The impact of climate change on wolf spider phenology

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Abstract

Anthropogenic climate change (ACC) and global warming are destabilizing factors for ecosystems worldwide. As ectotherms, invertebrates are among the first affected, with warmer temperatures causing faster growth rates. The goal of this research was to examine impacts of rising temperatures due to climate change have on phenology of the Brush-legged wolf spider, *Schizocosa ocreata*. Molt records of spiders collected from the Cincinnati Nature Center as part of ongoing research from 2001 to 2024 were evaluated. From each year, four dates were obtained: the dates when the first male and first female matured, and the dates when half of the male and half of the female populations had matured. Median annual temperatures and growing degree days (GDD - a measure of environmental heat accumulation), were calculated for each year prior to the start of maturation to determine the relationship between temperature and maturation rate. Results show a strong negative correlation between median temperature, GDD and maturation dates, with both male and female wolf spiders maturing 25 to 30 days earlier in 2024 than in 2001. The difference in peak maturation date of typically asynchronous males and females also decreased over the 23-year study, from > 10 days to < 5, with implications for sex ratio and sexual selection. These findings offer evidence that rising temperatures are having a significant effect on the phenology of these common forest-dwelling wolf spiders and underscore the importance of further investigation into the impacts of climate change on other spider populations.

Introduction

Global anthropogenic climate change (ACC) is having well-documented impacts on animal ecology and is a potential threat to worldwide biodiversity (Milligan et al. 2009; Iler et al. 2021). As ectotherms, invertebrates lack the metabolic capacity to regulate their internal temperature, which could make them especially susceptible to the impact of a changing climate, i.e., warmer temperatures speed up metabolism, leading to accelerated growth rates (Cayton et al. 2015; Sable and Rana 2016; Burraco et al. 2020; Harvey et al. 2023). Consequently, much research has focused on the biological responses of invertebrate animals to changes in climate over recent decades (Menendez 2007; Iler et al. 2021). Developmental impacts of climate change and accelerated growth on invertebrate animal ecology are varied, and include altered abundance, resource availability, mismatches in timing of interactions between trophic levels, migration and breeding phenology (Visser and Both 2005; Høye et al. 2009; Morse 2021; Iler et al. 2021).

In many species, survival and reproduction are closely tied to the timing of life-cycle events (Forrest and Miller-Rushing 2010). Phenological shifts in response to climate change have been documented in a wide variety of taxa (Parmesan 2007; Inouye 2022) and could therefore affect population as well as species persistence (Both et al. 2006; Hegland et al. 2009; Memmott et al. 2007; Miller-Rushing et al. 2010). A potentially critical fitness impact of climate changes, especially in ectothermic invertebrates, might be on timing of the reproductive season, especially in species where male and female maturation is asynchronous (Morse 2018; Harvey and Dong 2023), or when synchrony with resources is critical, e.g., plant-pollinator systems (Kudo and Ida 2013).

This study follows up anecdotal observations of increasingly earlier spring maturity in populations of wolf spiders in the Cincinnati area. The goal of this research was to understand what impact rising temperatures due to climate change have had on the reproductive phenology of the Brush-legged wolf spider *Schizocosa ocreata* (Hentz, 1844), which has been studied in our lab for over 45 years. We are fortunate enough to have detailed population records from the last 23 years, which we use here to examine changes in population life history over time.

Materials and Methods

To determine whether spiders were maturing earlier in the season, we evaluated molt records of spiders collected from the Cincinnati Nature Center as part of ongoing research from 2000 to 2024. From these data we obtained the dates when the first male and first female matured, as well as the median dates when 50% of the male and female populations had matured.

Male and female spiders were collected each year in late March/early April as sub-adults (penultimate instar) from the leaf litter at the Cincinnati Nature Center Rowe Woods, a deciduous forest in Clermont County, OH (N 39° 7' 32.894" W 84° 14' 57.692"). Spiders were brought to the laboratory at the University of Cincinnati and maintained under a controlled light/dark cycle (13:11 hour) cycle, stable relative humidity (65–75%) and temperature (22–25C). Individuals were placed into separate opaque plastic deli containers, fed two to three juvenile crickets twice a week and provided water *ad libitum*. Spiders were monitored daily for molt to adulthood, and the dates of maturity were recorded.

For comparison and standardization of spider maturity, we used ordinal dates (i.e., N days following January 1 for each year) for the first mature individual male and female and the median maturation date for 50% of male and female *S. ocreata* in the population collection. We correlated these data on spider maturity with climate data obtained from on-line resources. Data on median annual temperature and mean monthly temperatures for 2000–2024 were obtained from several sources, including websites of the National Oceanic and Atmospheric Administration https://www.weather.gov/wrh/Climate?wfo=iln, Climate Central https://www.climatecentral.org/, and the National Centers for Environmental Information Data Central: https://data.cincinnati.com/weather-data/clermont-county/39025/2024-01-01/?syear=1970&eyear=2024#history.

Previous studies of arthropod phenology and maturation have also used Growing Degree Days (GDD), a measure of heat accumulation, and an index of warming across the season, for prediction of different life stages and assessment of phenology change. We determined GDD values for Southwest Ohio using calculations for each year prior to the start of maturation (April 1) using the Ohio State University Buckeye Appelation GDD calculator https://ohiograpeweb.cfaes.ohio-state.edu/weather/gdd-your-area targeted on Milford, OH, site of the Cincinnati Nature Center where spiders were collected.

Results

The annual life cycle of *S. ocreata* (Fig. 1) has historically shown a peak of maturation for *S. ocreata* in early to mid-May, although recent anecdotal observations from the late 1990's and early 21st century suggested that a shift toward earlier maturation is in progress. Consequently, we sought to validate these early observations with data from our collections.

Ordinal dates of maturity from collections made in 2000–2024 show that first male and female *S. ocreata* maturation date and the median maturation date for 50% of males and females have significantly advanced over the last 24 years (Fig. 2A, B). Maturation now occurs approximately 30 days earlier than in the past.

Comparisons of maturation across years show a strong correlation between median annual temperature and advanced maturation dates. Both the ordinal date of first mature specimens (Fig. 3A) as well as the median or 50% population maturation of both sexes (Fig. 3B) show a significant negative relationship with temperature data. Results using Growing Degree Day values also show a significant correlation between ordinal date of maturation and GDD for the first mature male and female (Fig. 4A), as well as the median maturation data for males, but not females (Fig. 4B).

Males still tend to mature before females, but that time difference is shortening from greater than 10 days to less than 5. These changes in developmental asynchrony are reflected in differences between annual maturation dates of the sexes (Fig. 5). It is apparent from these data that a shift occurs after 2005.

Discussion

The results of this study offer clear evidence of a shift in phenology of *S. ocreata* wolf spiders to an earlier maturation date, and that rising temperatures in the Cincinnati area are having a significant effect. The data show a strong correlation between median annual temperature and advanced maturation dates, with male and female wolf spiders now maturing ~ 30 days earlier than they did in 2001. These results are consistent with previous studies of multiple arthropod species (Menendez 2007; Inouye 2022) as well as several spiders (see Morse 2018; review in Harvey and Dong 2023) in response to anthropogenic climate change (ACC).

Importantly, effects of shifts in climate can also be subtle, with impacts on diverse aspects of arthropod ecology and behavior (Sable and Rana 2016). For example, Kudo and Ida (2013) demonstrated the ecological impact of climate change on "phenological mismatch" underlying plant– pollinator interactions of spring ephemerals and their bumble bee pollinators, resulting in lower seed production from low pollination rates. Similar results were seen in a study by Morse (2021) of the phenological relationships of species in four trophic levels - ferns, a host caterpillar (and its moth), its principal primary parasitoid wasp, and hyperparasitoid wasp – r and hyperparasitoid wasp – in which climate change resulted in significant phenological mismatches measured over 15 years. Kumschick et al. (2011) found that the spider *Argiope bruennichi* has increased its range in Central and Northern Europe during the 20th century. The spread of *A. bruennichi* into formerly cooler areas is apparently driven by

temperature changes arising from global warming. Hu et al. (2024) found behavioral shifts in web mesh size and web area of two orb weaving spider species in response to experimental warming in an alpine meadow research site using open top chambers isolating plots for environmental control. Changes in mesh size were attributed to warming-induced changes in prey size spectra, arising from altered soil moisture and plant community composition. Morse (2018) found that rapid climate change between 1979 and 2010 affected oviposition times of female crab spiders (*Misumena vatia)*, resulting in decreased synchrony among spiders and their bumblebee prey, reducing potential foraging success and possibly fitness.

What impact might a 30 day shift in phenology have on populations of *S. ocreata*?

While we can only speculate, one possibility is that earlier maturation might result in eggs and spiderlings being exposed to more variable temperature and rainfall regimes associated with spring weather. Spiderlings would likely emerge into a different biological community of other arthropods, with potential for differences in prey availability, competition and predation. Importantly, early in the spring, conspicuously courting male *S. ocreata* might be exposed to more intense predation from vertebrate predators (Gunnarson 2007; Gunnarson and Wiklander 2007; Lohrey et al. 2009), such as passerine birds provisioning nestlings with taurine-rich spiders (Arnold et al 2007). In autumn, offspring of *S. ocreata* that matured early might be larger in size and closer to maturity when they enter winter diapause and mature even earlier in the following spring.

A shift in maturation between males and females seen in this study was another critical finding. Historically, males and females were offset in their peak maturation, with males maturing 10 or more days earlier than females, as has been shown in several *Schizocosa* species (Stratton 1984; Hebets 2003; Gilman et al. 2018). This gap has shrunk over time in Ohio *S. ocreata* and in recent years this offset between male and female maturation averages only 5 days apart and brings the sexes closer to synchrony in maturation (Fig. 5). Previous studies have shown that the relative abundance of mature and immature male and female *S. uetzi* can affect pre-mating experience of females, and bias subsequent mate preference (Hebets 2003). In a similar study with *S. ocreata*, the frequency of exposure to males by immature and mature females influenced preferences for male traits and propensity to mate (Stoffer and Uetz 2015, 2016). It is therefore possible that a climate change induced shift in the male-biased sex ratio early in the breeding season might ultimately affect mate preference and sexual selection.

Taken together, these findings confirm our anecdotal observations of a shift in maturity with warming temperatures over the past two decades and underscore the importance of further investigation into the impacts of climate change on invertebrate populations.

Declarations

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Ethics statement - For this type of study formal consent is not required, as it was conducted with previously collected data. Regardless, to our knowledge, no animal welfare laws or regulations in the USA or the State of Ohio govern the use of invertebrates such as spiders in research. During the original studies from which maturation data were collected, wherever possible we adhered to the "Guidelines for the treatment of animals in behavioral research and teaching" (Animal Behavior (2013) 85: 287–295) of the Animal Behavior Society. At the end of those studies, spiders were either transferred to another researcher in the Uetz lab for further study, or ultimately humanely euthanized with CO_2 and freezing.

Conflict of interest statement - The authors have no conflict of interest.

Data availability statement - The datasets generated during and/or analyzed during the current study are available at https://data.mendeley.com/datasets/j3yjv5b2t3/1 upon embargo release date on 30 January 2026.

Author Contributions - GU originally formulated the idea; ZH and OBN developed methodology; ZH and OBN conducted data collection; GU, ZH and OBN performed statistical analyses; ZN prepared the poster from which the manuscript is derived; GU wrote the manuscript.

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Figures

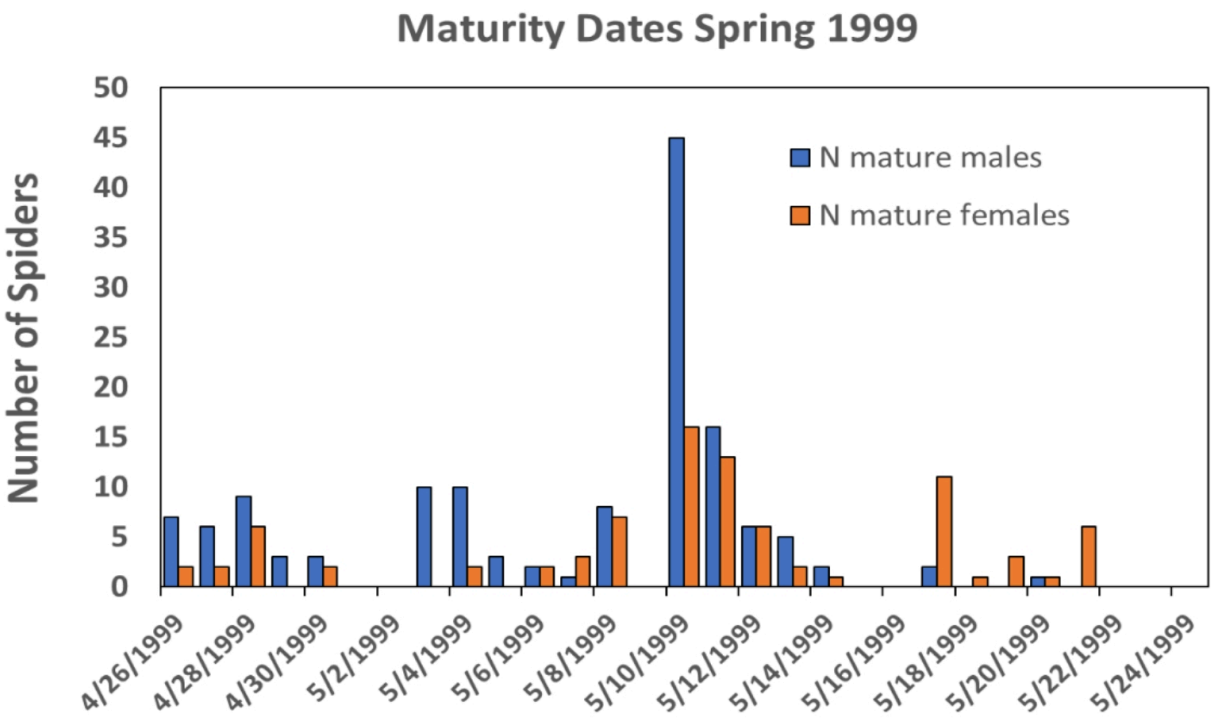

Figure 1

Typical phenology of *S. ocreata*. Bars indicate maturity dates of male and female spiders collected from the field in the spring of 1999 prior to the beginning of this study.

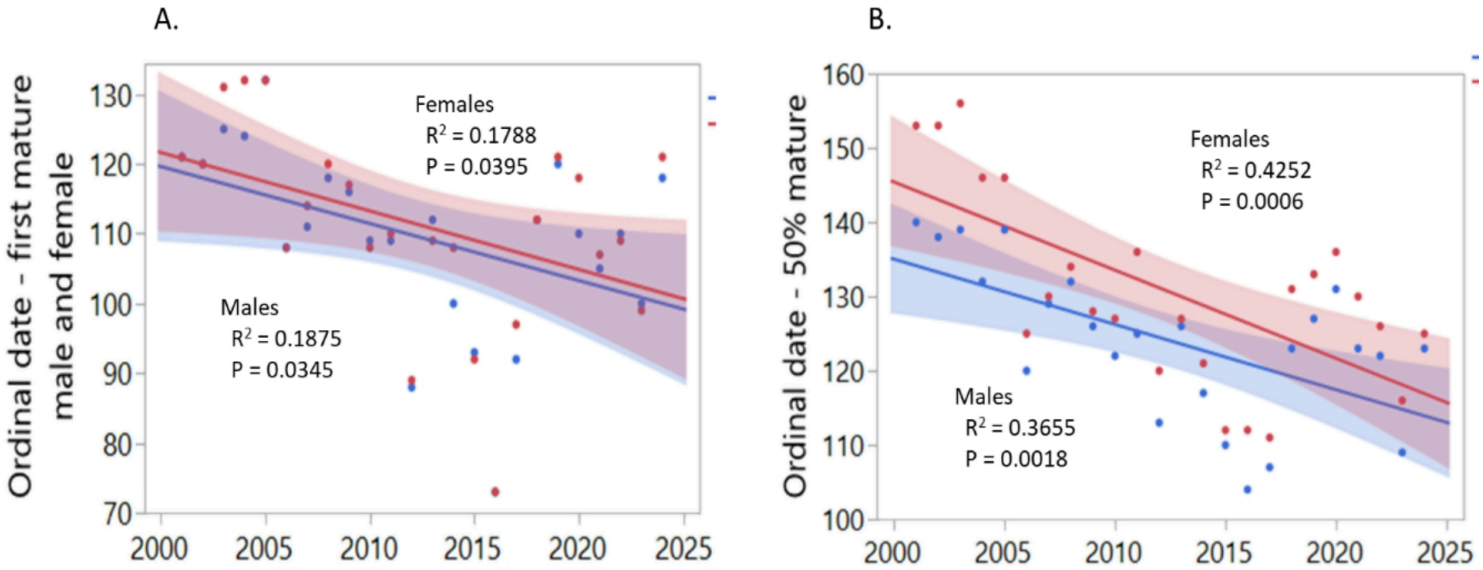

Figure 2

Regressions of ordinal dates of first mature specimen (A) and median (50%) population maturation (B) by year.

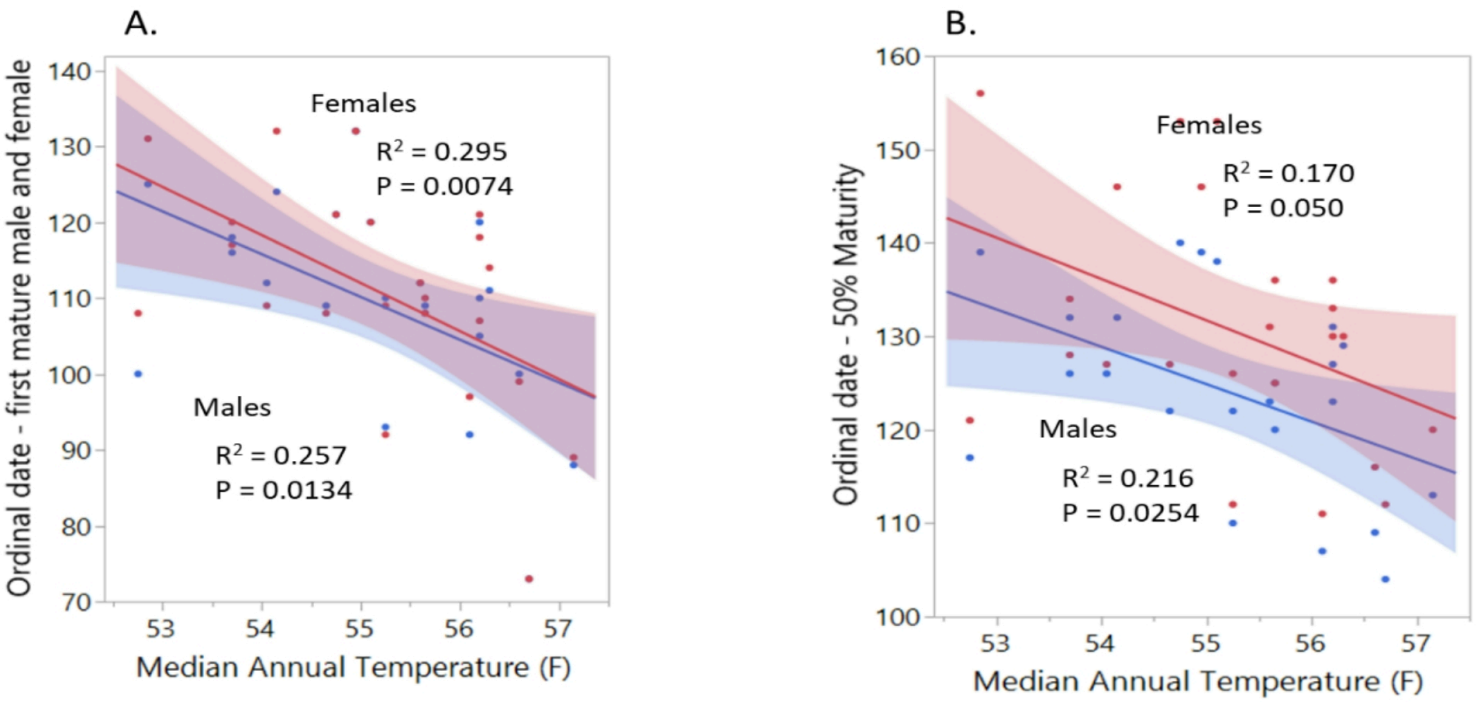

Figure 3

Regressions of ordinal dates of first mature specimen (A) and median (50%) population maturation dates (B) with median annual temperature for the Cincinnati, Ohio region.

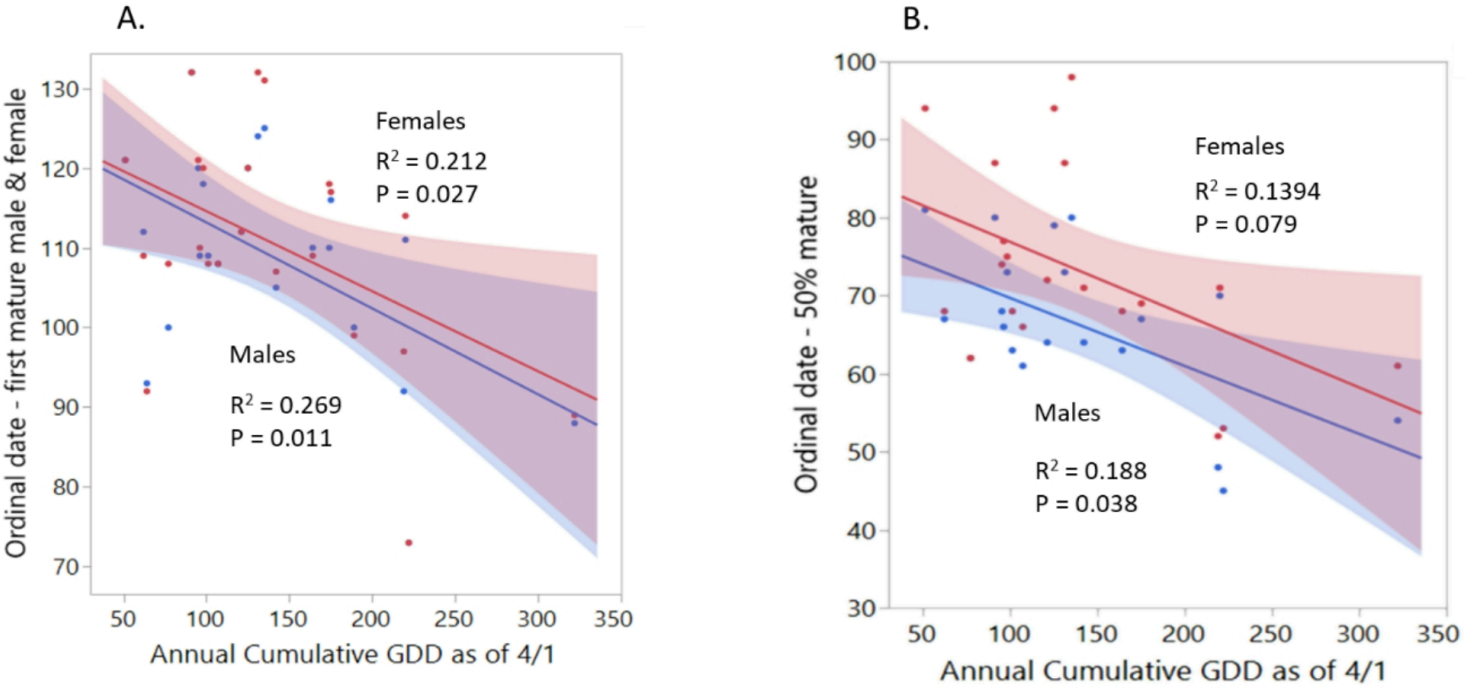

Figure 4

Regressions of ordinal dates of first mature specimen (A) and median (50%) population maturation dates (B) with cumulative Growing Degree Days (GDD) for the Milford, Ohio region.

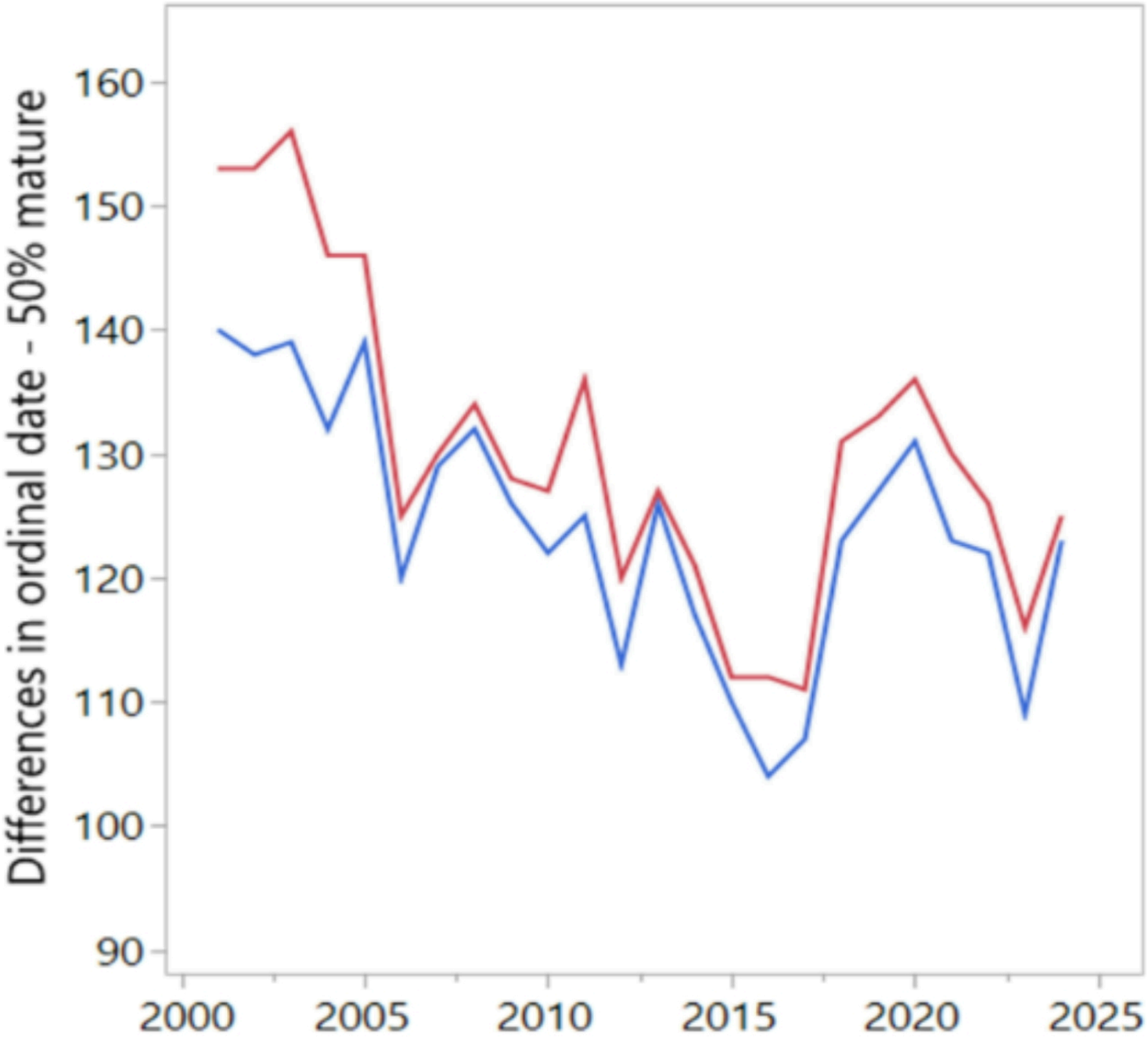

Figure 5

Differences in ordinal date of peak maturation (50% of population) between sexes. Red line – male, blue line – female.