



# Synergistic effects of elevated temperature with pesticides on reproduction, development and survival of dung beetles

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## Abstract

In times of global change, high temperatures can increase the negative effects of pesticides and other stressors. The goal of this study was to evaluate, under controlled laboratory conditions, the effect of a moderate increase in temperature in combination with ivermectin (an antiparasitic medication used in cattle that is excreted in dung), an herbicide, and parasitic pressure, on the reproductive success, development time and adult survival of dung beetles *Euoniticellus intermedius*. Whereas high temperature increased the number and proportion of emerged offspring, it had synergistic negative effects in combination with the ivermectin, herbicide and parasite treatments. Moreover, high temperature in combination with ivermectin and with parasitism caused a synergistic increase of adult offspring mortality and, in combination with the herbicide, it synergistically accelerated development. These results indicate that high temperatures can enhance the negative effects of other stressors and act synergistically with them, harming dung beetles, a group with high ecological and economic value in natural and productive ecosystems. Although adult sex ratio was not affected by experimental treatments, contrasting responses were found between males and females, supporting the idea that both sexes use different physiological mechanisms to cope with the same environmental challenges. The effects that combined stressors have on insects deepen our understanding of why we are losing beneficial species and their functions in times of drastic environmental changes.

**Keywords** Independent action model · Invasive species · Ivermectin · Parasitism · Fitness

## Introduction

Current global warming acts in combination with other environmental factors and influences the reproductive success and abundance of insects (Noyes et al. 2009; Gunderson et al. 2016; Tran et al. 2018; Iltis et al. 2020; Turschwell et al. 2022). Factors linked to changes in land cover and biodiversity loss, such as the presence of chemical contaminants, higher rates of parasitism, or the decrease in the availability of resources, can have negative consequences on the survival and reproduction of insects (Folt et al. 1999; Siviter et al.

2021; Verheyen and Stoks 2023). When two or more stressors occur simultaneously, their combined effects on organisms can be additive (the sum of their individual effects), antagonistic (smaller effect together than alone), or synergistic (greater effect in combination of stressors than the sum of their individual effects). The latter are of particular concern, due to the great threat they represent to living organisms (Folt et al. 1999; Verheyen et al. 2019; Siviter et al. 2021; Verheyen and Stoks 2023).

Insects are particularly vulnerable to temperature changes since they depend on environmental temperature to control their internal temperature (Atkinson 1994; González-Tokman et al. 2020a; Mastore et al. 2023). Therefore, insects have evolved physiological and behavioral strategies to avoid the noxious effects of warming (González-Tokman et al. 2020a; Bodlah et al. 2023), but such mechanisms can be highly costly and constrain insect adaptation to warm temperatures (García-Robledo et al. 2016). Consequently, insects are highly threatened by increasing temperatures and strongly rely on phenotypic plasticity to be able to face these thermal challenges

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