stages, with significant negative $P1$ or first-order terms, followed by significant negative $P2$ or second-order terms, except *N. cucumeris* fed on eggs of *P. citri* (weak type-II with non-significant negative $P1$). Attack rate increased significantly by feeding on adults > immatures > eggs by *N. californicus* and *S.*

Qayyoum *et al. Egyptian Journal of Biological Pest Control* 2021, **31**(1):143

Page 4 of 9

Table 1 Mean (± SE) consumption of three predatory mites at different densities of different stages of *P. citri*

Prey Stage	Prey density	*Neoseiulus californicus*	*Scapulaseius newsami*	*Neoseiulus cucumeris*	ANOVA
Adults	5	2.3 ± 0.260 dB	1.4 ± 0.163eC	3.2 ± 0.249eA	$df = 2,29$; $F\text{-}value = 15.51$; $P\text{-}value = 0.000$
	10	2.9 ± 0.233 dB	3.3 ± 0.213 dB	6.5 ± 0.269dA	$df = 2,29$; $F\text{-}value = 67.82$; $P\text{-}value = 0.000$
	20	4.6 ± 0.306cB	4.8 ± 0.291cB	9.5 ± 0.401cA	$df = 2,29$; $F\text{-}value = 68.08$; $P\text{-}value = 0.000$
	40	6 ± 0.298bB	6.3 ± 0.300bB	12.8 ± 0.533bA	$df = 2,29$; $F\text{-}value = 95.59$; $P\text{-}value = 0.000$
	80	8.8 ± 0.249aB	8.3 ± 0.335aB	16.2 ± 0.327aA	$df = 2,29$; $F\text{-}value = 208.85$; $P\text{-}value = 0.000$
	160	7.1 ± 0.277bB	7.1 ± 0.379abB	14.3 ± 0.367bA	$df = 2,29$; $F\text{-}value = 146.26$; $P\text{-}value = 0.000$
		$df = 5,59$; $F\text{-}value = 84.53$; $P\text{-}value = 0.000$	$df = 5,59$; $F\text{-}value = 77.99$; $P\text{-}value = 0.000$	$df = 5,59$; $F\text{-}value = 178.98$; $P\text{-}value = 0.000$	
Eggs	5	2.9 ± 0.277dA	3.6 ± 0.340dA	3 ± 0.258eA	$df = 2,29$; $F\text{-}value = 1.66$; $P\text{-}value = 0.209$
	10	5.7 ± 0.335cAB	5 ± 0.333 dB	6.5 ± 0.307dA	$df = 2,29$; $F\text{-}value = 5.32$; $P\text{-}value = 0.011$
	20	7.7 ± 0.367bB	7.4 ± 0.670cB	13.7 ± 0.496cA	$df = 2,29$; $F\text{-}value = 45.71$; $P\text{-}value = 0.000$
	40	10.7 ± 0.517aB	11.9 ± 0.586abB	16.3 ± 0.300bA	$df = 2,29$; $F\text{-}value = 37.20$; $P\text{-}value = 0.000$
	80	10.8 ± 0.512aC	13.9 ± 0.526aB	19.3 ± 0.300aA	$df = 2,29$; $F\text{-}value = 88.27$; $P\text{-}value = 0.000$
	160	8.3 ± 0.300bC	10.8 ± 0.727bB	15.2 ± 0.249bA	$df = 2,29$; $F\text{-}value = 53.75$; $P\text{-}value = 0.000$
		$df = 5,59$; $F\text{-}value = 58.53$; $P\text{-}value = 0.000$	$df = 5,59$; $F\text{-}value = 54.63$; $P\text{-}value = 0.000$	$df = 5,59$; $F\text{-}value = 361.53$; $P\text{-}value = 0.000$	
Immatures	5	1.9 ± 0.277eB	1.9 ± 0.233 dB	3.6 ± 0.340eA	$df = 2,29$; $F\text{-}value = 11.72$; $P\text{-}value = 0.000$
	10	4.5 ± 0.373 dB	4.4 ± 0.267cB	6 ± 0.298dA	$df = 2,29$; $F\text{-}value = 8.06$; $P\text{-}value = 0.002$
	20	5.8 ± 0.249cdB	5.4 ± 0.400cB	8.8 ± 0.416cA	$df = 2,29$; $F\text{-}value = 26.19$; $P\text{-}value = 0.000$
	40	6.5 ± 0.619cB	7.2 ± 0.359bB	13 ± 0.365bA	$df = 2,29$; $F\text{-}value = 59.16$; $P\text{-}value = 0.000$
	80	10.5 ± 0.500aB	8.9 ± 0.482aB	15.3 ± 0.517aA	$df = 2,29$; $F\text{-}value = 44.37$; $P\text{-}value = 0.000$
	160	8.6 ± 0.340bB	8.2 ± 0.573abB	13.9 ± 0.314abA	$df = 2,29$; $F\text{-}value = 55.90$; $P\text{-}value = 0.000$
		$df = 5,59$; $F\text{-}value = 53.56$; $P\text{-}value = 0.000$	$df = 5,59$; $F\text{-}value = 24.34$; $P\text{-}value = 0.000$	$df = 5,59$; $F\text{-}value = 151.25$; $P\text{-}value = 0.000$	

The means followed by different small letters in the table are significantly different ($P < 0.05$, Tukey's test) in the same column, the values followed by different capital letters in the table are significantly different ($P < 0.05$, Tukey's test) in the same line. The values are presented as mean ± SE

newsami, except for *N. cucumeris,* which trends as immatures > adults > eggs. The overall attack rate for *N. cucumeris* was significantly higher than the other two predatory mites (Table 3).

The Relative Control Potential (RCP) was calculated using the abundance data of the 3 predatory mites with a max. Feeding rate as presented in Table (4). *N. cucumeris* was much more abundant than *N. californicus* and *S. newsami*, resulting in greater RCP than both predators, as both functional response parameters were used (Table 4).

Overall, asymptotes (maximum feeding rate ($1/T_h$)) of functional response curve observed non- significant difference between *N. californicus* and *S. newsami,* but *N. cucumeris* maximum feeding rate was significantly different from other both species. There was a significant difference between the max. feeding rate in all life stages. The increase in max. feeding rate pattern varied within the species as: for *N. californicus,* adults > eggs > immatures; for *S. newsami,* adults > immatures > eggs and for *N. cucumeris,* immatures > adults > eggs (Table 5). By the

Qayyoum *et al. Egyptian Journal of Biological Pest Control* 2021, **31**(1):143

Page 5 of 9

Table 2 Mean (± SE) eggs laid by a female(three predatory mites) mites at different densities of different stages of *P. citri*

Prey Stage	Prey density	*Neoseiulus californicus*	*Scapulaseius newsami*	*Neoseiulus cucumeris*	ANOVA
Adults	5	0.1 ± 0.1aA	0 ± 0aA	0 ± 0cA	*df* = 2,29; *F-value* = 1.00; *P-value* = 0.381
	10	0.3 ± 0.153aA	0.1 ± 0.1aA	0.3 ± 0.153bcA	*df* = 2,29; *F-value* = 0.71; *P-value* = 0.503
	20	0.4 ± 0.163aA	0.2 ± 0.133aA	0.5 ± 0.167bcA	*df* = 2,29; *F-value* = 0.97; *P-value* = 0.392
	40	0.4 ± 0.163aA	0.4 ± 0.163aA	0.9 ± 0.180abA	*df* = 2,29; *F-value* = 2.92; *P-value* = 0.071
	80	0.5 ± 0.167aB	0.4 ± 0.163aB	1.3 ± 0.153aA	*df* = 2,29; *F-value* = 9.39; *P-value* = 0.001
	160	0.6 ± 0.163aB	0.4 ± 0.163aB	1.5 ± 0.167aA	*df* = 2,29; *F-value* = 12.70; *P-value* = 0.000
		df = 5,59; *F-value* = 1.26; *P-value* = 0.294	*df* = 5,59; *F-value* = 1.73; *P-value* = 0.144	*df* = 5,59; *F-value* = 15.31; *P-value* = 0.000	
Eggs	5	0.2 ± 0.133aA	0.1 ± 0.100aA	0.4 ± 0.163dA	*df* = 2,29; *F-value* = 1.29; *P-value* = 0.293
	10	0.5 ± 0.167aAB	0.1 ± 0.100aB	1.1 ± 0.277cdA	*df* = 2,29; *F-value* = 6.64; *P-value* = 0.005
	20	0.5 ± 0.167aB	0.2 ± 0.133aB	1.6 ± 0.163bcA	*df* = 2,29; *F-value* = 22.57; *P-value* = 0.000
	40	0.5 ± 0.167aB	0.6 ± 0.163aB	1.9 ± 0.180abcA	*df* = 2,29; *F-value* = 21.12; *P-value* = 0.000
	80	0.7 ± 0.153aB	0.6 ± 0.163aB	2.2 ± 0.200abA	*df* = 2,29; *F-value* = 26.78; *P-value* = 0.000
	160	0.8 ± 0.200aB	0.5 ± 0.167aB	2.5 ± 0.167aA	*df* = 2,29; *F-value* = 36.52; *P-value* = 0.000
		df = 5,59; *F-value* = 1.56; *P-value* = 0.188	*df* = 5,59; *F-value* = 2.98; *P-value* = 0.019	*df* = 5,59; *F-value* = 15.38; *P-value* = 0.000	
Immature	5	0.2 ± 0.133aA	0 ± 0.000aA	0.2 ± 0.133cA	*df* = 2,29; *F-value* = 1.12; *P-value* = 0.339
	10	0.4 ± 0.163aAB	0 ± 0.000aB	0.6 ± 0.163bcA	*df* = 2,29; *F-value* = 5.25; *P-value* = 0.012
	20	0.5 ± 0.167aB	0.2 ± 0.133aB	1.1 ± 0.180abA	*df* = 2,29; *F-value* = 8.10; *P-value* = 0.002
	40	0.4 ± 0.163aB	0.3 ± 0.153aB	1.3 ± 0.153aA	*df* = 2,29; *F-value* = 12.41; *P-value* = 0.000
	80	0.7 ± 0.153aB	0.4 ± 0.163aB	1.3 ± 0.153aA	*df* = 2,29; *F-value* = 8.59; *P-value* = 0.001
	160	0.8 ± 0.249aB	0.4 ± 0.163aB	1.6 ± 0.163aA	*df* = 2,29; *F-value* = 9.69; *P-value* = 0.001
		df = 5,59; *F-value* = 1.56; *P-value* = 0.187	*df* = 5,59; *F-value* = 2.14; *P-value* = 0.075	*df* = 5,59; *F-value* = 10.79; *P-value* = 0.000	

The means followed by different small letters in the table are significantly different (*P* < 0.05, Tukey's test) in the same column, the values followed by different capital letters in the table are significantly different (*P* < 0.05, Tukey's test) in the same line. The values are presented as mean ± SE

change in prey stage, the RCP of predators varied among each other and within prey-stage feeding (Table 5). Overall, *N. cucumeris* had a greater efficacy than *N. californicus* and *S. newsami*. In comparing *N. californicus* and *S. newsami*, *N. californicus* efficacy was greater than *S. newsami* by feeding on immatures of *P. citri,* followed by adults and eggs. In a comparison of *N. cucumeris* and *N. californicus*, *N. cucumeris* significantly showed a higher efficacy than *N. californicus* by feeding on the eggs of *P. citri,* followed by immatures and adults. While in comparison of *N. cucumeris* with *S. newsami*, resulted in higher efficacies than other comparisons, trend as; adults > eggs > immatures (Table 5). A significant difference between the predatory mites to response against prey consumption at different stages, with *N. cucumeris* exhibiting a higher predation efficacy by feeding on immatures (comparison with *S. newsami*) and eggs (comparison with *N. californicus*) was concluded. *N. cucumeris* was also observed consistently in its prey

Qayyoum *et al. Egyptian Journal of Biological Pest Control* 2021, **31**(1):143

Page 6 of 9

Table 3 Results of logistic regression to denote functional response type across predatory mites by feed on three life stages of *P. citri* using Holing's disc equation

Predator Species	Prey Stage	P1 (± SE)	t value	P value	a (h^{-1}) (± SE)	T$_h$ (h) (± SE)	AIC	T/T$_h$
N. californicus	Eggs	− 6.186e−02 (± 1.361e−02)	− 4.545	2.98e−05	1.238 (± 0.185) ***	0.091 (± 0.004) ***	241.594	263.736
	Immatures	− 4.971e−02 (± 1.640e−02)	− 3.031	0.00368	0.639 (± 0.088) ***	0.094 (± 0.005) ***	230.280	255.319
	Adults	− 9.008e−02 (± 1.580e−02)	− 5.700	4.65e−07	0.515 (± 0.059) ***	0.111 (± 0.005) ***	188.453	216.216
S. newsami	Eggs	− 9.445e−02 (± 1.774e−02)	− 5.324	1.85E−06	0.975 (± 0.139)***	0.070 (± 0.003)***	269.504	342.857
	Immatures	− 4.517e−02 (± 1.418e−02)	− 3.187	0.00235	0.675 (± 0.085)***	0.103 (± 0.004)***	208.841	233.009
	Adults	− 2.421e−02 (± 1.129e−02)	− 2.145	0.0363	0.518 (± 0.058)***	0.113 (± 0.004)***	183.015	212.389
N.cucumeris	[†]Eggs	− 8.079e−03 (± 1.307e−02)	− 0.618	0.5391	1.397 (± 0.157)***	0.049 (± 0.002)***	283.135	489.795
	Immatures	− 8.221e−02 (± 1.476e−02)	− 5.569	7.54E−07	1.0278 (± 0.083)***	0.059 (± 0.002)***	223.189	406.779
	Adults	− 6.375e−02 (± 1.148e−02)	− 5.553	8.00E−07	1.056 (± 0.084)***	0.057 (± 0.001)***	225.561	421.052

[†] Type-II response (weak) as it resulted innon-significant positive P1 followed by significant negative P2 which later convert into significant positive (P1 ± SE (−2.871e−02 ± 5.139e−03), *t*-value (− 5.588), P value (6.74E−07)) by reducing the complexity of polynomial regression. Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Table 4 Mean Relative Control Potential (RCP) using abundance mean per leaf (*n* = 6) (Additional file 1: Fig. S1), for *N. californicus, S. newsami,* and *N. cucumeris*, that the RCP output exceeds 1 using bootstrapped maximum feeding and attack rates

Predator A, Predator B comparison	FRs (1/T$_h$ (± SE))	Abundance (mean ± SE)	RCP	CIs (60%), P$_{RCP}$ > 1 (%)
N. californicus, S. newsami	10.131 (± 0.478), 10.862 (± 0.514)	2.850 (± 0.099), 1.783 (± 0.087)	1.497	1.383–1.608, 99.99 ***
N. cucumeris, N. californicus	18.163 (± 0.632), 10.131 (± 0.478)	4.033 (± 0.071), 2.850 (± 0.099)	2.545	2.393–2.694, 100 ***
N. cucumeris, S. newsami	18.163 (± 0.632), 10.862 (± 0.514)	4.033 (± 0.071), 1.783 (± 0.087)	3.701	3.457–3.939, 100 ***

RCP score is > 1 (* > 95%, ** > 99%, *** > 99.9%)

Table 5 Mean relative control potential (RCP) using fecundity (%) (Additional file 1: Table S1–3) across three life stages of *P. citri* for *N. californicus, S. newsami,* and *N. cucumeris*, that the RCP output exceeds 1 using bootstrapped maximum feeding and attack rates

Predator A, Predator B comparison	Prey stage	FRs (1/T$_h$ (± SE))	Fecundity (%)	RCP	CIs (60%), P$_{RCP}$ > 1 (%)
N. californicus, S. newsami	Eggs	10.924 (± 0.480), 14.129 (± 0.728)	0.072 (± 0.007), 0.036 (± 0.005)	1.58	1.351–1.795, 99.57 **
	Immatures	10.534 (± 0.555), 10.274 (± 0.564)	0.084 (± 0.007), 0.029 (± 0.009)	3.265	2.361–4.069, 99.97 ***
	Adults	8.935 (± 0.401), 8.834 (± 0.380)	0.074 (± 0.009), 0.041 (± 0.009)	1.917	1.495–2.301, 99.21 **
N. cucumeris, N. californicus	Eggs	20.074 (± 0.812), 10.924 (± 0.480)	0.136 (± 0.010), 0.072 (± 0.007)	3.511	3.103–3.899, 100 ***
	Immatures	16.904 (± 0.523), 9.624 (± 0.436)	0.097 (± 0.019), 0.084 (± 0.007)	2.046	1.663–2.401, 99.92 ***
	Adults	17.511 (± 0.535), 8.935 (± 0.401)	0.059 (± 0.015), 0.074 (± 0.009)	1.588	1.202–1.937, 93.22 *
N. cucumeris, S. newsami	Eggs	20.074 (± 0.812), 14.129 (± 0.728)	0.136 (± 0.010), 0.036 (± 0.005)	5.484	4.698–6.237, 100 ***
	Immatures	16.904 (± 0.523), 9.624 (± 0.436)	0.097 (± 0.019), 0.029 (± 0.009)	6.454	4.451–8.206, 99.99 ***
	Adults	17.511 (± 0.535), 8.834 (± 0.380)	0.059 (± 0.015), 0.041 (± 0.009)	2.995	2.125–3.752, 99.90 ***

RCP score is > 1 (* > 95%, ** > 99%, *** > 99.9%)

consumption response to different life stages (increase in movement) of *P. citri*.

Discussion

In biological control systems, phytoseiid predatory mites are considered effective biological control agents against different mites' species and insect pests (Gerson et al. 2003). Many attempts have been made to predict predatory mite efficacy, using functional and numerical responses to various population density levels (Teodoro et al. 2020). However, considering the functional response, these efforts

to predict predatory mites/natural enemies' efficacy/ consumption are insufficient (per capita effects) (Fernández-arhex and Corley 2003) and numerical response (population responses) (Dick et al. 2017) who used the RCP metric by combining both responses (functional and numerical), which gave more accurate predictive and explanatory results of biological control agents (invasive) with population reduction of target species (prey). Furthermore, RCP also efficiently integrated the dependencies associated with a change in environmental/ habitat conditions (Laverty et al. 2015) and food preference, for strong

Qayyoum et al. Egyptian Journal of Biological Pest Control 2021, **31**(1):143

Page 7 of 9

predator–prey interactions. This study presents the new RCP metric, which compares efficacy among predatory mites using per capita, population responses, and food preferences to predict change in their efficacies.

The functional responses of all predatory mites species exhibited the type-II by giving significant negative $P1$, which the consumption increased with the increase of prey availability and started to decline after gaining maximum peak as previously reported by Song et al. (2019) for *N. cucumeris* and *N. californicus* against *Tetranychus urticae*. At the same time, *N. cucumeris* exhibited a weak functional response type-II by offering eggs of *P. citri* (non-significant negative $P1$). The predators with functional response type-III are known as effective biological control agents (Pervez and Omkar 2005), but most of the predators showed type-II (Xiao and Fadamiro 2010) wrong arranged. *S. newsami* was identified as a dominant and efficient predator species from the citrus growing region of Southern China (Guangdong Province) during the highest infestation of *P. citri* (Song et al. 2019) with type-II functional responses similar to *N. californicus* (Table 3). In contrast, *S. newsami* was placed with functional response type-III (living on glabrous leaves) by McMurtry et al. (2013) due to habitat preferences, not prey consumption ability.

Here, RCP resulted in *S. newsami* with least efficient biological control agent than others which explained that other factors (like: environmental and alternative food source) involved in the expected availability of *S. newsami* in the citrus or lemon fields in China (Song et al. 2019). The change in prey life stage was shown to mediate changes to functional responses of all predatory mites. *N. cucumeris* was found more efficient than other predatory mites against *P. citri* with a higher RCP, integrated with fecundity (%) and field abundance as previously reported by Zheng et al. (2017) against *T. urticae*. The usages of abundance and fecundity estimate how predator–prey interaction strong (numerical response proxy) and their reproduction ability when introduced, respectively. *N. cucumeris* gave a higher RCP by feeding on eggs and immatures than *N. californicus* and *S. newsami*, respectively. The attack rate parameters revealed the efficacy of predators. The consumption rate of *N. cucumeris* was significantly higher than *N. californicus* and *S. newsami* due to increased metabolic demand. In contrast to Zhang et al. (2001), *N. cucumeris* by converting *P. citri* energy to maximum ($2 \times$ than Zhang et al. 2001) eggs production in this study. This can explain that even *N. cucumeris* was not associated with *P. citri*, but maximum potential against *P. citri* with a higher reproductive turnover than other predatory mites.

Obtained results on the preference of prey-stage profound effective on pre-predator interactions. All predatory mites preferred eggs of *P. citri* due to an effortless approach with more nutritional values (Ebrahim et al. 2014). In contrast, previously reported that *N. californicus* preferred active larval/nymphal stages (immature stages) of *T. urticae* (Zheng et al. 2017), *T. cinnabarinus* (*T. cinnabarinus* is a junior synonym of *T. urticae*) (Li et al. 2014), and *P. citri* (Xiao and Fadamiro 2010). These variations in preference within predatory species may be due to genetic diversity, experimental conditions, prey density differences, and rearing technology of both prey and predator. The above comparison of obtained results mostly with *Tetranychus* spp. as prey (Popov and Kondryakov 2008) suggested that the predacious ability may change with change in prey species. There was a slighter difference in fecundity rate of all 3 predatory mites by feeding on eggs of *P. citri* compared to immatures and adults (Table 2), which resulted in non-significant dependency on the prey life stage, except for *N. cucumeris* (Table 1). These results explained that nutritional level had no impact on the *N. californicus* and *S. newsami* with the same profitability, while in the case of *N. cucumeris,* a maximum nutritional intact with a maximum output (reproduction).

Conclusions

In conclusion, using the RCP metric provides a successful explanation and prediction of predators /invasive species for the selection of the best biocontrol agent. Overall, change in prey stage will induce change in predation ability of predatory mites towards *P. citri*. *N. cucumeris* was the most suitable predatory mite for the control of *P. citri* with a higher RCP and potential to maximum reproduction. *S. newsami* used for the first time gave almost similar results compared to *N. californicus* with less efficacy. The addition of environmental variations and prey responses will be more helpful to get better RCP for the selection of biocontrol agents as a future consideration.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41938-021-00489-0.

Additional file 1. Figure S1: Prey consumption and eggs laid responses of N. californicus, S. newsami, and N. cucumeris, and their relationship between prey density and rate of oviposition by feeding on three different life stages of P. citri over the 24 h experimental duration.

Qayyoum *et al. Egyptian Journal of Biological Pest Control* 2021, **31**(1):143

Page 8 of 9

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not Applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Plant Protection Research Institute, Guangdong Academy of Agricultural Sciences, 7 Jinying Road, Tianhe District, Guangzhou 510640, China. [2]Department of Entomology, Faculty of Agriculture, University of Agriculture, Faisalabad 38040, Punjab, Pakistan. [3]Department of Entomology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan. [4]Department of Plant Breeding and Genetics, The University of Haripur, Haripur, KPK, Pakistan.

References
Cakmak I, Janssen A, Sabelis MW, Baspinar H (2009) Biological control of an acarine pest by single and multiple natural enemies. Biol Control 50:60–65

Cuthbert RN, Dick JT, Callaghan A, Dickey JW (2018) Biological control agent selection under environmental change using functional responses, abundances and fecundities; the Relative Control Potential (RCP) metric. Biol Control 121:50–57

Dick JT et al (2017) Invader Relative Impact Potential: a new metric to understand and predict the ecological impacts of existing, emerging and future invasive alien species. J Appl Ecol 54:1259–1267

Ebrahim A, Abdallah A, Halawa A (2014) Potential of *Neoseiulus californicus* (Mc-Gregor) as a biocontrol agent of *Panonychus citri* (Mc-Gregor) (Phytoseiidae-Tetranychidae). J Egypt Soc Acarol 8:13–17. https://doi.org/10.21608/ajesa.2014.4903

Fernández-arhex V, Corley JC (2003) The functional response of parasitoids and its implications for biological control. Biocontrol Sci Technol 13:403–413. https://doi.org/10.1080/0958315031000104523

Gerson U, Smiley RL, Ochoa R (2003) Mites (Acari) for pest control, vol 558. Wiley, London

Juliano SA (2001) Nonlinear curve fitting: predation and functional response curves. In: Cheiner SM, Gurven J (eds) Design and analysis of ecological experiments, 2nd edn. Oxford University Press, New York, pp 178–196

Keetch DP (1968) Some aspects of the ecology of the citrus red mite, *Panonychus citri* (McGregor), in the eastern cape province. Ph.D. Thesis, Rhodes University

Kennett C, McMurtry JA, Beardsley J (1999) Biological control in subtropical and tropical crops. In: Bellows TS, Fischer TW (eds) Handbook of biological control. Academic Press, San Diego, CA, pp 713–742

Laverty C, Dick JT, Alexander ME, Lucy FE (2015) Differential ecological impacts of invader and native predatory freshwater amphipods under environmental change are revealed by comparative functional responses. Biol Invasions 17:1761–1770

Li L, Wang R, Waterhouse DF (1997) The distribution and importance of arthropod pests and weeds of agriculture and forestry plantations in southern China. ACIAR Monograph 46. Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia

Li Q, Cui Q, Jiang C, Wang H, Yang Q (2014) Control efficacy of Chinese *Neoseiulus californicus* (McGregor) population on *Tetranychus cinnabarinus* (Boisduval). Acta Phytophylacica Sin 41:257–262

McMurtry JA, de Moraes GJ, Sourassou NF (2013) Revision of the lifestyles of phytoseiid mites (Acari: Phytoseiidae). Syst Appl Acarol 18:297–320. https://doi.org/10.11158/saa.18.4.1

Mendel D, Schausberger P (2011) Diet-dependent intraguild predation between the predatory mites *Neoseiulus californicus* and *Neoseiulus cucumeris*. J Appl Entomol 135:311–319

Messelink GJ, Sabelis MW, Janssen A (2012) Generalist predators, food web complexities and biological pest control in greenhouse crops. In: Larramendy ML, Soloneski S (eds) Integrated pest management and pest control-current and future tactics. InTech, Rijeka, pp 191–214

Murdoch WW, Oaten A (1975) Predation and population stability. Adv Ecol Res 9:1–131. https://doi.org/10.1016/S0065-2504(08)60288-3

Pervez A, Omkar (2005) Functional responses of coccinellid predators: an illustration of a logistic approach. J Insect Sci 5. https://doi.org/10.1093/jis/5.1.5

Popov SY, Kondryakov A (2008) Reproductive tables of predatory phytoseiid mites (*Phytoseiulus persimilis*, *Galendromus occidentalis*, and *Neoseiulus cucumeris*). Entomol Rev 88:658–665

Qayyoum MA, Song ZW, Zhang BX, Li DS (2021a) Dispersal Mechanism Assessment for Panonychus citri (Acari: Tetranychidae) Secondary Outbreaks. Ann Entomol Soc Am 114(4):501–510

Qayyoum MA, Song Z-W, Zhang B-X, Li D-S, Khan BS (2021b) Behavioral response of *Panonychus citri* (McGregor) (Acari: Tetranychidae) to synthetic chemicals and oils. Peer J 9:e10899. https://doi.org/10.7717/peerj.10899

RCore-devlopment-team (2019) R: a language and environment for statistical computing, R x64 4.0.3 edn. R Foundation for Statistical Computing, Vienna, Austria

Solomon M (1949) The natural control of animal populations. J Anim Ecol 18:1–35

Song Z-W, Fang XD, Zhang B-X, Li D-S (2019) Pilot study of the population dynamics of predatory mites and pest leaf mites in citron-lemon orchards Chinese. J Appl Entomol 56:766–771. https://doi.org/10.7679/j.issn.2095-1353.2019.089

Symondson W, Sunderland K, Greenstone M (2002) Can generalist predators be effective biocontrol agents? Annu Rev Entomol 47:561–594

Teodoro AV, de Oliveira NNFC, Galvão AS, de Sena Filho JG, Pinto-Zevallos DM (2020) Interference of plant fixed oils on predation and reproduction of *Neoseiulus baraki* (Acari: Phytoseiidae) feeding on *Aceria guerreronis* (Acari: Eriophyidae). Biol Control 143:104204. https://doi.org/10.1016/j.biocontrol.2020.104204

Trexler JC, McCulloch CE, Travis J (1988) How can the functional reponse best be determined? Oecologia 76:206–214

Xiao Y, Fadamiro HY (2010) Functional responses and prey-stage preferences of three species of predacious mites (Acari: Phytoseiidae) on citrus red

Qayyoum *et al. Egyptian Journal of Biological Pest Control* 2021, **31**(1):143

Page 9 of 9

mite, *Panonychus citri* (Acari: Tetranychidae). Biol Control 53:345–352. https://doi.org/10.1016/j.biocontrol.2010.03.001

Zhang Y-XX, Zhang Z-QQ, Chen C-PP, Lin J-ZZ, Chen X (2001) *Amblyseius cucumeris* (Acari: Phytoseiidae) as a biocontrol agent against *Panonychus citri* (Acari: Tetranychidae) on citrus in China. Syst Appl Acarol 6:35. https://doi.org/10.11158/saa.6.1.6

Zheng Y, Patrick DC, Song Z-W, Dun-Song L, Bao-Xin Z (2017) Functional response of two *Neoseiulus* species preying on *Tetranychus urticae* Koch. Syst Appl Acarol 22:1059–1069. https://doi.org/10.11158/saa.22.7.13

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.