

Climate Change–Induced Alterations in Sexual Development and Reproductive Timing

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ABSTRACT

Climate change constitutes an unprecedented threat to global biodiversity, profoundly affecting reproductive success and the long term viability of species. This review consolidates current knowledge on how climate driven alterations, chiefly rising temperatures, shifting precipitation regimes, ocean acidification, and increased frequency of extreme weather events, disrupt sexual development and reproductive timing across a broad range of taxa. Both direct and indirect pathways are examined, including shifts in temperature dependent sex determination, hormonal perturbations, impairment of gametogenesis, and phenological mismatches. A worldwide synthesis reveals consistent trends of earlier breeding, modified migration patterns, and skewed sex ratios in aquatic, terrestrial, and avian organisms. The ecological and evolutionary ramifications of these shifts are discussed, highlighting reductions in population fitness, heightened extinction risk, and the potential for maladaptive responses. The review concludes by identifying critical research gaps and emphasizing the urgent need for systematic monitoring, mechanistic investigations, and the implementation of robust conservation strategies to address these pervasive reproductive challenges.

KEYWORDS

Climate change, sexual development, reproductive timing, global synthesis

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INTRODUCTION

Climate change, driven overwhelmingly by anthropogenic greenhouse gas emissions, is rapidly altering Earth's physical and biological systems¹. Global mean temperatures have risen, precipitation patterns are increasingly erratic, oceans are acidifying and warming, and the frequency and intensity of extreme weather events are escalating². These profound environmental shifts are eliciting widespread biological responses, ranging from physiological stress to ecosystem-level transformations³. Among the most critical and vulnerable biological processes impacted are sexual development and reproductive timing, which are fundamental to species propagation and persistence⁴.

Sexual development, encompassing sex determination, gonadal differentiation, and the maturation of reproductive systems, is a finely tuned process often sensitive to environmental cues⁵. Similarly, reproductive timing, or phenology, reflects the precise synchronization of breeding activities



(e.g., migration, spawning, nesting, parturition) with optimal environmental conditions and resource availability⁶. Disruptions to either of these processes can have cascading effects on individual fitness, population dynamics, and ultimately, species survival⁷.

This comprehensive review synthesizes the current scientific understanding of climate change-induced alterations in sexual development and reproductive timing across a global spectrum of organisms. We aim to identify common patterns, underlying mechanisms, and the ecological and evolutionary consequences of these disruptions, highlighting critical areas for future research and conservation efforts.

CLIMATE CHANGE DRIVERS AND REPRODUCTIVE VULNERABILITIES

The primary climate change drivers impacting reproduction include:

- **Rising temperatures:** Direct effects on metabolic rates, enzyme activity, and developmental pathways⁸
- **Altered precipitation patterns:** Shifts in water availability, affecting habitat quality, food resources, and reproductive success⁹
- **Ocean acidification:** Reduced pH and carbonate saturation, impacting calcifying organisms and marine food webs¹⁰
- **Extreme weather events:** Heatwaves, droughts, floods, and storms directly destroy nests, offspring, and adult breeders, or indirectly reduce resource availability¹¹

Reproduction is inherently vulnerable to environmental perturbations due to its high energetic demands and the exquisite sensitivity of developmental and hormonal pathways¹². The endocrine system, in particular, is a common target, with climate stressors mimicking or disrupting natural hormonal signals critical for gonadal development, gamete production, and reproductive behavior¹³.

ALTERATIONS IN SEXUAL DEVELOPMENT

Climate change is profoundly affecting sexual development, leading to altered sex ratios, impaired gonadal function, and reduced reproductive potential.

Shifts in sex determination mechanisms: Many species rely on environmental cues, especially temperature, for sex determination. These are particularly vulnerable to warming trends:

- **Temperature-dependent sex determination (TSD):** Found in many reptiles (turtles, crocodiles, lizards) and some fish, where incubation temperature during a critical period dictates offspring sex¹⁴. Rising global temperatures are shifting incubation conditions, leading to heavily male- or female-biased sex ratios. For instance, warmer nests often produce a disproportionate number of female sea turtles, raising concerns about future breeding success due to a lack of males¹⁵. Similarly, some fish species exhibiting TSD show feminization at higher temperatures, threatening population viability¹⁶
- **Genotypic sex determination (GSD) species:** Even in species where sex is genetically determined (e.g., mammals, birds, many fish), climate stressors can indirectly influence sex differentiation. Extreme temperatures or associated physiological stress can alter gene expression, disrupt hormonal pathways, and lead to intersexuality or reduced fertility¹⁷. Epigenetic modifications, potentially induced by thermal stress during early development, are also emerging as a mechanism by which climate change could influence sex-related traits in GSD species

Impaired gonadal development and gametogenesis: Climate change exerts significant pressures on reproductive physiology across a wide range of species, extending well beyond its documented effects on sex determination. Elevated environmental temperatures and associated stressors directly compromise

gonadal development and gamete production through multiple interconnected pathways. Elevated temperatures have been shown to impair both spermatogenesis and oogenesis in diverse taxonomic groups. In fish, heat stress is linked to diminished sperm motility and viability, reduced fecundity, and increased incidence of follicular atresia, all of which contribute to reproductive decline¹⁸. Comparable disruptions are evident in invertebrate species, where thermal stress can interfere with larval development and significantly lower reproductive output¹⁹. In addition, climate-related stressors, such as extreme temperatures and shifts in water chemistry, including ocean acidification, can function as endocrine disruptors. These stressors interfere with the synthesis, transport, and receptor binding of key reproductive hormones, including estrogens, androgens, and thyroid hormones²⁰. Hormonal imbalances induced by such disruptions can alter gonadal differentiation, impair the development of secondary sexual characteristics, and modify reproductive behaviors. In some cases, these effects culminate in the emergence of hermaphroditic or intersex conditions, particularly in fish and amphibian populations exposed to prolonged environmental stress.

Furthermore, direct thermal exposure during critical developmental stages can result in structural and functional abnormalities in the gonads. Studies on amphibians, for example, have documented reduced gonad size, abnormal gonadal morphology, and even complete reproductive failure in larvae reared under elevated temperature regimes²¹. These developmental impairments underscore the vulnerability of early life stages to climate-induced environmental change and highlight the long-term risks to population sustainability. Collectively, these findings demonstrate that climate change not only affects sex ratios but also undermines fundamental aspects of reproductive biology, with potentially cascading consequences for species fitness and ecosystem stability.

SHIFTS IN REPRODUCTIVE TIMING (PHENOLOGY)

One of the most widely observed biological responses to climate change is the alteration of reproductive phenology, often leading to mismatches with critical resource availability.

Advanced breeding and spawning: Many species are breeding earlier in the year in response to warming temperatures:

- **Birds:** Numerous avian species across temperate regions are initiating egg-laying earlier, tracking warmer spring temperatures and earlier leaf-out or insect emergence²². While some species successfully adjust, others may experience phenological mismatch, where their young hatch before peak food availability, leading to reduced fledging success and population declines²³
- **Mammals:** Some small mammals and ungulates are showing earlier parturition dates, responding to earlier snowmelt and vegetation growth²⁴. This can be beneficial if resource synchrony is maintained, but problematic if mothers are unable to access sufficient high-quality forage early in the season
- **Fish and amphibians:** Warmer water temperatures can trigger earlier spawning in fish and earlier breeding migrations and egg-laying in amphibians²⁵. This can be problematic if temperature cues are decoupled from other essential resources or if early life stages are exposed to subsequent thermal extremes or reduced food availability
- **Invertebrates:** Many insect species are emerging earlier, influencing predator-prey dynamics and pollination services²⁶. Earlier diapause termination and reproductive initiation have also been documented in various marine invertebrates in response to warming ocean temperatures²⁷

Altered migration and nesting patterns: Climate change is altering environmental cues critical to the timing and success of migratory and reproductive behaviors in various species, with cascading ecological and socioeconomic implications. Migratory birds, which rely on fixed triggers such as photoperiod (day length) to initiate seasonal movements, face challenges as advancing local spring phenology occurs out of sync with their migratory schedules. This asynchrony can lead to delayed arrivals at breeding

grounds, increasing the risk of missing peak insect resources or critical breeding windows, thereby reducing reproductive success²⁸. In response, some bird populations are adapting by altering traditional migratory routes or shortening distances, likely in reaction to milder winter conditions.

Similarly, marine turtles exhibit shifts in nesting behavior due to climate-driven changes. Rising sand temperatures not only accelerate nest development but also skew hatchling sex ratios, as sea turtle sex is temperature-dependent, with warmer conditions favoring female production. Altered storm patterns and sea-level rise further threaten nesting habitats by eroding or flooding nests, reducing viable incubation sites²⁹.

Fish species with spawning aggregations are also vulnerable to climate disruptions. Changes in oceanographic conditions—such as temperature fluctuations and current patterns, compromise the timing and spatial accuracy of these gatherings, which are essential for reproductive success in many commercially valuable species. These disruptions pose significant challenges to fisheries sustainability and management strategies, as traditional spawning sites become less predictable³⁰. Collectively, these examples underscore the complex interplay between climate change, phenological shifts, and the ecological responses of species, highlighting the urgent need for adaptive conservation measures to mitigate biodiversity loss and maintain ecosystem services.

Phenological mismatch and reproductive failure: One of the most significant consequences of altered reproductive timing due to climate change is phenological mismatch, a phenomenon in which the timing of a critical life-history event such as breeding or hatching, becomes misaligned with the peak availability of essential resources such as food or suitable habitat⁷. This decoupling can have cascading effects on individual fitness and population dynamics. For instance, when offspring emerge before the peak abundance of insects or plant growth, they face reduced food availability, leading to lower survival rates, as documented in multiple avian species. Similarly, shifts in phenology can disrupt established predator-prey relationships, potentially exposing vulnerable life stages to heightened predation risk or creating novel ecological interactions. Furthermore, changes in climatic patterns, such as earlier snowmelt or altered precipitation regimes, can compromise habitat quality by affecting the duration and availability of breeding ponds for amphibians or foraging areas for mammals, ultimately diminishing reproductive success⁹. These interrelated impacts underscore the ecological risks posed by climate-driven shifts in phenology.

GLOBAL SYNTHESIS AND TAXONOMIC EXAMPLES

The impacts of climate change on sexual development and reproductive timing are observed across diverse global ecosystems and taxa:

Aquatic environments

- **Fish:** Many fish species are exhibiting earlier spawning due to warmer waters. TSD fish populations (e.g., Atlantic silverside, sea bass) are experiencing skewed sex ratios, often towards feminization, which could severely limit reproductive potential³¹. Ocean acidification further impacts marine fish by affecting olfactory cues critical for spawning site selection and larval dispersal
- **Marine invertebrates:** Warmer waters accelerate larval development but can also lead to smaller adult sizes and reduced fecundity in crustaceans and mollusks. Ocean acidification impairs shell formation in mollusks and can disrupt reproduction in corals and echinoderms by affecting fertilization and larval survival³²
- **Amphibians:** Many frog and salamander species are breeding earlier in the spring, driven by warmer temperatures³³. However, altered precipitation can lead to desiccation of temporary breeding pools, or extreme rainfall events can wash away eggs and larvae, resulting in complete reproductive failure

Terrestrial environments

- **Reptiles:** Sea turtles are a prime example of TSD species facing severe feminization due to warming beach sands¹⁵. Crocodylians and many lizard species also show vulnerable TSD mechanisms, leading to local population imbalances. Habitat degradation and extreme weather events further threaten nesting sites and hatchling survival
- **Birds:** Hundreds of bird species globally are breeding earlier, with species in temperate zones showing more pronounced shifts³⁴. Arctic-breeding birds face challenges with rapidly melting ice and snow affecting nesting sites and food availability. Phenological mismatch with insect prey is a significant driver of declines in some passerine populations
- **Mammals:** Hibernating mammals are emerging earlier, while some ungulate species are experiencing earlier parturition, sometimes leading to mismatches with peak forage quality. Reproductive success in polar bears is directly threatened by shrinking sea ice, which reduces access to seals, their primary food source, and impacts maternal condition and cub survival³⁵

ECOLOGICAL AND EVOLUTIONARY IMPLICATIONS

The pervasive alterations in sexual development and reproductive timing carry profound ecological and evolutionary consequences:

- **Population demographics:** Skewed sex ratios can drastically reduce effective population size and lower reproductive output, pushing populations towards decline or local extinction³⁶. Reduced fecundity from impaired gametogenesis or reproductive timing failure directly impacts recruitment and population growth.
- **Biodiversity loss:** Species unable to adapt to these rapid changes face heightened extinction risk, contributing to the global biodiversity crisis³⁷
- **Genetic diversity:** Persistent biased sex ratios can lead to a loss of genetic diversity, making populations less resilient to future environmental challenges³⁸
- **Ecosystem function:** Disruptions to fundamental reproductive processes can ripple through food webs, alter species interactions (e.g., pollination, seed dispersal), and impact ecosystem stability and services³⁹
- **Evolutionary trajectories:** While some populations may adapt through plasticity or rapid evolution (e.g., selection for earlier breeding), rapid environmental change may outpace evolutionary rates, leading to maladaptation or evolutionary traps⁴⁰. For instance, shifts in TSD could select for altered temperature sensitivities or the evolution of GSD, but such changes are slow and uncertain

FUTURE DIRECTIONS AND CONSERVATION STRATEGIES

Addressing the reproductive consequences of climate change demands a comprehensive and scientifically informed approach. A deeper understanding of the molecular and physiological mechanisms through which climate stressors affect reproductive processes is essential, including investigations into epigenetic modifications, endocrine disruption, and the cumulative effects of multiple environmental stressors such as rising temperatures and pollutant exposure. Concurrently, the establishment of robust, long-term monitoring initiatives is critical to document shifts in reproductive timing, sexual development, and population dynamics across a wide range of species and ecosystems. Such data are vital for detecting early warning signs of reproductive impairment and projecting future biodiversity risks. Equally important is the evaluation of species-specific vulnerabilities, particularly those with temperature-dependent sex determination or highly specialized reproductive requirements, to prioritize conservation actions. In cases where natural adaptation may be insufficient, proactive measures including assisted migration, habitat rehabilitation, and direct management of reproductive conditions, such as shading sea turtle nests to

balance sex ratios may be warranted. However, while adaptive interventions can provide localized relief, the most effective and sustainable solution lies in aggressive global mitigation of greenhouse gas emissions to slow the pace of climate change and protect the integrity of reproductive systems across the tree of life.

CONCLUSION

Climate change is fundamentally reshaping the reproductive landscape of species worldwide. From the delicate process of sex determination in developing embryos to the synchronized dances of breeding seasons, every aspect of sexual development and reproductive timing is vulnerable to the rapid environmental shifts. The observed patterns of skewed sex ratios, impaired gametogenesis, and widespread phenological mismatches underscore a profound disruption to the very processes that ensure life's continuity. A global synthesis reveals that these challenges are not isolated incidents but a pervasive threat to biodiversity across aquatic and terrestrial realms. Unless significant strides are made in understanding these complex interactions and implementing robust mitigation and adaptation strategies, the long-term reproductive success of myriad species, and the stability of global ecosystems, will remain critically imperiled.

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