

Predator- and killed prey-induced fears bear significant cost to an invasive spider mite: Implications in pest management

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Abstract

BACKGROUND: The success of biological control using predators is normally assumed to be achieved through direct predation. Yet it is largely unknown how the predator- and killed prey-induced stress to prey may contribute to biological control effectiveness. Here, we investigate variations in life-history traits and offspring fitness of the spider mite *Tetranychus ludeni* in response to cues from the predatory mite *Phytoseiulus persimilis* and killed *T. ludeni*, providing knowledge for evaluation of the nonconsumptive contribution to the biological control of *T. ludeni* and for future development of novel spider mite control measures using these cues.

RESULTS: Cues from predators and killed prey shortened longevity by 23–25% and oviposition period by 35–40%, and reduced fecundity by 31–37% in *T. ludeni* females. These cues significantly reduced the intrinsic rate of increase (r_m) and net population growth rate (R_0), and extended time to double the population size (D_t). Predator cues significantly delayed lifetime production of daughters. Mothers exposed to predator cues laid significantly smaller eggs and their offspring developed significantly more slowly but these eggs had significantly higher hatch rate.

CONCLUSION: Predator- and killed prey-induced fears significantly lower the fitness of *T. ludeni*, suggesting that these nonconsumptive effects can contribute to the effectiveness of biological control to a great extent. Our study provides critical information for evaluation of biological control effectiveness using predators and paves the way for identification of chemical odors from the predator and killed prey, and development of new materials and methods for the control of spider mite pests.

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1 INTRODUCTION

Predator–prey interactions affect the life-history traits and behavioral strategies of species involved,^{1–4} resulting in demographic changes in these species.⁵ Plant-feeding mites can detect predation risk through chemical cues from predators and killed conspecifics, and respond accordingly.^{6–18} Buchanan *et al.*¹⁹ suggested that the risk cues affect both behavioral and physiological traits in prey but have stronger impacts on behavioral traits. For example, spider mites tend to stay away from the areas with predator cues,^{20,21} aggregate more tightly in such areas,²² change locomotion activity,⁹ or shift their oviposition site from leaf surface to their webs.^{23,24}

Predation risk incurs trade-offs between risk avoidance and other life functions in prey,^{25,26} altering their life-history traits,^{13,16,23,27–32} and reducing their fitness and population size.^{19,33} These nonconsumptive impacts on prey by predation risk may be transgenerational,^{32,34,35} can affect more individuals compared to the consumptive impacts,³⁶ and have influence at least as strong as direct predation on prey population dynamics.^{19,37–40} For example, predation risk lowers spider mites' fecundity,^{34,41} shortens their adult lifespan,³⁴ and prolongs their

offspring development.^{34,42} Furthermore, shift of oviposition from leaf surface to webs in response to predation risk results in higher egg mortality due to wind and rain.⁴³

Application of predatory mites for biological control is a well-established method against spider mite pests around the world, with *Phytoseiulus persimilis* Athias-Henriot (Acari: Phytoseiidae) being the most used predator for the control of the serious invasive pest, *Tetranychus urticae* Koch (Acari: Tetranychidae).^{44–48} These reports mainly evaluated the effectiveness of biological control based on the relationship between the release of *P. persimilis* and population size changes of *T. urticae*, assuming that the spider mite population decline is caused by direct

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predation. However, nonconsumptive effects of predators on prey fitness and forage may also contribute to pest biological control but have been rarely evaluated.^{49,50} Two recent reports shed some light on this matter using insect⁵¹ and mammal⁵² predator-prey systems, respectively. The former indicated that predator cues can significantly reduce pest fitness and suppress pest population, and the latter shows that these cues can repel the pest. To date, little is known about whether the predator- and killed prey-induced fears could enhance the effectiveness of spider mite biological control and help develop novel pest control measures for this important group of plant pests.

Tetranychus ludeni Zacher (Acari: Tetranychidae) is an important invasive spider mite pest that is native to Europe and now occurs in all continents except Antarctica.^{53,54} It attacks over 300 hosts, including many economically important crops such as bean *Phaseolus vulgaris* L. (Fabales: Fabaceae), eggplant *Solanum melongena* L. (Solanales: Solanaceae), cotton rose *Hibiscus mutabilis* L. (Malvales: Malvaceae), China rose *H. rosa-sinensis* L., apple *Malus domestica* Borkh (Rosales: Rosaceae), pumpkin *Cucurbita pepo* L. (Cucurbitales: Cucurbitaceae), and many other cucurbitaceous plants, causing significant economic losses.^{53,55} Gotoh *et al.*⁵⁶ suggested that *T. ludeni* could replace *T. urticae* to become a major crop pest in the world. Yet, biological control of *T. ludeni* using predatory mites is still poorly understood and knowledge about the effect of predator- and killed prey-induced stress on its fitness is lacking. The limited studies on *T. ludeni* biological control so far have mainly focused on the predators from the genus *Neoseiulus* (Acari: Phytoseiidae).^{57–59} However, Escudero and Ferragut,⁶⁰ and Zhang⁶¹ showed that *P. persimilis* performs similarly well on both *T. ludeni* and *T. urticae*, suggesting that this predatory mite can also control *T. ludeni* effectively.

In the present study, we aimed to evaluate how cues from *P. persimilis* and killed *T. ludeni* affected the life-history traits and offspring performance of *T. ludeni* females. We exposed mated adult females of *T. ludeni* to these cues throughout their life and recorded their longevity, and offspring production and fitness. We then analyzed the changes in their life-history traits and calculated life table parameters. This study generated critical information about nonconsumptive effects by predation risk on prey population regulations, offering the first knowledge for evaluation of nonconsumptive contribution to the biological control of *T. ludeni* and for development of novel spider mite control measures using predator cues.

2 MATERIALS AND METHODS

2.1 Environmental conditions

Mite colonies were maintained and all experiments were conducted at 25 ± 1 °C and 50–70% relative humidity with a photoperiod of 16 h light:8 h dark.

2.2 *T. ludeni* colony and experimental mites

T. ludeni were reared on approximately 20 potted kidney bean plants (*Phaseolus vulgaris* L.) in an environmental room of the Massey University Entomology and IPM Laboratory in Palmerston North, New Zealand. Every fortnight we replaced 10 of the oldest plants with new ones. We cut the leaves of the old plants and placed them on the top of the new plants, allowing mites to move to the latter.

To obtain 1-day-old mated adult females for experiment, we randomly took deutonymph females from the colony and introduced them onto a bean leaf disc (3 × 3 cm, 30 individuals per leaf

disc) placed on a water-saturated cotton pad in a Petri dish (5.5 cm diameter × 1.0 cm height) until they developed to adult stage. Immediately after adult emergence we transferred 20 of those females and five males randomly taken from the colony onto a new leaf disc in a Petri dish and allowed them to stay together for 24 h before being used for experiment.

2.3 *P. persimilis* colony and experimental mites

We obtained the predatory mite *P. persimilis* from Bioforce Ltd, New Zealand, and reared them on four potted kidney bean plants heavily infested with *T. ludeni* in the laboratory. We replaced the two oldest plants with new ones every 3 days and allowed mites to migrate as above. The predatory mite colony was maintained in a metal framed cage (120 cm length × 60 cm height × 60 cm width) with transparent mica plastic and fine woven wire mesh walls (0.25 × 0.25 mm aperture) in a separate environmental room.

2.4 Effect of predatory and killed conspecific cues on life history traits of *T. ludeni*

To assess how maternal stress induced by predators and injured conspecifics affected the life history traits of *T. ludeni*, we exposed 1-day-old mated adult females to three different types of cues: (i) bean leaf disc with trace of predators, (ii) bean leaf disc with killed conspecifics, and (iii) clean bean leaf disc (control with neither predator nor killed conspecific cues). Each treatment had 20 replicates. Predator trace consists of metabolic waste products, eggs, and footprints left by the predators on the leaf surface.³⁰ For each replicate in treatment (i), we randomly selected five adult female predators from the colony and transferred them onto a bean leaf disc (2 × 2 cm) placed on a water-saturated cotton pad in a Petri dish (14 cm diameter × 1.5 cm height). Twenty-four hours later,³⁰ we removed the predator adults and redundant eggs, ensuring two predator eggs remained on the leaf disc. If the number of eggs on the disc was fewer than two, we transferred predator egg(s) onto the disc from a separate leaf disc (3 × 3 cm). We maintained two eggs on each disc to keep predator cues consistent in all replicates. For treatment (ii), we randomly collected four adult females of *T. ludeni* from the colony and transferred them to a leaf disc. We then killed them with an insect pin and left their bodies on the leaf disc.⁹ We used an insect pin instead of a predator to obtain killed *T. ludeni* for two reasons: (i) we aimed to test predator cue and killed prey cue separately, and examine the relative impact of these two cues on the spider mite's life-history traits (see Results), and (ii) *T. ludeni* killed by predators would bear cues from both predators and killed prey, making it impossible to evaluate the relative effect of each cue.

In each replicate, we released a 1-day-old mated adult female of *T. ludeni* to the middle of a leaf disc, bearing either predator cues, killed conspecifics, or none of these, placed on a water-saturated cotton pad in a Petri dish, and allowed it to stay on the leaf disc for 24 h. We then transferred the mite to a new leaf disc with the same cues daily until death. We recorded oviposition period (from the first to last eggs laid), daily fecundity (the number of eggs produced per day), lifetime fecundity (total number of eggs produced), and adult lifespan (from emergence to death). We randomly selected two eggs laid by each female daily and measured their diameter under a stereomicroscope (Leica MZ12, Wetzlar, Germany) connected to a digital camera (Olympus SC30, Tokyo, Japan), using imaging software (CellSens GS-ST-V1.7; Tokyo, Olympus). We calculated the egg size as volume = $4/3\pi r^3$, where r is the radius (= diameter/2). We reared all eggs laid by *T. ludeni* each day on their original leaf disc

[predator eggs in treatment (i) were removed]. We allowed eggs laid on each leaf disc to hatch and then transferred mites to a fresh and clean leaf disc without any predators' cues and replaced the leaf disc once every 5 days until the mites developed to adults. We checked all leaf discs daily and recorded the number of eggs hatched, number and sex of emerged adults, and developmental time from egg to adult stage. We calculated the life table parameters⁶² for each treatment using the above data (see Statistical analysis below).

2.5 Statistical analysis

All data were analyzed using SAS 9.4 with a rejection level set at $\alpha < 0.05$. Data on adult survival were compared using a Wilcoxon test (LIFETEST procedure). Data on the $\ln(x)$ -transformed oviposition period, fecundity, and adult emergence rate were normally distributed (Shapiro–Wilk test, UNIVARIATE procedure) and thus analyzed using ANOVA (GLM procedure) followed by a Tukey test for multiple comparisons. A generalized linear model (GLIMMIX procedure) was applied to compare the difference in egg size, egg hatch rate, and offspring developmental period, with a log function and gamma distribution for egg size and egg hatch rate and a Poisson distribution for developmental time after the model. Multiple comparisons between treatments were performed using the Tukey test.

We modified an exponential functional model⁶³ to fit the data on the cumulative proportion of daughters produced over female age (NLIN Procedure), i.e. cumulative proportion of daughters = $a \times \exp(b \times \text{age})$, where a is a constant and b is the increase rate of cumulation. The difference in b was compared between socio-environmental cues according to Julious⁶⁴: if the 95% confidence limits (CLs) overlap, then there is no significant difference.

We calculated the intrinsic rate of increase (r_m , daughters/female/day) by solving the Lotka–Euler equation, $\sum e^{-r_m x} l_x m_x = 1$, where x is the female pivotal age, l_x is the proportion of females surviving to age x , and m_x is the number of daughters produced per female at age x . We also calculated other life table parameters, including the net reproductive rate ($R_0 = \sum l_x m_x$, daughters/female/generation), mean generation time [$T = \log_e(R_0)/r_m$, days], and doubling time [$Dt = \log_e(2)/r_m$, days]. We used the bootstrap method^{65,66} with 50 000 bootstrap samples to calculate

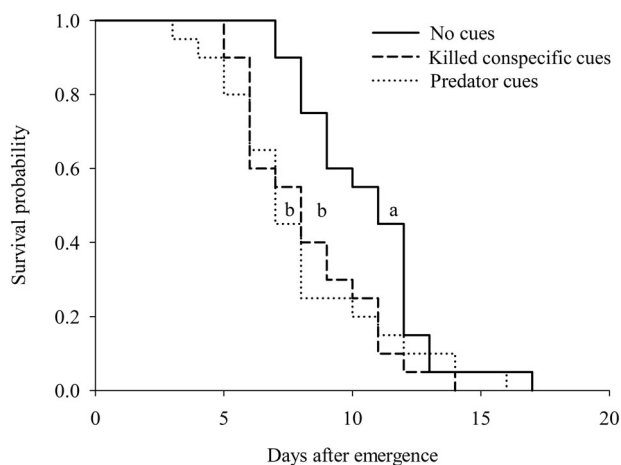


Figure 1. Survival probability of *Tetranychus ludeni* in response to no cues, killed conspecific cues, and predator cues. Lines with the same letters are not significantly different ($P > 0.05$).

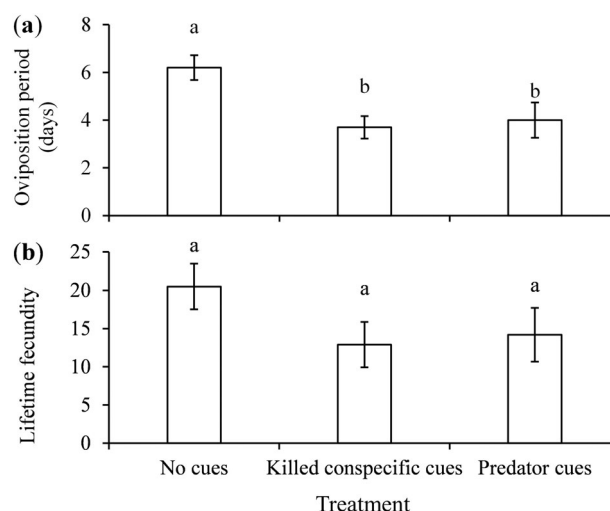


Figure 2. Mean (\pm SE) oviposition period (a) and lifetime fecundity (b) of *Tetranychus ludeni* females in response to no cues, killed conspecific cues, and predator cues. Columns with the same letters are not significantly different ($P > 0.05$).

the pseudo-values of a given parameter and employed the paired-bootstrap test^{67–69} for multiple comparisons between any two cues (TTEST Procedure). The significance was determined according to the 95% t -based CLs, i.e. if 0 is not within the 95% CLs, the mean difference between the two cue treatments is significantly different.

3 RESULTS

3.1 Effect of predation risks on adult survival, fecundity, and daughter production

Females exposed to killed conspecific or predator cues died significantly earlier than the control ($\chi^2_2 = 11.06$, $P = 0.0040$; Fig. 1). Exposure to killed conspecific or predator cues significantly shortened the oviposition period ($F_{2,55} = 5.60$, $P = 0.0061$; Fig. 2(a)) and marginally reduced lifetime fecundity ($F_{2,55} = 3.03$, $P = 0.0566$; Fig. 2(b)). Predator cues resulted in significantly slower increase of cumulative daughter production compared to control (non-overlapping 95% CLs) (Fig. 3 and Table S1). Killed conspecific cues also caused slow-down of cumulative daughter production to

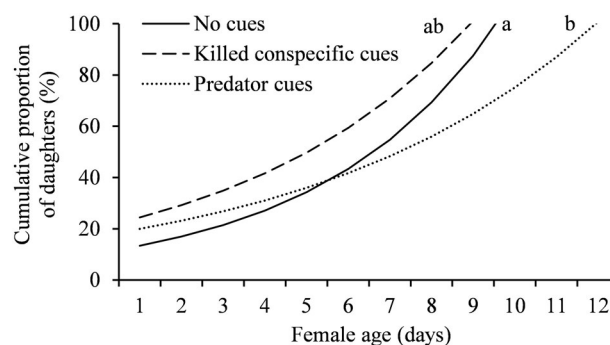


Figure 3. Cumulative proportion of daughters produced by *Tetranychus ludeni* females in response to no cues, killed conspecific cues, and predator cues. Lines with the same letters are not significantly different (overlapping 95% confidence limits).

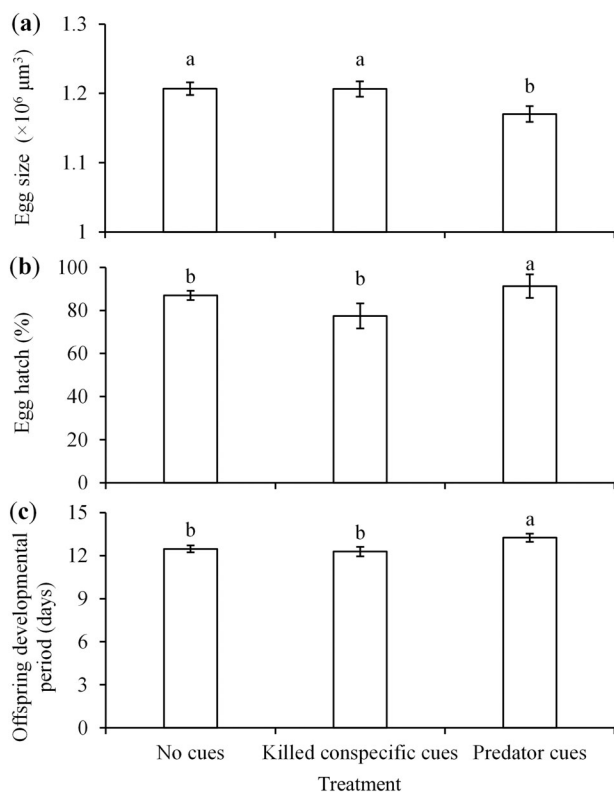


Figure 4. Effect of mothers' exposure to no cues, killed conspecific cues, and predator cues on mean (\pm SE) egg size (a), egg hatch rate (b), and offspring developmental period (c) in *Tetranychus ludeni*. Columns with the same letters are not significantly different ($P > 0.05$).

some extent but this effect was not significantly different from that of control (overlapping 95% CLs) (Fig. 3 and Table S1).

3.2 Effect of predation risks on offspring fitness

Eggs laid by mothers exposed to predator cues were significantly smaller than those laid by mothers exposed to either killed conspecific or no cues ($F_{2,451} = 3.68, P = 0.0260$; Fig. 4(a)). After mothers were exposed to predator cues, the hatch rate of their eggs was significantly higher than that of other treatments ($F_{2,53} = 4.25, P = 0.0194$; Fig. 4(b)). Furthermore, the developmental time of immatures produced by mothers exposed to predator cues was significantly longer than that of other treatments ($F_{2,280} = 3.08, P = 0.0475$; Fig. 4(c)).

3.3 Effect of predation risks on life table parameters

As shown in Table 1, females exposed to killed conspecific and predator cues had significantly lower intrinsic rate of increase (r_m) and net population growth rate (R_0), and required significantly longer time to double the population size (Dt). Females had significantly longer generation time (T) after exposed to predator cues and significantly shorter generation time after exposed to conspecific cues (Table 1).

4 DISCUSSION

In the present study, we demonstrate that cues from predatory mite *P. persimilis* and killed spider mite *T. ludeni* shortened the longevity of *T. ludeni* females by 25% and 23%, respectively (Fig. 1). These findings suggest that in addition to direct predation, the nonconsumptive mortality caused by cues from both predators and killed prey can substantially reduce the spider mites' feeding time and thus damage to crops. The earlier prey death induced by these cues could be attributed to various factors, such as the energetic costs of natural enemy avoidance,²⁶ decrease of foraging rate or food intake,^{12,35,70} and increase of oxidative damage.⁷¹ Furthermore, predator cues may affect prey through physiological pathways by inducing stress hormones to divert its resource allocation to other physiological process that may translate into lower survivorship.^{72,73}

Clinchy *et al.*⁷⁴ suggested that the presence of predators could induce sustained stress in prey and compromise their reproductive fitness. We show that fears induced by cues from predators and killed conspecifics lowered reproductive outputs and population growth in *T. ludeni*. For example, these cues shortened the oviposition period by 35–40% (Fig. 2(a)) and reduced fecundity by 31–37% (Fig. 2(b)). As shown in Fig. 3, cues from predators but not killed *T. ludeni* slowed down lifetime daughter production. Furthermore, predation risk reduced intrinsic rate of increase (r_m) and net population growth rate (R_0), and extended time to double the population size (Dt) (Table 1). These results suggest that predator- and killed conspecifics-induced stress can help suppress pest population growth by reducing their reproductive outputs and delaying production of daughters. Our results support the notion that the nonconsumptive impacts on prey may be as strong as direct consumption.³⁷ Similarly, in response to predator cues, both oviposition period^{34,75} and fecundity^{75–78} significantly decline in *T. urticae* and several other prey species.

The present study partially supports previous reports that non-consumptive impacts of predation risk on prey are transgenerational.^{32,34,35} We found that *T. ludeni* mothers exposed to

Table 1. Mean (\pm SE) intrinsic rate of increase (r_m), net reproductive rate (R_0), generation time (T), and doubling time (Dt) of *Tetranychus ludeni* in response to no cues, killed conspecific cues, and predator cues

Cue	r_m	R_0	T	Dt
No cues (No)	0.1002 \pm 0.0004 a	5.04 \pm 0.04 a	16.15 \pm 0.07 b	6.92 \pm 0.03 b
Killed conspecific (Kil.)	0.0828 \pm 0.0014 b	3.35 \pm 0.06 c	14.58 \pm 0.14 c	8.42 \pm 0.15 a
Predator (Pred.)	0.0852 \pm 0.0010 b	4.20 \pm 0.06 b	16.84 \pm 0.14 a	8.16 \pm 0.10 a
95% CLs (No vs Kil.)	0.0144–0.0204	1.56–1.83	1.25–1.89	–1.81–1.19
95% CLs (No vs Pred.)	0.0128–0.0172	0.13–0.25	–0.10–0.39	–1.44–1.04
95% CLs (Kil. vs Pred.)	–0.0059–0.0011	0.19–0.37	–2.65–1.87	–0.09–0.62

Estimated values in columns followed by different letters are significantly different. For each parameter, 95% confidence limits (CLs) >0 or <0 indicate a significant difference between treatments.

predator cues laid significantly smaller eggs (Fig. 4(a)) and their offspring had a significantly longer developmental period (Fig. 4(c)) as compared to other treatments. Smaller eggs may result in smaller adults which may have lower reproductive fitness^{79,80} but prolonged developmental time may help gain more body mass.^{81,82} Moreover, eggs laid by mothers exposed to predator cues had significantly higher hatch rate than those in other treatments (Fig. 4(b)). These results suggest that *T. ludeni* juveniles can somewhat compensate for egg mass loss caused by their mothers' experience in predation risk. The present study did not find any evidence that mothers' experience of killed prey cues could influence their offspring fitness (Fig. 4). Taken together, the impact of predation risk on offspring fitness appears to be weaker than on their mothers' fitness, and its contribution to pest population suppression could be less significant. However, in the presence of predation risk, *T. kanzawai* females shift their oviposition from leaf surface to webs, resulting in higher egg mortality due to wind and rain.⁴³ This could increase offspring mortality further in *T. ludeni*, which is worth testing in the future.

We suggest that the nonconsumptive effects reported in this study may play a critical role in biological control using predators and should be considered for the evaluation of total *T. ludeni* population suppression by *P. persimilis*. After the release of predators in the field, cues from both predators and killed prey should coexist. However, it is not yet known whether they have synergistic or additive impacts on prey mortality and reproductive fitness because these two cues were tested separately in the present study. Further investigations into their combined effects on prey are thus warranted. In addition, recent reports show that chemical cues from predators can be used for insect⁵¹ and rodent⁵² pest management. These studies have laid new foundations for future research on novel pest control materials and methods for spider mite and other plant pests. For example, future studies can involve extraction of odors released by *P. persimilis* and killed prey, identification of key compounds in these odors, and tests of the effects of individual and combined compounds on prey behavior and fitness, and plant damage.

5 CONCLUSION

T. ludeni females exposed to cues from predatory mite *P. persimilis* and killed *T. ludeni* have significantly higher mortality, lower reproductive fitness, and slower population growth. In addition to predation, these nonconsumptive effects on the spider mite can make a major contribution to the effectiveness of its biological control using predators. The transgenerational impact of the predation risk appears to be weaker and its contribution to pest population suppression could be less significant. Identification and tests of chemical odors from the predator and killed prey may have high potential for the development of novel materials and methods for the control of spider mite and other plant pests.

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AUTHORS' CONTRIBUTION

DR, XZH, and QW conceived and designed the study. DR collected the data. All authors contributed to data analysis and manuscript preparation.

CONFLICT OF INTEREST DECLARATION

The authors declare they have no conflict of interest.

SUPPLEMENTARY INFORMATION

The supplementary material may be found at online version.

AVAILABILITY OF DATA AND MATERIAL

The datasets from the current study are available from the corresponding author on request.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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