Rethinking Stress Through an Ecological Genomic Lens: From Predatory Pressures to Modern Mismatch

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Abstract

Stress, traditionally seen as a psychological issue with physiological consequences, is now viewed as part of an evolutionary continuum. While modern stressors have shifted from immediate threats to chronic psychosocial challenges, our physiological responses remain the same. In contrast, stress in the wild is acute; today's chronic stressors keep the body in a prolonged fight-or-flight mode, diverting energy from other vital physiological functions and leading wide range of health issues.

Beyond its impact on individual health, Chronic stress also affects biological and social patterns, potentially linking increased life expectancy with declining birth rates, a trend seen in both humans and wildlife exposed to human-induced stress. Understanding the relationship between stress and demographic shifts could play a crucial role in public health planning and biodiversity conservation.

This work integrates genomic and ecological perspectives, promoting interdisciplinary research to better understand stress and its effects on human health and ecosystem resilience.

Keywords: Chronic stress, life history strategies, birthrate, demographic shifts, prey-predatory stress

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1. Introduction

Stress is a universal feature of life that has shaped the evolution of species over millennia. Acute stressors such as prey-predator interactions have historically driven adaptive physiological and behavioral responses critical for survival (Clinchy et al., 2013). Prolonged exposure to such acute stress can produce effects comparable to those observed in human chronic stress, including altered reproductive success and offspring survival (Zanette et al., 2024; Adamo and McKee, 2017). While these ecological stressors have honed stress response systems as survival tools, modern humans now face a paradox: chronic psychosocial stress arising from societal pressures contributes to widespread epidemics of metabolic, immune, and psychiatric disorders (McEwen, 2007; Slavich, 2016).

In an era marked by rapid environmental changes driven by climate dynamics and evolving social complexities, it is imperative to understand how stress influences organisms at demographic and evolutionary scales. This study explores the multifaceted role of stress in shaping life-history trade-offs between fertility and longevity across taxa. By framing stress within an ecological genomic context, we aim to explore how evolutionary legacies interact with contemporary environmental and psychosocial challenges to influence demographic patterns and population health.

A deeper understanding of these mechanisms is essential not only for addressing the health burdens posed by chronic stress in modern societies but also for informing conservation strategies in ecosystems undergoing rapid transformation due to anthropogenic pressures.

2. Prey-Predatory to Psycho-Social: The Continuum of Stress

Exposure to biological, environmental, and psychosocial stressors exerts profound effects across animal taxa as well, influencing behavior, reproductive success, lifespan, and immunity. In wild settings, acute stressors such as predation or resource scarcity typically provoke transient activation of the hypothalamic-pituitary-adrenal (HPA) axis, resulting in short-lived glucocorticoid surges.

The effects range from phenotypic plasticity, reduced juvenile growth (de Meo I et al., 2021; Ling et al., 2019) to anxiety-like behaviors and anhedonia, yet these responses dissipate once threats subside (Burgado et al., 2014). Key genomic adaptations like swift down-regulation of cortisol after threat removal or prioritization of immediate survival (e.g., flight) over long-term immunity and restoring homeostasis post-stress enables this resilience. These adaptations reflect genetic assimilation—stress-induced traits becoming canalized over generations.

Most humans no longer face survival crises related to prey-predatory stress unlike other animals. Modern stressors are not typically related to predator-prey threats, yet the pathways and hard-wiring of our genome remain adapted to the conditions of life in the wild, where ecological stressors were common. Over time, humans settled down, developed tools for protection and easier hunting, and gradually freed themselves from the constant struggle for food and survival. This newfound security allowed the emergence of societal structures, which introduced new forms of social pressure and competition.

As civilizations formed and evolved, psychosocial stress increased, particularly with the rise of modern lifestyles. Unlike acute or episodic predator-prey stress, which is short-lived and situational, modern psychosocial stress tends to be chronic. While stress originally evolved as a survival strategy to cope with immediate threats, captive and modern human environments often impose chronic, unpredictable stress, leading to sustained glucocorticoid elevation and allostatic overload (Karaer et al., 2023).

The transition from ecological to societal stressors occurred rapidly, but the human genome adapts slowly. As a result of this mismatch, our physiological stress response remains largely the same—it still channels energy toward immediate fight-or-flight reactions. However, in the context of chronic modern stress, this response disrupts physiological homeostasis and contributes to a range of health problems, affecting systems such as the gastrointestinal, cardiovascular, immune and reproductive systems.(Rooney and Domar, 2018; Yaribeygi et al., 2017)

3. Thriving Amidst Stress: The Continuum of life History Strategies

Persistent stress activates secondary homeostatic mechanisms that demand increased energy to restore physiological balance. When stress becomes prolonged or severe, tertiary responses ensue, where the energetic costs exceed the organism's capacity, leading to physiological dysfunction and diminished fitness. This reflects a fundamental energy allocation trade-off, where organisms must balance reproduction, maintenance, and survival depending on environmental pressures. Cortisol, the primary stress hormone, initiates these physiological responses; while essential for reproductive processes such as gonadal maturation and embryonic development in fishes (Muruganan-thkumar and Sudhakumari, 2022), chronic elevation of cortisol can impair fertility. Interestingly, human studies indicate that psychosocial stress does not always correlate with reduced fecundity when measured solely by cortisol levels (Lynch et al., 2012), yet chronic stress-induced activation of the sympathetic-adrenal-medullary (SAM) pathway is associated with decreased conception rates (Louis et al., 2011).

From an evolutionary perspective, early humans adapted to acute environmental stressors by conserving energy and, under certain conditions, increasing fecundity. Animal studies demonstrate that life-history strategies predict individual stress responses within species, leading to variation among populations (Schultner et al., 2013). Genomic and epigenetic analyses reveal that traditional populations like the Hadza, who experience episodic environmental stress, possess greater metabolic resilience and stress-adaptive genetic variants compared to urban populations (Jones, 2016), where chronic stress correlates with adverse health outcomes.

4. Stress as the Modulator: The continuum of Demographic Dimensions

As advances in medicine and technology have reduced mortality and extended lifespan, the role of stress in shaping demographic patterns has become increasingly evident. Disposable soma and antagonistic pleiotropy models, suggest that longevity and fertility are linked through resource allocation trade-offs, with stress acting as a key modulator of these processes. Empirical studies indicate that women with two to three children tend to have greater life expectancy compared to those with either no children or more than three offspring (Kuningas et al., 2011) highlighting an optimal balance between reproductive output and longevity. This relationship is observed across taxa, ranging from Drosophila to primates (Novoseltsev et al., 2003; Holliday, 1994) demonstrating that fecundity and lifespan are shaped by genetic, environmental and stress-related factors.

As reflected by spatio-temporal variation in birth rates and life expectancy across human populations worldwide (Fig. 1A), humans occupy a continuum along the K-selection spectrum, influenced by ecological, socioeconomic, cultural and stress-related factors. With these factors influencing the contin-

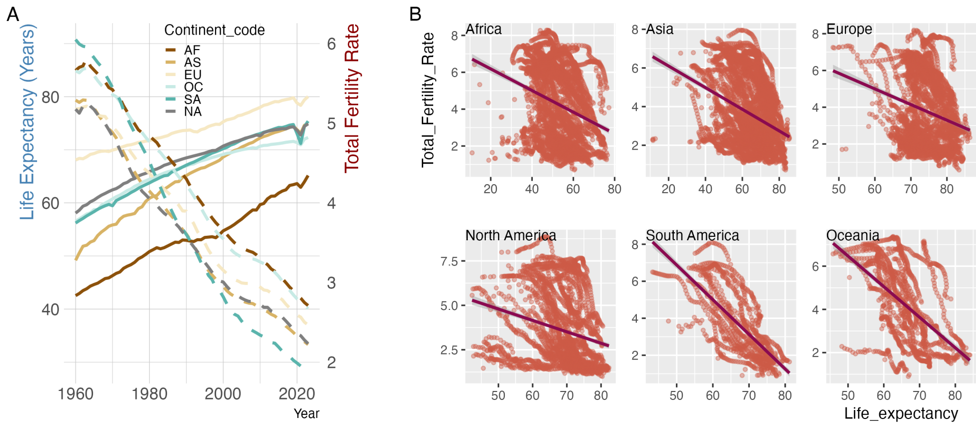

Figure 1: Spatio-temporal trends in life expectancy and total fertility rate across continents. Panel A displays temporal line graphs for each continent, illustrating a consistent increase in life expectancy (solid lines, primary y-axis) alongside a marked decline in total fertility rate (dashed lines, secondary y-axis) from 1960 to 2023. Panel B presents scatterplots of life expectancy versus total fertility rate for individual continents, with trend lines highlighting the robust inverse relationship between these variables, while also revealing regional differences in the magnitude and pace of demographic transition.This figure underscores the global demographic shift toward higher longevity and lower fertility, with notable variability in the trajectories and current positions of different continents.

uum, it is largely understood that across lifeforms, Life Expectancy (LE) is inversely proportional to Total Fertility Rate (TFR).

The pattern obtained from global demographic data (WBG, 2024) reflects the universal shift from high fertility/low longevity to low fertility/high longevity as societies develop socioeconomically. However, figure 1B also is indicative of continental variability in slope steepness, revealing divergent paces of demographic transition globally. Noticeably, while Oceania demonstrates higher life expectancy than Africa, both continents show similar higher TFR trends (2.4 children per woman) and therefore shows an intermediate LE/TFR trajectory (Fig. 2). This could be attributed to Oceania's demographic heterogeneity: Australia and New Zealand exhibit post-transitional characteristics while Pacific Island nations retain fertility rates of 3.9-4.2 children per woman. The other continent South America on the other hand exhibits the steepest LE/TFR acceleration, reaching the highest demographic transition index by 2020 (Fig. 2). This rapid transformation reflects the region's compressed demographic transition, where life expectancy increased from 50 to 76 years while fertility halved to 2.0 children per woman within decades (Fig.1A).

The observed continental variations in demographic trajectories underscore that traditional socioeconomic and cultural explanations alone cannot fully account for divergent transition patterns. These disparities suggest that objective, biologically-grounded stress metrics must be incorporated into demographic models, particularly measures reflecting genetic variability in stress response systems to modern environmental challenges. Therefore, we propose the LE/TFR ratio as a novel composite indicator of demographic transition stage. Though not directly measuring population dynamics, this ratio captures the fundamental evolutionary trade-off between somatic maintenance and reproductive investment; a balance modulated by stress exposure across generations.

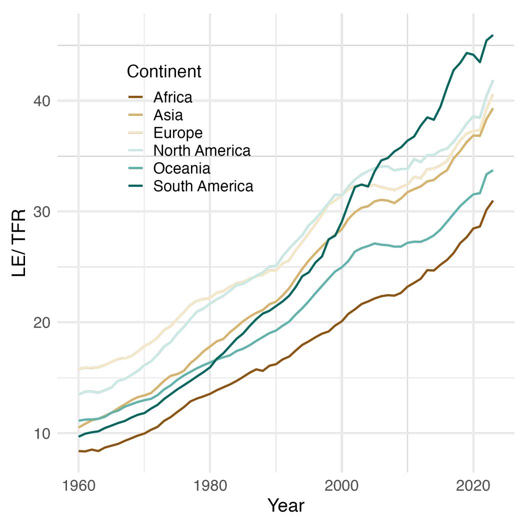

Figure 2: Temporal Trends in Life Expectancy to Total Fertility Rate Ratio (LE/TFR) by Continent (1960-2023)

Populations that effectively balance fertility and longevity in the face of environmental and psychosocial stressors may be better adapted to diverse selective pressures, though these trade-offs remain context-dependent and evolutionarily plastic. Understanding the complex interplay between stress, endocrine regulation, and life-history strategies is essential for predicting demographic shifts in human populations and conserving wildlife in changing habitats.

5. Conclusion

Stress responses in humans and other animals share conserved genomic and physiological foundations, but differ in their dominant forms—acute ecological threats in prey species and chronic psychosocial stress in modern humans. These stress mechanisms influence key demographic dimensions such as fertility, longevity, and population structure. Integrating ecological genomics into public health and demographic research can clarify how evolutionary adaptations to stress shape current health and reproductive outcomes. Future studies should aim to identify genetic and environmental factors that promote adaptive stress responses and demographic resilience across diverse human populations.

Authorship contribution statement

Manasi Mukherjee contributed to conceptualization, investigation, methodology, formal analysis, writing original draft, review, and editing. **Ashish Sharma** contributed to data curation, investigation, writing original draft and review.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

Conflict of interest disclosure

The authors declare they have no conflict of interest relating to the content of this article.

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