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Plasticity vs. Climate: The Hidden Survival Costs for Bees and Wasps

Biology * Environment * Climate Change

Introduction: Climate-Driven Phenological Shifts and Ectothermic Constraints

Global climate change is rapidly reshaping terrestrial communities, altering the metabolic rates and seasonal phenology of ectothermic organisms.[1] Temperate insects must synchronize their post-winter emergence with spring floral blooms or invertebrate prey availability. When rising ambient temperatures disrupt historical thermal cues, the resulting phenological shifts carry severe consequences for individual fitness, population demography, and broader ecosystem stability.

Emergence timing is governed by the interaction between regional genetic adaptation and phenotypic plasticity -- the ability of a genotype to alter its physiological or phenological response to immediate environmental variation.[1] While plasticity buffers populations against short-term anomalies, it exacts a steep energetic toll. Because ectothermic metabolic kinetics scale exponentially with temperature according to the Arrhenius equation, warmer overwintering temperatures accelerate resting respiration and deplete finite energy stores, eroding emergence body mass, longevity, and fecundity.[1]

A landmark 2026 study by Ganuza et al. in Functional Ecology -- titled "Climatic origin and plasticity shape emergence timing and fitness in bees and wasps under experimental climate regimes" -- quantifies these eco-evolutionary trade-offs across 14,921 wild cavity-nesting hymenopterans.[1][2] Combining regional space-for-time sampling across southern Germany with common-garden climate chambers, the researchers show that while solitary bees and predatory wasps exhibit pronounced thermal plasticity, local adaptations and developmental constraints severely erode emergence body mass under accelerated warming, placing cool-adapted spring pollinators at acute demographic risk.[1]

Evolutionary Architecture of Trait Variation and the LandKlif Multi-Scale Framework

Across thermal gradients, phenotypic reaction norms are shaped by the covariance between environmental temperature potentials and underlying genetics.[4] Under cogradient variation, genetic adaptation and environmental influence covary positively, amplifying phenotypic divergence across a gradient.[4][5] In cogradient insects, warm-origin genotypes possess an intrinsic predisposition for early emergence that acts synergistically with warm spring temperatures to trigger hyper-early emergence.[1]

Conversely, countergradient variation arises when genetic and environmental effects covary negatively.[4][5] Driven by natural selection in cold habitats with compressed growing seasons, cold-origin populations evolve lower thermal thresholds

or faster developmental rates to compensate for ambient cold, whereas warm-origin populations evolve conservative, higher thermal thresholds to avoid premature emergence during false springs.[1][5][6][7] When relocated to a common garden, cold-origin genotypes develop faster or emerge earlier than warm-origin conspecifics under identical temperatures.[1][7]

To isolate these evolutionary patterns from habitat disturbance, the Ganuza et al. (2026) investigation operated within the Bavarian Climate Research Network (bayklif) LandKlif project led by Prof. Dr. Ingolf Steffan-Dewenter at the University of W rzburg.[8] Utilizing a multi-scale space-for-time substitution design across a 5.8 km x 5.8 km Bavarian grid, the consortium selected 60 independent landscapes spanning forests, grasslands, arable agriculture, and urban settlements crossed orthogonally with regional multi-annual mean temperatures (MAT) to decouple warming from land-use intensification on biodiversity.[8][9]

Experimental Climate Regimes and Ecological Profiles of Target Taxa

Researchers extracted 14,921 hibernating hymenopterans from 6,449 wild trap nests across 161 sites spanning a regional MAT gradient from 5.9 deg C to 10.0 deg C.[1] After overwintering outdoors under ambient conditions to standardize diapause, nests were transferred into climate chambers from March 16 to September 24, 2019, under three post-winter thermal regimes:[1]

* Cold Treatment (CT): Cooler-than-average, delayed spring conditions testing minimum emergence thresholds.[1]

* Warm Treatment (WT): Intermediate baseline simulating current regional averages and moderate near-term warming.[1]

* Hot Treatment (HT): Extreme accelerated warming calibrated to the warmest origin site plus 5 deg C.[1]

Upon emergence, individuals were frozen at 20 deg C and oven-dried at 60 deg C to determine scaled dry body mass.[1] In solitary hymenopterans, emergence dry mass reflects finite larval lipid reserves governing adult lifespan, flight range, and brood provisioning.[1] Models also tracked T -- the temperature deviation from long-term MAT during the pre-emergence larval year -- to separate developmental acclimation from genetic origin.[1]

| Species Name | | Taxonomic Family | | Seasonal Niche | | Overwintering Stage | | Ecological Role |

| Osmia bicornis | | Megachilidae | | Spring | | Fully developed adult | | Solitary pollinator |

| Chelostoma florisomne | | Megachilidae | | Spring | | Fully developed adult | | Solitary pollinator |

| Heriades truncorum | | Megachilidae | | Late Summer | | Prepupa / Larva | | Solitary pollinator |

| Hylaeus difformis | | Colletidae | | Summer | | Prepupa / Larva | | Solitary pollinator |

| Trypoxylon figulus | | Crabronidae | | Summer | | Prepupa / Larva | | Predatory

hunting wasp |

Table 1: Ecological profiles and overwintering stages of the five cavity-nesting hymenopteran species analyzed.[1][3]

Cogradient vs. Countergradient Emergence Responses and Fitness Costs

Across all five taxa, emergence occurred earliest in the Hot Treatment (HT) and latest in the Cold Treatment (CT), confirming pronounced post-winter plasticity.[1] However, climatic origin (MAT) interacted with thermal regime in opposite directions depending on overwintering stage.[1][3]

Spring-emerging species (Osmia bicornis and Chelostoma florisomne), which overwinter as fully developed adults inside cocoons, exhibited cogradient variation: individuals from warmer origin sites (higher MAT) emerged earliest in the Warm and Hot treatments.[1][3] Conversely, summer-emerging species (Heriades truncorum, Hylaeus difformis, and the hunting wasp Trypoxylon figulus), which overwinter as prepupae or larvae and complete metamorphosis post-winter, displayed countergradient variation.[1][3] In the Cold Treatment, female H. truncorum from warmer origin sites emerged 14.1 to 22.9 days later than females from cooler climates, reflecting a high thermal threshold evolved in warm regions to avoid premature mid-spring metamorphosis.[1] Furthermore, emergence timing in the Warm Treatment was modulated by larval-year T, showing that early-life thermal anomalies leave a physiological or epigenetic legacy.[1]

These plastic shifts incurred severe metabolic fitness costs. For spring species like O. bicornis, warming progressively eroded emergence mass, with individuals achieving peak mass only in the Cold Treatment.[1] The steepest mass losses occurred in cool-adapted populations from low-MAT sites, whose unadapted metabolic machinery rapidly burned through stored lipids under elevated heat.[1] Conversely, summer species reached higher body mass in the Warm and Hot treatments because warmth facilitated post-winter metamorphosis; however, summer females whose emergence was delayed within those warm regimes lost up to 34% of their total dry body mass prior to nest exit.[1]

Phenological Mismatch, Trophic Cascades, and Synergistic Land-Use Stressors

Because flowering plants often rely on photoperiods while insects respond to accumulated degree-days, rapid warming drives plant-pollinator phenological mismatch.[11][13] Early-emerging spring bees with depleted lipid reserves risk starvation if emergence precedes blooming, triggering pollinator declines and secondary plant extinctions -- especially at higher latitudes and among specialists.[11][12] Phenological decoupling in the wasp Trypoxylon figulus similarly disrupts spider and aphid predation and propagates into ichneumonid parasitoids (Nematopodius debilis), initiating a trophic cascade across guilds where hymenopterans act as keystone species.[1][9][10]

| Land-Use Type | | Primary Environmental Stressor | | Compounding Effect on Pollinators |

| Urban Settlements | | Urban Heat Islands (UHI) | | Amplifies warming, increasing

metabolic mass loss. |

| Urban Settlements | | Impervious Surfaces | | Alters hydrology, increases drought, reduces floral abundance. |

| Conventional Agriculture | | Pesticide Application | | Disrupts chemical communication and navigation. |

| Conventional Agriculture | | Floral Homogenization | | Reduces resource diversity needed by specialist taxa. |

| Semi-Natural Forests | | Edge Habitat Provision | | Buffers thermal extremes, provides woody nesting cavities. |

Table 2: Interactive effects of local land-use regimes on climate-stressed hymenopteran populations.[9]

In urban zones, impervious surfaces amplify Urban Heat Islands while disrupting local hydrology and groundwater recharge, intensifying drought and floral scarcity.[9] In conventional agriculture, floral homogenization and insecticides such as flupyradifurone disrupt cuticular signaling in H. truncorum, compounding the 34% mass penalty, whereas semi-natural forest edges buffer thermal extremes.[9][14]

Conclusion: Synthesis of Phenological and Demographic Dynamics

The 2026 Ganuza et al. investigation across 14,921 cavity-nesting bees and wasps proves that phenotypic plasticity alone cannot protect ectotherms from accelerated climate warming.[1] With cool-adapted spring pollinators suffering acute lipid depletion under warming and delayed summer females losing up to 34% of their emergence mass, conservation strategies must pair climate mitigation with pesticide-free forest-edge and grassland refugia to prevent plant-pollinator network collapse.[1][9][12]

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