Poeciliid Research

Ecological and evolutionary divergence in wild guppies: biogeography, life-history strategies, and behavioral adaptation across contrasting environments

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https://doi.org/10.67784/0086

Abstract. Wild guppies of the *Poecilia reticulata* species complex, together with the closely related *Poecilia wingei*, represent important natural models for investigating ecological divergence, adaptive evolution, sexual selection, and eco-evolutionary feedbacks. Across northeastern South America and Trinidad, populations occupy geographically and ecologically heterogeneous river systems in which variation in predation pressure, resource availability, parasite communities, habitat structure, and anthropogenic disturbance generates repeated opportunities for divergent selection. This mini-review synthesizes evidence for geographic and ecological differentiation among guppy populations, with particular emphasis on the contrasting evolutionary trajectories observed between high-predation lowland habitats and low-predation montane headwaters. We examine how differences in mortality regimes are associated with predictable changes in maturation, reproductive investment, offspring size, body size, and longevity, and how these life-history shifts can generate feedbacks extending from individual phenotypes to ecosystem processes. We further review divergence in mating tactics, antipredator behavior, male coloration, female mate choice, foraging, social behavior, and developmental plasticity. Recent genomic and experimental studies indicate that adaptation can occur rapidly following environmental transitions, while geographic history and drainage-level population structure constrain the extent and repeatability of evolutionary responses. Collectively, the evidence demonstrates that guppy divergence is shaped by the interaction of natural selection, sexual selection, phenotypic plasticity, historical isolation, and ecological feedbacks rather than by predation alone. Wild guppy populations therefore provide a powerful comparative framework for understanding how heterogeneous environments generate and maintain phenotypic, behavioral, life-history, and genomic differentiation over contemporary and evolutionary timescales.
Keywords: predation pressure, phenotypic plasticity, life-history evolution, female mate choice, male coloration, antipredator behavior, river drainage, population structure, genomic adaptation, eco-evolutionary feedbacks, reproductive investment, developmental plasticity.

Introduction. Natural populations of the guppy species complex (*Poecilia reticulata* and *Poecilia wingei*) across northeastern South America and Trinidad serve as benchmark models for ecological divergence, sexual selection, and life-history evolution (Reznick & Travis, 2019; Alexander et al., 2006; Breden et al., 1999) (Figure 1). Repeated ecological contrasts across montane and lowland streams provide replicated natural experiments for testing how directional selection and phenotypic plasticity interact (Reznick & Travis, 2019; Heckley et al., 2022; Yang et al., 2023).

The aim of this mini-review is to synthesize current evidence on the ecological and evolutionary differentiation of wild guppy populations across northeastern South America and Trinidad, with particular emphasis on the interaction between environmental heterogeneity and phenotypic divergence. The review focuses on four interconnected

dimensions of guppy diversification: (i) the biogeographic and genetic structure imposed by river drainage systems; (ii) divergence in life-history strategies under contrasting mortality and resource regimes; (iii) behavioral and phenotypic differentiation arising from the interaction between natural and sexual selection; and (iv) the contribution of phenotypic plasticity and rapid genomic adaptation to population responses following environmental change.

Rather than treating predation as a single, universal selective force, this review considers guppy populations as components of spatially structured ecological systems in which predator communities, habitat architecture, resource availability, parasites, demographic processes, and historical isolation interact. Particular attention is therefore given to the distinction between repeated patterns of upstream–downstream divergence and geographically contingent evolutionary responses among independent drainage systems. The review also considers how changes in individual life-history and behavioral traits can propagate to population and ecosystem levels through density dependence, altered resource use, nutrient cycling, and other eco-evolutionary feedbacks.

By integrating biogeographic, ecological, behavioral, life-history, experimental, and genomic evidence, this mini-review seeks to clarify why guppy populations repeatedly exhibit divergent phenotypes while simultaneously retaining substantial geographic specificity and evolutionary contingency. The broader objective is to highlight wild guppies as a natural system for understanding how selection, plasticity, historical structure, and ecological feedbacks jointly shape contemporary evolutionary change.

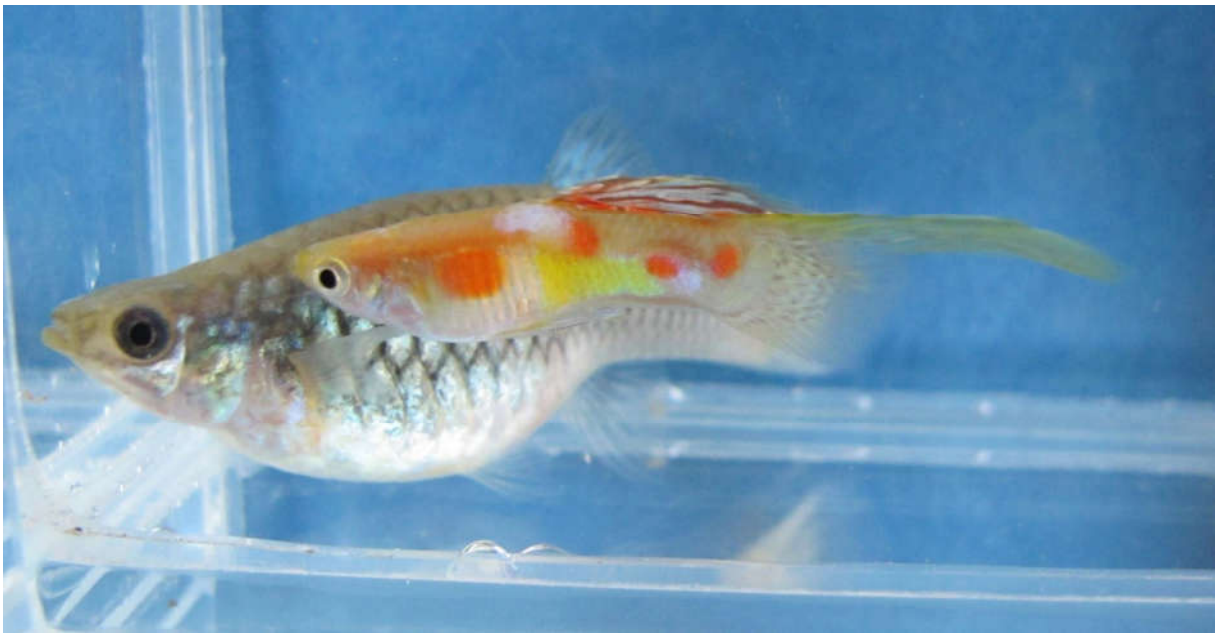


Figure 1. *Poecilia reticulata* Peters, 1859, original picture, photographed at the breeding facility of the author Grzegorz Prusinowski (https://www.facebook.com/GenetykaGupika).

Biogeography and River Drainages. Guppies originated in northeastern South America, encompassing mainland river networks in Venezuela, Guyana, and Suriname, alongside continental shelf islands such as Trinidad and Tobago (Alexander et al., 2006; Petrescu-Mag, 2008). In northern Trinidad, populations are structured across discrete river basins comprising the Caroni, North Slope, and Oropouche drainages, exhibiting ancient genetic divergence and marked allelic differentiation (Alexander et al., 2006; Mohammed et al., 2020; Carvalho et al., 1991). These drainages contain replicated upstream and downstream habitats separated by barrier waterfalls, which establish distinct predator communities (Reznick & Travis, 2019; Künstner et al., 2016).

High-predation lowland stretches feature diverse piscine predators such as cichlids and characins, whereas low-predation montane headwaters typically contain only the killifish *Rivulus hartii* or freshwater prawns (De Waele et al., 2025; Luyten & Liley, 1985; Endler & Houde, 1995). Genomic and allozyme analyses confirm that while upstream and

downstream sites show strong local adaptation, population structure is primarily delineated across major river systems rather than selective regimes alone (Künstner et al., 2016; Alexander et al., 2006; Carvalho et al., 1991). Whole-genome mapping of individuals from high-predation sites like the Guanapo River demonstrates substantial nucleotide diversity that underpins rapid adaptation (Künstner et al., 2016) (Table 1).

Table 1
Geographic distribution and primary research foci of South American guppy study populations

Drainage basin	*Focal river systems*	*Predation regimes*	*Key evolutionary research themes*	*Source*
Caroni Drainage	Guanapo, Aripo, Arima	High and low predation	Genomic sweeps, canopy thinning, sexual coloration	Künstner et al., 2016; Van Der Zee et al., 2021; Kemp et al., 2018
North Slope	Marianne, Paria, Yarra	Disjunct predator communities	Parasite richness mosaics, courtship display variation	Mohammed et al., 2020; Luyten & Liley, 1985
Oropouche Drainage	Oropouche mainstream	Vicariant lineages	Deep phylogeographic divergence, nonparallel adaptation	Heckley et al., 2022; Alexander et al., 2006; Mohammed et al., 2020
Mainland / Sucre	Campoma, Cumaná (*P. wingei*)	Lowland lagoons and streams	Speciation, female choice, secondary sexual isolation	Reznick & Travis, 2019; Alexander et al., 2006; Breden et al., 1999
Invasive Watersheds	Southeastern Brazil streams	Urban and industrial gradients	Multi-stressor life-history shifts, toxicity selection	Riesch et al., 2026.

Spatial heterogeneity across these basins also drives divergent parasite communities, creating geographic mosaics of selection independent of piscine predator regimes (Mohammed et al., 2020; Endler & Houde, 1995). Replicate headwater transplant experiments initiated from high-predation Guanapo stocks into previously guppy-free low-predation tributaries show that genomic convergence occurs within eight generations, displaying prominent signatures of selection on chromosome 15 (Van Der Zee et al., 2021; Kemp et al., 2018).

Life History Divergence and Eco-Evolutionary Dynamics. The divergence between upstream and downstream guppies is characterized by predictable life-history trade-offs governed by demographic mortality rates and ecological feedbacks (Reznick & Travis, 2019; Van Der Zee et al., 2021). Fish from high-predation regimes mature earlier and invest more heavily in early reproduction, whereas low-predation guppies experience intense resource competition at high densities, driving the evolution of delayed maturation, larger offspring, and extended longevity (Reznick & Travis, 2019). Direct artificial selection experiments demonstrate that adult predation mortality immediately selects for larger early broods, smaller adult body sizes, and altered body mass allometry (De Waele, 2024; De Waele et al., 2025). These phenotypic shifts alter broader freshwater ecosystems by changing nutrient excretion stoichiometry, primary algal production, and invertebrate community structure (Reznick & Travis, 2019; Kemp et al., 2018). These ecosystem alterations subsequently feed back to influence density-dependent natural selection on the guppies themselves (Reznick & Travis, 2019). In novel anthropogenic environments, including polluted waterways in Brazil and multi-generational harvesting experiments, populations rapidly shift reproductive effort toward

fast life-history schedules with higher fecundity and reduced somatic investment (Riesch et al., 2026; Pauli et al., 2026).

Behavioural Ecology, Sexual Selection, and Divergence. Behavioural divergence between guppy populations balances natural selection from predators against sexual selection mediated by female choice (De Waele, 2024; Alexander et al., 2006; Farr, 1983; Endler & Houde, 1995). Males from low-predation streams execute elaborate sigmoid courtship displays and exhibit conspicuous structural and carotenoid pigmentation, whereas males in predator-dense lowland waters rely predominantly on coercive gonopodial thrusting and express muted visual coloration (De Waele, 2024; Kemp et al., 2018; Luyten & Liley, 1985). Female preference for rare and novel color patterns helps maintain polymorphism within wild populations (Kemp et al., 2018; Farr, 1983). However, comprehensive meta-analyses and visual modeling indicate that color parallelism across populations is weak, shaped heavily by ambient light, canopy cover, and distinct evolutionary histories (Heckley et al., 2022; Kemp et al., 2018; Fuller, 2022) (Table 2).

Table 2

Behavioral and phenotypic divergence between contrasting predation regimes in *Poecilia reticulata*

Trait domain	*High-predation populations*	*Low-predation populations*	*Underlying driver or mechanism*	*Source*
Mating tactics	Frequent gonopodial thrusting; opportunistic sneak attempts	Elaborate, prolonged sigmoid courtship displays	Risk of predatory interception versus female visual assessment	Yang et al., 2023; Luyten & Liley, 1985; Mag-Mureşan & Pop 2004; Petrescu & Mag, 2006
Antipredator behavior	Tight schooling; heightened predator inspection and avoidance	Reduced cohesion; minimal schooling behavior	Dilution effect and early detection in open waters	De Waele, 2024; Luyten & Liley, 1985; Endler & Houde, 1995
Male nuptial color	Reduced conspicuousness; drainage-contingent iridescence	Elaborate carotenoid orange and structural iridescence	Female choice constrained by predator visual detection	De Waele et al., 2025; Kemp et al., 2018; Endler & Houde, 1995
Behavioral plasticity	Socially transmitted tactics; predator-induced learning	Context-dependent responses without juvenile social learning	Rapid developmental plasticity and neural reorganization	Yang et al., 2023; Earl et al., 2024
Foraging efficiency	Higher overall foraging rate; sex-specific plasticity	Slower foraging latency; genetically constrained uptake	Resource limitation versus predation risk management	Earl et al., 2024.

Behavioural differentiation also extends to social dynamics, cognitive flexibility, and developmental plasticity across sexes (Earl et al., 2024). Under exposure to predator chemical cues during rearing, high-predation males dynamically adjust courtship levels and develop distinct brain morphologies, while females exhibit genetically canalized

foraging efficiency (Yang et al., 2023; Earl et al., 2024). In *Poecilia wingei* (Endler's guppy) and related Venezuelan populations, these behavioural differences in male display and female mate assessment are reinforced by reproductive character displacement, serving as primary drivers of lineage diversification across northern South America (Reznick & Travis, 2019; Endler & Houde, 1995).

Conclusions. Wild guppy populations provide compelling evidence that ecological divergence emerges from the interaction of multiple selective and historical processes rather than from a single environmental factor. Across northeastern South America and Trinidad, major river drainages impose a strong geographic framework within which contrasting predator communities, resource regimes, parasite assemblages, and habitat conditions repeatedly generate divergent evolutionary trajectories. The recurrent differentiation between high-predation lowland populations and low-predation montane populations demonstrates the predictability of some life-history and behavioral responses, while comparisons among independent drainages reveal substantial evolutionary contingency.

Life-history divergence is particularly consistent with differences in mortality regimes. High-predation populations generally exhibit greater reproductive investment at earlier ages, whereas populations experiencing reduced adult mortality tend toward delayed maturation, larger offspring, and increased investment in survival and somatic growth. These changes are not isolated population-level responses: alterations in density, resource use, nutrient excretion, and community interactions can generate ecological feedbacks that subsequently modify the selective environment experienced by guppies.

Behavioral and sexual traits show a similarly complex pattern. Predator-mediated selection favors reduced conspicuousness and mating tactics that minimize exposure, whereas relaxed predation permits greater expression of male coloration and elaborate courtship behavior. Female preferences, rare-male advantages, social interactions, and developmental plasticity further contribute to the maintenance of phenotypic diversity. Importantly, recent genomic and experimental evidence indicates that substantial evolutionary change can occur over relatively few generations following environmental transitions, although the magnitude and genomic basis of such responses may differ among geographic populations.

Overall, the guppy system illustrates that contemporary evolution is simultaneously shaped by natural selection, sexual selection, phenotypic plasticity, demographic feedbacks, and historical biogeography. Consequently, apparently similar ecological contrasts should not be assumed to produce identical evolutionary outcomes. The combination of replicated natural experiments, controlled translocation studies, behavioral assays, and genomic approaches makes wild guppy populations particularly valuable for determining when evolutionary responses are predictable and when they remain constrained by geographic history and local ecological context. Future research integrating these levels of organization will be essential for understanding how rapid environmental change, habitat modification, and novel selective pressures reshape evolutionary trajectories in freshwater fishes.

Acknowledgements. An AI-powered search engine for research - https://consensus.app – Consensus NLP, Inc – was used to summarize data in tables.

Authors Contributions. BM, and BPM wrote the manuscript; GP read and revised the manuscript.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. Not applicable.

Funding. This research received no external funding.

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Received: 15 August 2026. Accepted: 07 October 2026. Published online: 20 October 2026.
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How to cite this article:
Moldovan, B., Petrescu-Mag, B., Prusinowski, G. (2026). Ecological and evolutionary divergence in wild guppies: biogeography, life-history strategies, and behavioral adaptation across contrasting environments. *Poeciliid Research*, *16*(1), 32-38. https://doi.org/10.67784/0086