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Research Paper

Rapid evolution of life history of two water fleas in response to inter-specific competition*

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Abstract Interspecific competition drives ecological niche partitioning, biodiversity maintenance, and social structure evolution, yet empirical evidence for its role in rapid evolution remains limited. We examined whether competitive pressures could accelerate life history divergence in two zooplankton species, *Ceriodaphnia cornuta* and *Moina micrura*, using an experimental evolution approach. Under controlled competitive conditions, the life-history traits (survival, fecundity, and body size) were tracked in newborns over 10-d intervals across generations. *C. cornuta*, the dominant competitor in monocultures and mixtures, responded to competition by accelerating neonate maturation, reducing neonate body size, thereby reinforcing its ecological dominance. Conversely, subordinate *M. micrura* delayed first reproduction and reduced adult body size to conserve resources under competitive stress. Crucially, competition induced rapid life history divergence between the species, with both employing reproductive trade-offs and morphological plasticity. This study provided direct experimental evidence for rapid evolution driven by competition, and elucidated a potential mechanism by which evolutionary processes may maintain ecological equilibrium.

Keyword: competitiveness; interaction; life history; experimental selection; rapid evolution; ecological process

1 INTRODUCTION

Life histories represent dynamic adaptive strategies for species in response to natural selection; growth and reproduction strategies of species are shaped by the interplay between environmental pressures and genetic constraints (Beladjal et al., 2003). At the core of this interaction lies the fact that life history traits themselves exhibit heritable variation and are regulated by quantitative genetic architecture, such as genetic correlations (Dingle and Hegmann, 1982). For example, cladocerans respond to abrupt environmental changes by altering their reproductive modes (Piraino et al., 1996). Deciphering how species adjust their life history strategies in response to abrupt environmental perturbations, such as urbanization, is critical for predicting ecological responses and conserving biodiversity (Lambrinos, 2004; Shine, 2005). Climate change, biological invasions, and environmental pollution frequently induce reduction in body size in organisms, as

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elevated mortality rates of larger individuals are observed under these anthropogenic stressors (Esin et al., 2020; González-Delgado et al., 2023; Zhang et al., 2023). This form of size-selective mortality fundamentally represents directed selection acting on quantitative traits. It not only reduces population density but also rapidly alters population-related genetic structures, thereby driving adaptive evolution of life history traits (Dingle and Hegmann, 1982; Ives, 1995). Analogous selective pressures arise in reproductive strategies, where thermal extremes (both colder and hotter) and photoperiodic shifts can precipitate phenological shifts in reproductive timing and fecundity schedules (Loosanoff and Davis, 1951; Wilbor and Hans, 1956; Warren et al., 2012). Among the multifactorial stressors driving life-history evolution, predation risk, and resource competition emerge as key biotic drivers, complementing the well-established roles of abiotic environmental changes (Ball and Baker, 1996; Bouskila et al., 1998; Bassar et al., 2016; Grainger and Levine, 2022). Understanding how these multifactorial pressures jointly mold the genetic architecture of life-history traits is crucial for predicting long-term evolutionary trajectories (Dingle and Hegmann, 1982).

Interspecific competition shapes community dynamics through the dual mechanisms of direct interference competition and competitive exclusion. The size-efficiency hypothesis demonstrates that short-term resource competition and long-term adaptive evolution synergistically underpin fundamental ecological and evolutionary processes. As a central mechanism structuring community assembly and regulating ecosystem functioning, interspecific competition has historically underpinned pivotal biological theories, including modern coexistence theory and metacommunity dynamics (Crombie, 1947; Hsu et al., 1981; Damas-Moreira et al., 2020). Competition modulates population growth through resource limitation, manifesting as a zero-sum game that can drive competitive exclusion (Goldberg and Barton, 1992; Loreau et al., 2001). The size-efficiency hypothesis posits that large individuals secure direct resource monopolization via competitive dominance, whereas small individuals gain indirect advantages through enhanced metabolic efficiency and niche exploitation (Dodson, 1974). While contemporary studies primarily address short-term physiological or behavioral responses to competitive pressures, the evolutionary mechanisms driving rapid adaptive divergence under prolonged selection remain poorly characterized (Aschehoug et al., 2016; Ghoul and Mitri, 2016; Adler et al., 2018). Notably, these reciprocal eco-evolutionary feedbacks, where evolutionary changes reshape ecological interactions and vice versa, constitute a fundamental driver of adaptive diversification in biological networks (Thompson, 1998).

Experimental evolution directly observes real-time evolutionary processes in populations under controlled laboratory conditions and reveals the evolutionary mechanisms by integrating phylogenetic analyses, genomic variation data, and other approaches (Kawecki et al., 2012). While traditional evolutionary research primarily examines historical patterns, experimental evolution elucidates the interplay between adaptive mutations and natural selection in real-time evolutionary dynamics (Soong and Venkatesh, 2006; Agrawal et al., 2009). This approach is increasingly employed to study adaptive evolution and test evolutionary hypotheses (Garland and Kelly, 2006; Preisser and Elkinton, 2008; Balfour et al., 2015). Notable breakthroughs have been achieved through experimental evolution across multiple fields: the evolution of citrate utilization in *Escherichia coli* has elucidated the dynamics of mutation accumulation (Blount et al., 2008); reduced body size and accelerated yolk protein synthesis during thermal adaptation in *Drosophila* have revealed evolutionary strategies involving gene copy number expansion (Bettencourt et al., 1999); the fitness cost of antibiotic resistance in *Pseudomonas aeruginosa* has demonstrated energy allocation trade-offs (Crompton et al., 2010); and a 40-generation coevolutionary arms race between the CRISPR-Cas system of *Pseudomonas fluorescens* and bacteriophage anti-CRISPR proteins has dynamically illustrated the Red Queen hypothesis (Paterson et al., 2010). These laboratory-based microevolutionary systems capture the fundamental mechanisms of natural selection-driven biological evolution. By precisely controlling environmental variables (e.g., resource fluctuations, predation pressure), monitoring population dynamics in real-time, and integrating multi-omics data, experimental evolution facilitates the transition from phenotypic observation to causal mechanistic analysis.

In this study, we used two freshwater filter-feeding zooplankton species to investigate whether interspecific competition drives rapid evolution of life-history traits and how such evolutionary changes reciprocally affect competitive outcomes. To this end, we integrated population dynamics experiments with life table experiments. The former reveals macro-level phenomena arising from competitive interactions at the population level, while the latter dissects their underlying life history mechanisms at the individual level. Together, these experiments systematically address the causes and consequences of competitive fitness, progressing from observing phenomena to elucidating mechanisms. Each species was subjected to long-term experimental evolution under noncompetitive and competitive conditions, respectively. Throughout the experiment, replicate lineages were periodically sampled for demographic analysis using life table experiments to quantify temporal changes in life-history traits. To test the hypothesis that competitive selection induces adaptive evolutionary responses, we contrasted life-history parameters (e.g., age at maturity, fecundity schedules) between ancestral controls and evolved populations under competitive versus non-competitive conditions.

2 MATERIAL AND METHOD

2.1 Collection and culture of organism

In August 2021, zooplankton samples were collected using a 64-μm mesh plankton net from Shangyi Pond (31°01′38″N, 121°26′52″E), East China Normal University campus, Shanghai, China. The collected cladocerans were examined under a stereomicroscope and identified to be dominated by two species: *Ceriodaphnia cornuta* and *Moina micrura*. In subtropical regions, these two cladoceran species have been observed as long-term dominant species, and their distribution is documented as extremely widespread (Hong et al., 2004; Forró et al., 2008; Zhang et al., 2022). Furthermore, the detection of large quantities of dormant eggs from both organisms in lake sediments has been documented across multiple years, indicating a persistent competitive relationship between them (Murugan, 1975; Zhang and Jiang, 2022). Representative individuals of these species were selected for a 120-d laboratory acclimation and cultivation experiment. The experiment was conducted in 5-L aquaria containing 4.8 L of aerated and aged tap water. Incubation conditions were maintained at a temperature of 25±1 °C and a 16-h∶8-h light∶dark photoperiod (Chen et al., 2015), approximating the average conditions of Shangyi Pond in August.

Before the experiment start, the green alga *Chlorella pyrenoidosa* Chick (FACHB-15) was cultured daily as the food source for zooplankton. The algae were obtained from the Freshwater Algae Culture Collection at the Institute of Hydrobiology (FACHB-collection), Chinese Academy of Sciences, and were grown in BG-11 medium at 25±1 °C under a 12-h∶12-h light∶dark photoperiod (Chen et al., 2015). A standardized algal food concentration of 500-μg C/L was provided daily to each 5-L aquarium (Chen et al., 2015). The medium in the experimental tanks was replaced weekly with fresh BG-11 medium prepared according to the same.

2.2 Selection experiment

Our experiments included three zooplankton treatment combinations: two monospecific cultures (40 neonates of *Ceriodaphnia cornuta* or *Moina micrura* per 1 000-mL beaker) and one mixed-species culture (40 neonates of each species mixed in 1 000-mL beakers) (Jiang et al., 2014). All treatments were replicated four times (Fig.1). The start date was designated as day 0 (Fig.1). Cultures were maintained in a constant-temperature incubator at 25±1 °C (Jiang et al., 2014). Each beaker contained 1 000 mL of culture medium, with 50% medium renewal performed daily throughout the experimental duration (Burns, 2000). In comparison with *Ceriodaphnia cornuta* or *Moina micrura*, this space is adequately large to eliminate mortality caused by insufficient space (Feniova et al., 2025). Zooplankton densities were quantified every 4 d from day 4 to 40 (Fig.1). On day 4, all surviving individuals were counted due to low population sizes. Subsequently, 50% of the medium volume was examined on day 8, and 20% was examined from day 12 to 40. Population growth curves were constructed using per-liter survival counts of each species across treatments. These data were fitted to logistic growth and Gaussian growth models to characterize demographic trajectories (Eberhardt and Breiwick, 2012).

2.3 Life table experiment

From each experimental replicate, 12 neonates were selected within 24 h of birth on days 0, 10, 20, and 30 of the selection experiment (Jiang et al., 2014). Daily monitoring included counts of surviving adults (N_x) and newly hatched neonates (F_x) (Lampert and Trubetskova, 1996). The age at maturity was recorded for all individuals, and digital images were captured of the first clutch of offspring upon reaching reproductive maturity (Jiang et al., 2013). After the experiment, imaging was performed on the surviving parental individuals from the life

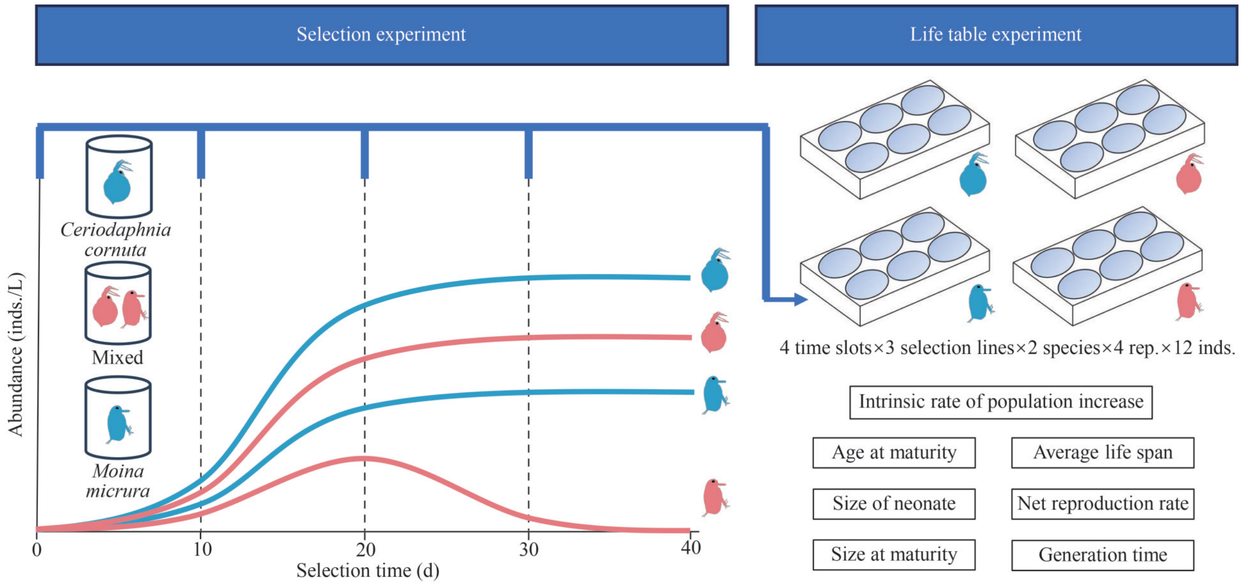

Fig.1 Schematic diagram of the study design

Ceriodaphnia cornuta and *Moina micrura* underwent a 40-d selection experiment in separate or mixed environments (blue/red). Newborn individuals were sampled from both environments every 10 d for life history monitoring. Survival, reproductive output, maturation time, and morphological characteristics were recorded.

table experiment. The collected morphometric data included: age at maturity, neonates body length, adult body length (for both species), neonate tail spine's length, and adult tail spine's length of *C. cornuta* (Fig.1) (Jiang et al., 2013). Culturing conditions maintained a 25±1-°C constant-temperature environment using 6-well culture plates (17-mL total volume per well) containing 500-μg C/L *Chlorella pyrenoidosa*. Each well received 10 mL of medium with 50% daily renewal. The experimental period spanned 10 d (Gehrs and Robertson, 1975).

2.4 Data analysis

Demographic parameters, such as the initial population size (N), the number of survivors at day x (N_x), age at maturity, and the number of new births at day x (F_x), fecundity (m_x), survival probability (l_x), average life span (L), net reproductive rate (R_0), generation time (T), and intrinsic rate of population increase (r) were calculated for each species via the analysis of life table experimental data collected on days 0, 10, 20, and 30. Data visualization was performed using GraphPad Prism 7. All demographic metrics were computed using the following standardized equations (Lampert and Trubetskova, 1996):

fecundity: $m_x=F_x/N_x$,
survival probability: $l_x=N_x/N$,
average life span: $L=\Sigma l_x$,
net reproduction rate: $R_0=\Sigma l_x\cdot m_x$,
generation time: $T=(\Sigma l_x\cdot m_x\cdot x)/R_0$.

The r of each population was determined iteratively by the Euler-Lotka equation: $1=\int e^{-rx}\cdot l_x\cdot m_x\cdot \mathrm{d}x$, where l_x is the proportion of survival at day x, and m_x is the number of neonates produced at day x (Lampert and Trubetskova, 1996).

Following the plotting of the count data spanning from day 0 to 40 in the selection experiment, GraphPad Prism 7 was employed to fit a logistic curve or a Gaussian curve, and the environmental carrying capacity value or peak was subsequently extracted. In the life-table experiment, the number of survivors at day x (N_x) was transformed into percentages to construct the survivorship curve. The number of new births at day x (F_x) was directly plotted to derive the fecundity curve. Statistical analysis was performed using IBM SPSS Statistics 24.0 software. To address the repeated-measures data, linear-mixed effects models were utilized to analyze the impacts of species, environment, and time on population size, fecundity, survival probability, average life span, net reproductive rate, generation time, intrinsic rate of population increase, age at maturity, and body length. Parameters were estimated via restricted maximum likelihood. The significance level for all statistical analyses was set at $\alpha=0.05$, and Type III sums of squares were used for fixed-effect tests.

3 RESULT

3.1 Selection experiment

Post-experimental analysis indicated distinct population dynamics for the two study species (Fig.2). Competitive interactions imposed negative density-dependent effects on both taxa. *Ceriodaphnia cornuta* exhibited lower population densities than *Moina micrura* during the initial 12-d period, after which its abundance exceeded that of *M. micrura*. Both species reached peak population densities approximately between day 20 and 24. In terms of asymptotic population sizes, *C. cornuta* demonstrated significantly higher carrying capacity compared to *M. micrura* (linear mixed-effects model, df=176.000, *F*=117.042, *P*<0.001; Fig.2). Peak densities across treatments revealed significant competitive suppression in both species (df=176.000, *F*=53.265, *P*<0.001; Fig.2).

3.2 Life table experiment

Analysis of age-specific survivorship curves demonstrated that, for both species during the initial 30 d of the selection experiment, despite the data at day 20 showed fluctuations compared to day 0, survival rates in both the control and mixed groups

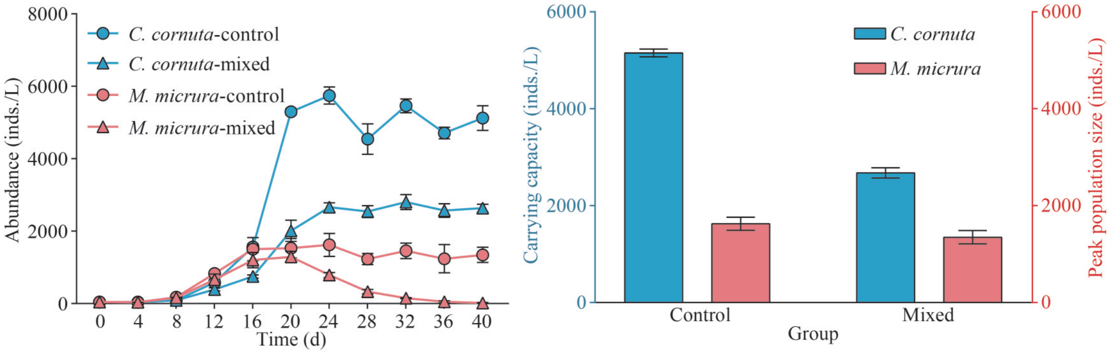

Fig.2 Population dynamics of the two species with peaks after fitting the growth model

Left: 40-d population abundance of *Ceriodaphnia cornuta* (blue) and *Moina micrura* (magenta) in the control groups (circle) and mixed groups (triangle); right: carrying capacity of *C. cornuta* (derived from the logistic curve) and peak population size of *M. micrura* (derived from the Gaussian curve).

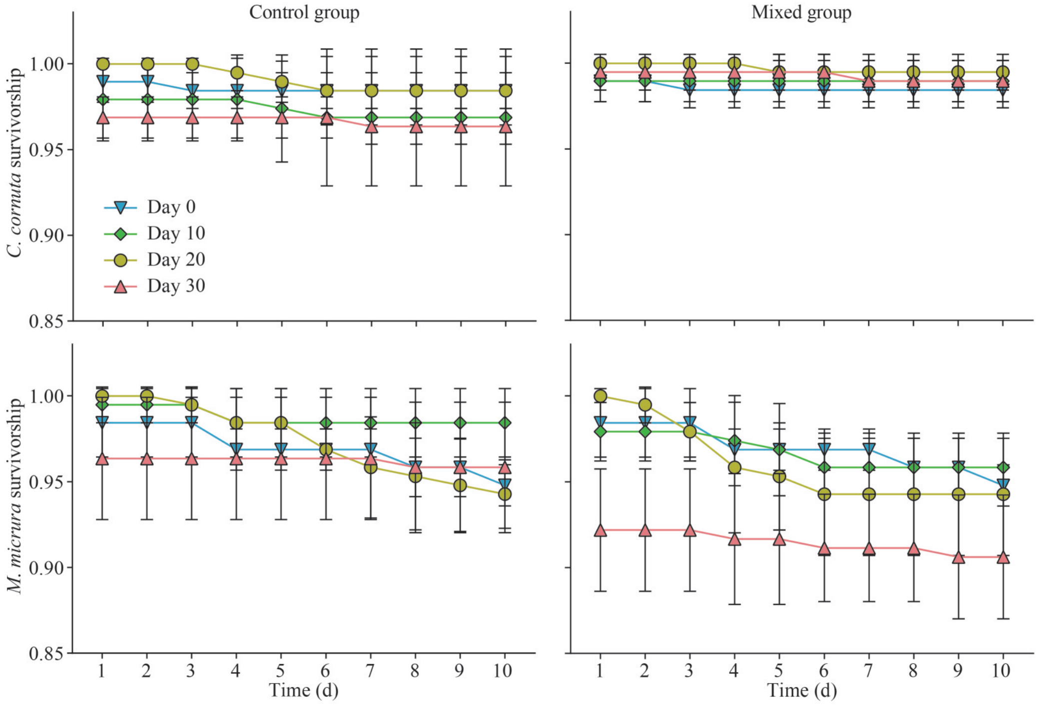

Fig.3 Age-specific survivorship curves of *Ceriodaphnia cornuta* (upper panel) and *Moina micrura* (lower panel)

The control group (left) consisted of only a single species, while the mixed group (right) incorporated two species.

remained unaffected (Fig.3). However, data at day 30 indicated that competition led to a significant decline in survival rates for *M. micrura* (df=160.000, *F*=47.034, *P*<0.001; Fig.3), whereas no such effect was observed for *C. cornuta* (df=3.843, *F*=3.956, *P*=0.113; Fig.3).

The age-specific survivorship curves indicated that both *C. cornuta* and *M. micrura* groups exhibited significant changes in reproductive rates throughout the 40-d experimental period. For *C. cornuta*, the reproductive rate in the mixed group increased significantly compared to the control group after day 20 (df=141.507, *F*=4.719, *P*=0.004; Fig.4). For *M. micrura*, the reproductive rate in the mixed group significantly decreased when compared to the control group after day 30 (df=47.556, *F*=3.069, *P*=0.037; Fig.3).

In the case of *C. cornuta*, upon the completion of the 40-d life table experiment, the mixed group demonstrated a significantly higher intrinsic rate of population increase (df=24.101, *F*=10.358, *P*=0.004; Fig.5) and net reproductive rate (df=22.763, *F*=4.293, *P*=0.050; Fig.5) in comparison to the control group. The generation time (df=23.136, *F*=9.425, *P*=0.005; Fig.5) and age at maturity (df=24.000, *F*=22.444, *P*<0.001; Fig.5) were significantly reduced, while the average lifespan showed an increase, albeit the result was not statistically significant (df=14.713, *F*=4.190, *P*=0.059; Fig.5). When compared to day 0, the generation time had significantly decreased by day 30 (df=9.793, *F*=42.958, *P*<0.001; Fig.5). For the measured data, the larva body length of the mixed group was significantly shorter than that of the control group at day 30 (df=244.209, *F*=4.697, *P*=0.031; Fig.5) and also significantly shorter than at day 0 (df=23.789, *F*=6.514, *P*=0.001; Fig.5).

In contrast to *C. cornuta*, for the competitively disadvantaged species *M. micrura*, the intrinsic rate of population increase in the mixed group demonstrated a significant decline when compared to the control group (df=8.448, *F*=23.707, *P*=0.001; Fig.6). This decline was attributable to a significant delay in the age at maturity (df=28.000, *F*=24.580, *P*<0.001; Fig.6). Similarly, in comparison with the intrinsic rate of population increase (df=8.448, *F*=13.802, *P*=0.001; Fig.6) and age at maturity (df=28.000, *F*=4.972, *P*=0.007; Fig.6) observed at day 0, *M. micrura* also exhibited significant reductions and delays. Under the competitive influence from another species, the adult body length of the mixed

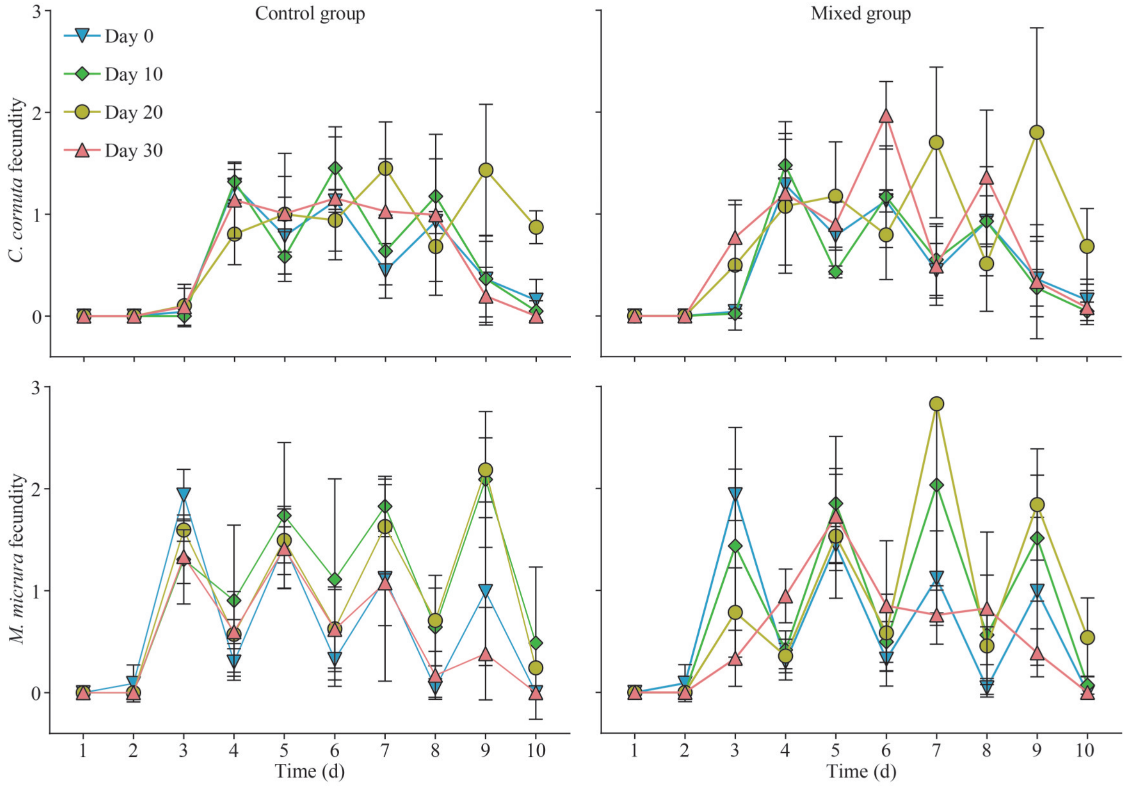

Fig.4 Age-specific fecundity (m_x) curves of *Ceriodaphnia cornuta* (upper panel) and *Moina micrura* (lower panel)

The control group (left) and the mixed group (right) as indicated in Fig.3.

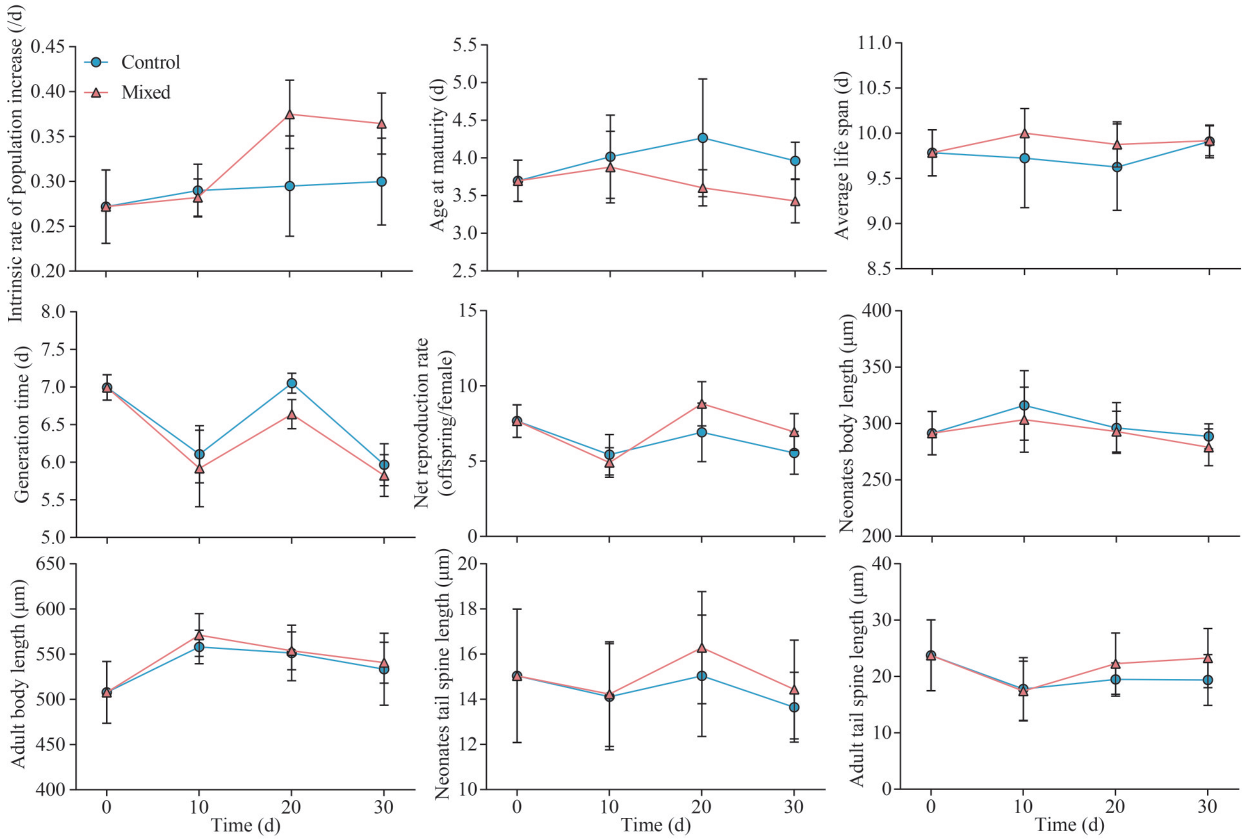

Fig.5 Response styles of 9 life history traits of *Ceriodaphnia cornuta* under no competitive stress (control group, blue circles) or under competitive stress (mixed group, magenta triangles)

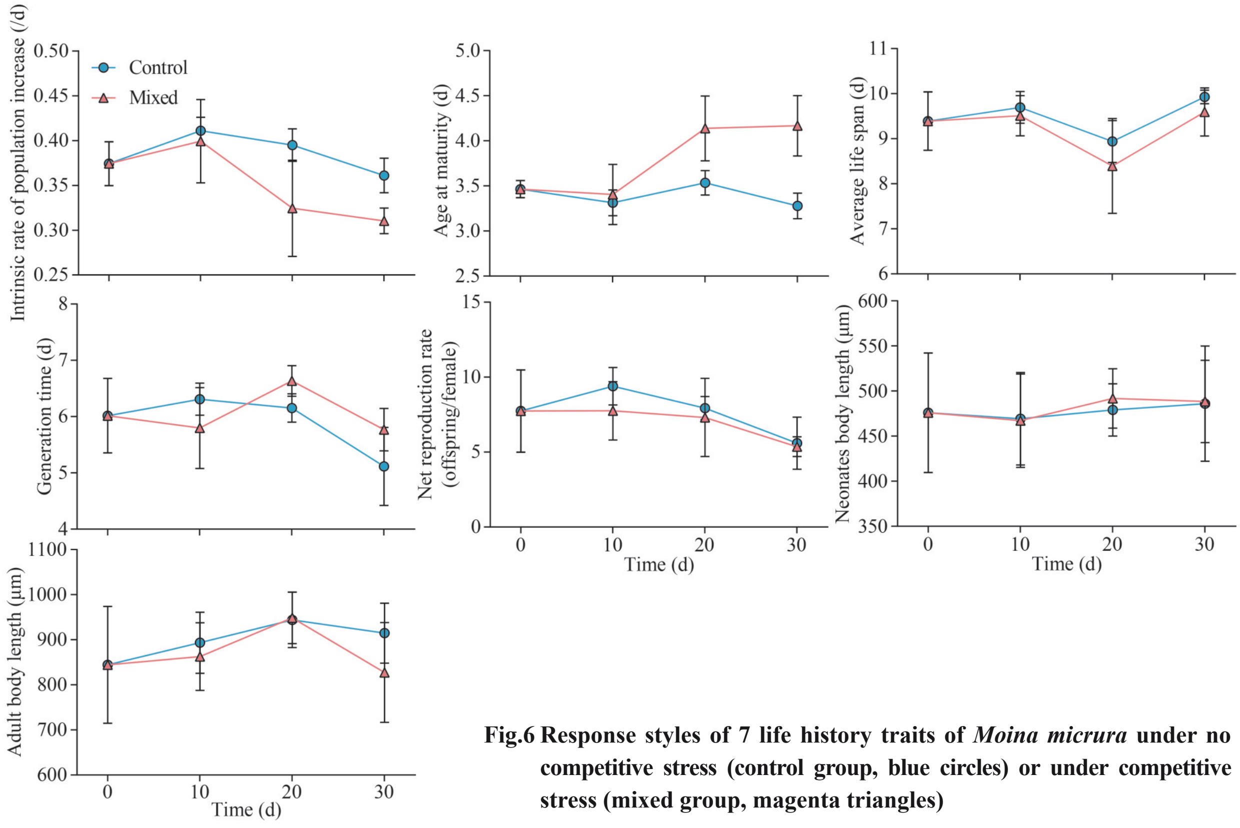

Fig.6 Response styles of 7 life history traits of *Moina micrura* under no competitive stress (control group, blue circles) or under competitive stress (mixed group, magenta triangles)

group was significantly diminished compared to the control group (df=160.000, F=6.863, P=0.010; Fig.6), a phenomenon that only became evident around day 30 (df=160.000, F=11.634, P<0.001; Fig.6).

4 DISCUSSION

4.1 Rapid evolution of life history caused by competition

This study reveals that populations with a history of competition may exhibit both more stable coexistence dynamics and avoidance of competitive interactions, closely linked to adaptive differentiation in their life history strategies (Fig.7). Specifically, complementary adjustments in key parameters such as developmental rates and reproductive investment, as revealed by life table experiments, provide a direct mechanistic explanation for the observed competitive relief in population dynamics (Fig.7). Rapid divergence in life-history strategies between *Ceriodaphnia cornuta* and *Moina micrura* is attributed to resource limitation and density-dependent selection during interspecific competition, as evidenced by experimental evolution and demographic analyses (Chen et al., 2015). *C. cornuta* exhibits competitive dominance through a strategy of neonate miniaturization and accelerated development, whereas *M. micrura* faces ecological extinction through evolutionary trajectories characterized by delayed reproduction and reduced fitness. Under nutrient-restricted conditions, population densities of both species declined significantly, with the carrying capacity (K) of *C. cornuta* lower in sympatry than in allopatry. These findings indicate that interspecific competition imposes intense selective pressures on life-history evolution (Eberhardt and Breiwick, 2012; Wilson, 2014). At the start of the experiment, *M. micrura* already exhibited a prolonged maturation period and smaller adult body size, reflecting an immediate competitive disadvantage that affected its demographic performance. Over the 40-d experiment, the experimental populations completed approximately 10 generations, providing an evolutionary timeframe for adaptive responses. Under competitive stress, *C. cornuta* exhibited an accelerated maturation schedule (reaching maturity by day 4) with offspring demonstrating progressive reductions in body length, whereas *M. micrura* showed no clear adaptive adjustments in life history. The observed life-history trade-off between neonates' body size and maturation timing conferred a selective advantage to *C. cornuta* (Jiang et al., 2013). In contrast, the intrinsic rate of population increase (r) of *M. micrura* declined consistently, indicating that although the species displayed some evolutionary plasticity, its overall trajectory led toward experimental extinction. In comparison with *M. micrura* role of adaptive life-history evolution in determining species coexistence outcomes and provides mechanistic insights into predicting ecological consequences of competitive exclusion dynamics (Bengtsson, 1987; Pagano, 2008).

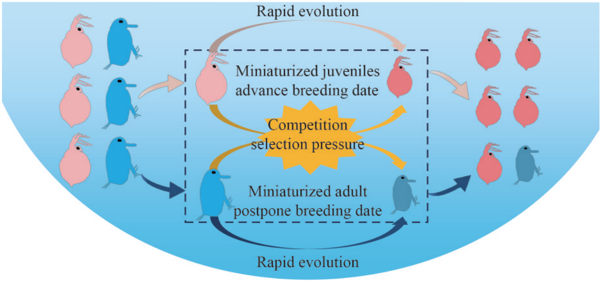

Fig.7 Rapid evolution driven by competition in two water fleas

After 40 d of selection, *Ceriodaphnia cornuta* evolved shorter body length and faster reproduction, while *Moina micrura* evolved shorter body length but slower reproduction, leading to differences in their environmental adaptability.

Under the experimental conditions described, the rapid adaptive evolution observed in both zooplankton species primarily resulted from directional natural selection filtering pre-existing genetic variation, with shifts in allele frequencies within the experimental populations enhancing competitive fitness. Biological evolution fundamentally involves changes in allele frequencies within populations, driven primarily by natural selection, genetic drift, and gene flow (Barrett and Schluter, 2008). In this experiment, the controlled design prevented dispersal and range expansion. Genetic drift was also ruled out because the evolutionary patterns were consistent across all four replicates. Although natural selection generally acts on standing genetic variation and new mutations, the 40-d selection period made the rise of novel alleles unlikely. The synchronous appearance of adaptive traits across replicates further argues against a major role of new mutations, which would arise stochastically rather than in parallel. Therefore, given that the two cladoceran species were first maintained in isolation for 120 d before the 40-d competitive experiment, their rapid adaptation most likely arose from selection on pre-existing genetic variants. Interspecific competition acted as a directional selective pressure, favoring alleles that increased competitive fitness, thereby altering allele frequencies and driving population-level adaptation to the competitive environment (Barrett and Schluter, 2008).

Consistent with prior findings, interspecific competition between these cladoceran species primarily affected demographic rates rather than survival, reducing the intrinsic rate of population increase mainly through delayed age at first reproduction (Nandini and Sarma, 2002). Under ad libitum resource conditions, *C. cornuta* exhibits higher intrinsic growth potential and superior competitive ability compared to *M. micrura* (Pagano, 2008; Wilson, 2014). The life-history syndrome of *C. cornuta*, characterized by accelerated development, precocious reproduction, elongated adult tail spines, and rapid, sustained population growth, is typical of classic *r*-strategists (Southwood, 1974). These patterns corroborate the “small-body advantage” hypothesis, which posits that reduced body size confers competitive superiority under resource limitation through enhanced demographic resilience (Neill, 1975). Previous studies have documented that *C. cornuta* exhibits reduced body size under abiotic stress conditions (Hong et al., 2004; Huang et al., 2021). When exposed to vertebrate predation risk, this species shows rapid phenotypic plasticity through either a reduction in body size or elongation of the tail spine (Spaak and Boersma, 1997; Gu et al., 2020; Huang et al., 2021). The expression of these traits under competition may reflect adaptive strategies to increase competitive dominance or to mechanically interfere with competitors (Amarasekare, 2002). Furthermore, larger cladoceran species often exhibit reduced energetic investment in carapace development relative to smaller congeners, potentially compromising reproductive output during periods of resource limitation (Lynch, 1980). Studies on *M. micrura* indicate that its early life stages are particularly sensitive to changes in food availability (Guo et al., 2020); this sensitivity, together with the effects of starvation (Threlkeld, 1976; Tessier et al., 1983) and population crowding (Matveev and Gabriel, 1994), likely contributes to its competitive inferiority in multispecies assemblages.

4.2 Impact of life-history evolution on interspecific competition

Interspecific competition can drive adaptive evolution, and the resulting evolutionary trajectories may subsequently shape organism responses to novel environmental challenges (Jones, 2008). Natural selection acts as an ecological filter, favoring phenotypes with superior adaptive capacity and thereby enhancing population-level fitness (Jones, 2008). Phenotypic plasticity in cladocerans includes body size reduction that aids survival during cyanobacterial blooms and heatwaves (Zhang and Jiang, 2022), or tail spine’s elongation that enhances antipredator defenses (Jiang et al., 2014). Conversely, the delayed maturation observed in *M. micrura* should not be interpreted solely as maladaptive, given that this species attains seasonal dominance in Shangyi Pond despite transient density reductions (Burns, 2000). Such life-history shifts may represent an adaptive strategy for resource conservation, enabling population recovery when favorable conditions resume (Burns, 2000). In fluctuating environments, organisms encounter multifactorial selection pressures, and the efficacy of their evolutionary responses determines their potential to adapt to new conditions and their long-term persistence (Johansson, 2008; Osmond and de Mazancourt, 2013). The extent to which competitive outcomes influence other ecological processes depends on whether associated evolutionary changes constrain or facilitate adaptation to different environments (Johansson, 2008). Evolutionary trajectories shaped by competition may either conflict with or align with selective pressures from novel environmental conditions (Johansson, 2008). When competitive pressures overlap with new environmental challenges, competitive selection can accelerate adaptive evolution in the new ecological context (Osmond and de Mazancourt, 2013).

To further explore the molecular mechanisms underpinning competition-driven evolution and the influence of evolutionary life histories on organisms, subsequent investigations may employ a multi-omics integration approach. Firstly, joint transcriptomic and metabolomic analyses on samples exposed to competitive stress can be conducted to systematically identify key genes that exhibit significant differential expression in response to competitive pressure (Mao et al., 2025). Subsequently, functional validation of candidate core genes in zooplankton should be carried out using gene silencing or gene editing technologies (Rong and Golic, 2001). By comparing alterations in life-history traits before and after genetic manipulation, the causal relationship between these genes in connecting competition and life history can be elucidated. It is proposed that this research path, transitioning from "association discovery" to "causal validation", in conjunction with our experimental results, shows potential for systematically uncovering key regulatory genes driving life history evolution and the ecological changes resulting from genetic alterations.

5 CONCLUSION

Ceriodaphnia cornuta achieved competitive dominance through accelerated reproduction and reduced body size, whereas *M. micrura* suffered population decline due to an energy-conserving life-history strategy. These findings demonstrate that divergent evolutionary trajectories mediate species coexistence and determine demographic resilience under environmental stress. *C. cornuta* exhibited r-selected evolutionary responses under competitive stress, characterized by precocious reproduction and neonate miniaturization, while *M. micrura* displayed *K*-selected traits including delayed maturation and greater somatic investment. Despite showing adaptive phenotypic plasticity, the energy-conserving strategy of *M. micrura* ultimately led to its competitive exclusion. This evolutionary contrast highlights the key role of adaptive life-history evolution in structuring zooplankton communities (Bengtsson, 1987; Pagano, 2008).

6 DATA AVAILABILITY STATEMENT

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

7 ACKNOWLEDGMENT

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