BIODIVERSITY
Published: 10 February 2023
doi: 10.3389/frym.2023.863219

WHY INSECTS CANNOT STAND THE HEAT OF CLIMATE CHANGE

Kris Sales[1*], *Jessie Gardner*[2], *Louis G. O'Neill*[3,4] *and Ramakrishnan Vasudeva*[5]

[1] *Urban Forest Research Group, Forest Research, Forestry Commission, Farnham, United Kingdom*
[2] *Arctic Marine System Ecology, The Arctic University of Norway, Tromsø, Norway*
[3] *Department of Biological Sciences, Macquarie University, Sydney, NSW, Australia*
[4] *Centre for Ecology and Conservation, University of Exeter, Penryn, United Kingdom*
[5] *School of Biological Sciences, University of East Anglia, Norwich, United Kingdom*

YOUNG REVIEWER:

MELODY
AGE: 12

Climate change is gripping our planet. News headlines proclaim warmer winters and hotter summers, and these changes are impacting Earth's biodiversity. Have you ever wondered how climate change causes extinctions? This is an important, ongoing research question because understanding how heat impacts living organisms could help us predict how species will cope in a warmer world and give us the knowledge we need to help vulnerable organisms. Insects make honey, pollinate crops, control pests, and recycle waste into nutrients. Despite being numerous and often helpful to humans, insects, and the effects that climate change is having on them, are often overlooked. Due to climate change, heatwaves are becoming more common and intense. In this article, we explore the impact of simulated heatwaves on a beetle species in the laboratory. Keep

reading to learn about how heatwaves could cause damage that lasts over generations, potentially leading to extinctions.

CLIMATE CHANGE: MOVE, ADAPT, OR DIE

Climate change is gradually raising the temperature of our planet. This warming is increasing the intensity, length, and frequency of unusual and extreme weather patterns. **Heatwaves** are a hazardous type of extreme weather event. A heatwave can be defined as 5 days in a row with temperatures 5°C hotter than historical averages. In the future, heatwaves will be even more common and intense. To cope with heatwaves, people and animals must change how they live. If they fail to do so, species may face severe consequences, including stress or even extinction.

HEATWAVE

An extreme weather event in which temperatures are hotter than expected. Heatwaves are becoming more common and hotter because of climate change.

For decades, as Earth has warmed, we have seen nature respond to the stress of higher temperatures. Some species have shifted where they live and when they reproduce, while others have changed how they live (Figure 1) [1]. For example, some birds are breeding earlier in the year when the weather is milder. Plants and animals have moved

		Some impacts of climate change							
Group	Example animals	Heat deaths	Reduced health	Habitat loss	Disease	Extreme weather	Increased predation / competition	Reduced resources	Ocean acidification
Mammal	American pika Spectacled flying fox Polar bear Mosaic-tailed rat	✓	✓	✓	✓	✓	✓	✓	
Bird	Pied flycatcher House finch Helmeted honey eater Hawaiian honeycreeper	✓	✓	✓	✓	✓		✓	
Reptile	Green turtle Common lizard Australian bearded dragon Ridley sea turtle		✓	✓	✓	✓		✓	
Amphibian	Poison dart frog Common toad Rough skinned newt Strawberry poison frog		✓	✓	✓	✓	✓	✓	
Fish	Chinook salmon Damselfish Brown trout Eelpout	✓	✓		✓		✓	✓	✓
Shellfish/Coral	Green sea urchin Tellin clam Porcelain crab Gorgonian coral	✓	✓	✓	✓	✓	✓	✓	✓
Plankton	Sea butterflies Foraminifera Antarctic diatoms Sea urchin larvae	✓	✓				✓	✓	✓
Bee	Arctic bumblebee Fragrant bumblebee Buff-tailed bumble-bee Honeybee			✓	✓	✓		✓	
Butterfly	Monarch Edith checkerspot Wall brown Large skipper		✓	✓	✓	✓		✓	
Beetle	Chestnut weevil South American rove beetles Bark beetles 7 spot ladybird			✓		✓	✓	✓	

Figure 1

Figure 1

Climate change can affect species in a variety of ways. Check marks show where scientific studies have found different negative impacts on different animal groups. Scientists are still researching the responses of species to climate change, so this table will likely keep changing over time as we learn more.

further up mountains or toward the poles, searching for cooler areas. Many insects have become smaller and lighter in color to cope with higher temperatures. However, if warming is too great or happens too quickly, species risk extinction. Some organisms, like coral, are very vulnerable because they are slow to grow and move. Others, like polar bears, have shrinking habitats and nowhere else to go. It has already been too late to save some species, like the golden toad, from extinction due to climate change.

HOW DOES CLIMATE CHANGE CAUSE EXTINCTIONS?

Humans are face drastic changes to Earth's weather due to climate change, including droughts, flooding, and unusual rainfall; and extinctions due to climate change are already happening. In 2013, scientists realized that very few studies on climate change (only 1 in 20) investigated *how* climate change causes extinctions [2]. Learning how climate change impacts Earth's species will help us predict how those species will cope in the future. This knowledge will also help us focus our efforts to help vulnerable life forms as their habitats change.

The idea for our study came from some research reporting that short and unnatural heat shocks damaged reproduction in male humans and farm animals. We thought that, with rising temperatures, male reproduction could be negatively affected. To test this hypothesis, we exposed an insect species to simulated heatwaves in a laboratory. We studied whether damage to reproduction occurred after heat exposure, and whether it could be repaired after a certain time.

WHY STUDY INSECTS?

Despite existing in huge numbers and making up about half of all species, insects are often overlooked. Many insects are helpful to us; they pollinate crops, produce fertilizer, and make foods like honey. They are also very important for the planet's health because they are food for larger animals and they help to control certain pests. Insects are "cold blooded," so they need external warmth to be active. However, too much heat can be damaging. This makes certain insects good model animals to use in laboratory experiments exploring the impact of heatwaves. Hopefully, laboratory findings like ours can help inform conservation efforts for vulnerable life forms and biodiverse ecosystems.

PUTTING THE HEAT ON MALES

Several years ago, red flour beetles (*Tribolium castaneum*) were caught in the wild. These beetles can be grown in dishes filled with flour, yeast, and oats. At 30°C, it takes a month for an egg to develop into a fertile adult. Adults mate every month, and their offspring form a new generation. This keeps population numbers healthy.

To explore the impact of heatwaves, males and females were separated during the cocoon stage, to make sure they could not mate. This research looked at males, which were kept at either the normal 30°C or given a 5-day, 42°C "heatwave". We chose 42°C because this is the summer heatwave temperature in over 90 countries. Afterwards, the survival of heated and unheated males was compared. Each survivor was paired with an unheated female, for a chance to mate. The success of mating behavior was recorded, and the male beetles were dissected so their reproductive organs and sperm could be examined with a microscope. After mating, the females were isolated in flour until they produced offspring, which were then counted. We looked at the impact of heatwaves on offspring health and lifespan, and male offspring fertility. The number and quality of offspring produced is important for success in nature.

MALE REPRODUCTION CANNOT STAND THE HEAT

We found that heatwaves damaged various aspects of male reproduction (Figure 2). First, we saw that males exposed to heatwaves had worse mating behavior, being less likely to start and slower to finish it. Heat exposure also shrank the size of males' testes, which limited sperm creation. Heated males created 75% less sperm than unheated males, and half of the sperm produced were dead! After heated males transferred sperm packets to females, only half the number of sperm were stored inside her, compared to packets from unheated males.

Females mated to heated males laid fewer eggs, and the eggs they did produce were half as likely to hatch. It may be that sperm from heated males were unable to fertilize eggs, or that the heat damaged genes and caused the embryos to stop growing, or both. Concerningly, heatwaves experienced by adult beetles caused long-term damage to the health of unheated offspring [3]! On average, unheated flour beetles live for around a year, but offspring from heated fathers died 8 weeks earlier! Male offspring from heated fathers were slower at mating, less likely to fertilize females, and created fewer offspring from successful matings.

LIFE STAGE

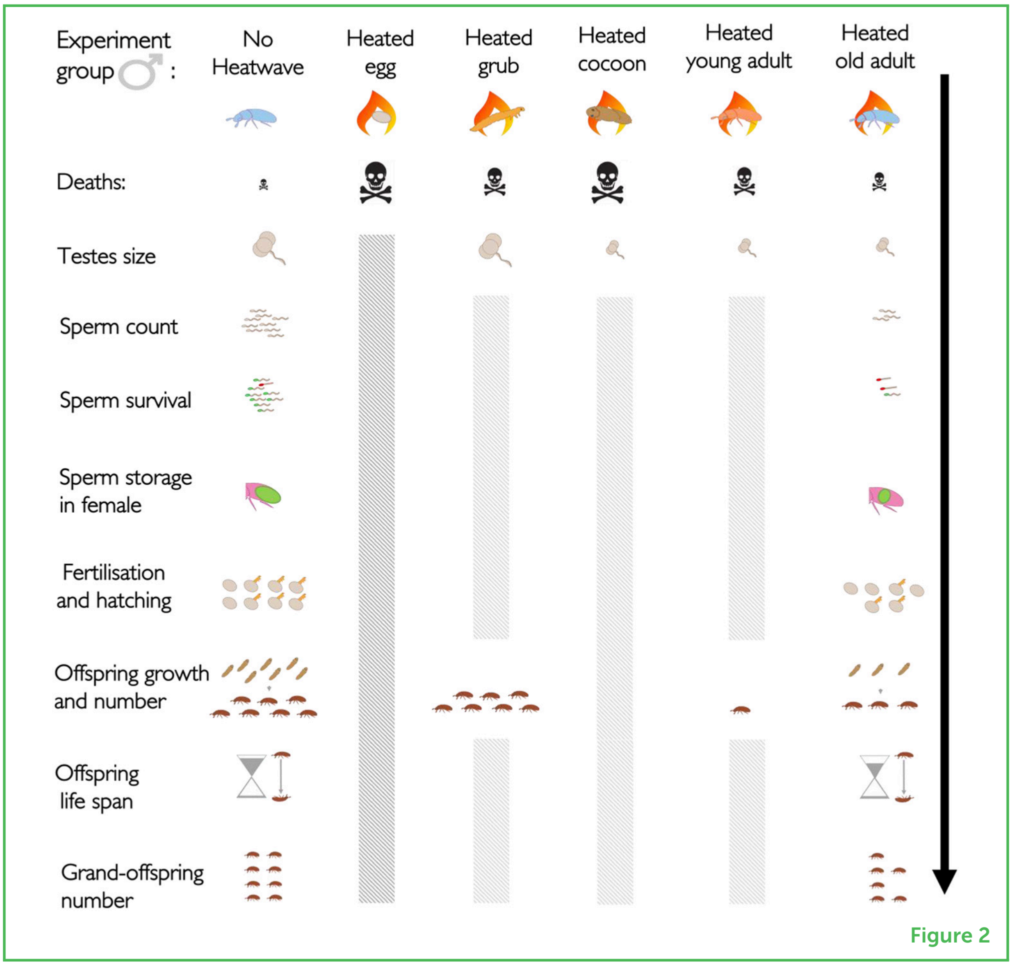
A life stage is one part of a complex life cycle. For example, beetle growth changes drastically from ova (eggs) to larvae (grubs), then pupae (cocoons), followed by imago (adults).

INSECT LIFE STAGES MATTER!

The findings described above were all from heating adult beetles. However, insects have a complex life cycle in which big changes happen in stages; think about caterpillars becoming butterflies, for example. We wondered whether these very different **life stages** might respond differently to heat stress. We compared the response of

Figure 2

Heatwaves can impact a series of traits in male insects, which vary depending on the life stage exposed. Heatwaves were most deadly for beetles at the egg or cocoon stage. Heated adult males had damage to their testes, sperm quantity, and sperm quality. This reduced males' ability to fertilize eggs, and the number and health of offspring produced. Impacts were even seen in grand-offspring production! The seriousness of damage is shown by the amount icons are reduced in number or size. Grey bars display traits for life stages which were not practical (light), or possible (dark), to measure.



eggs, grubs, cocoons, young adults, and mature adults to 5-day, 42°C heatwaves.

We found that heatwaves killed all eggs and cocoons, showing these are the most vulnerable life stages. The heat might have impacted the sensitive developmental changes occurring during these stages. Most mature adults survived heatwaves, probably thanks to their thick shells. Surviving male grubs, young adults, and mature adults were then given females to mate with. As expected, heated mature adults created half as many offspring. Interestingly, heating sterilized young adults (making them completely unable to produce offspring), while it did not hurt the reproduction of grubs! This pattern may be linked to sperm production. Young sperm could be heat resistant, middle-aged sperm could be very vulnerable, and old sperm could be somewhere between the two.

COULD INSECT REPRODUCTION COPE IN A WARMER WORLD?

Our results show that heatwaves cause alarming damage to insects, particularly to the reproductive functions of males at immature life

HARDENING

Process by which stress causes changes in an individual that protect that individual from future stress.

RESILIENCE

The ability of an individual to repair damage caused by stress, if given sufficient recovery time.

stages. We wondered whether beetles could adapt by increasing their defense against heatwaves. So, we tested whether heated males were more resistant to a second heatwave. The process by which stress causes changes in an individual that make it more resistant to future stress is called **hardening**. Unfortunately, the second heatwave was even *more* damaging for males, showing that hardening did not happen.

On the bright side, however, we found that heatwave damage was not permanent. Males showed **resilience**, meaning they could recover to the way they were before heating, possibly through the processes cells use to repair themselves after an injury. We tested this by mating heated males with females every 5 days after a heatwave. Some of the males' reproductive functions recovered to normal levels 15–25 days after the heatwave (Figure 3). Repair was even possible for males that had been sterilized by heat, such as those that were heated twice or heated while they were young. Other experiments showed that females could cope with the risk of mating with a heat-damaged male

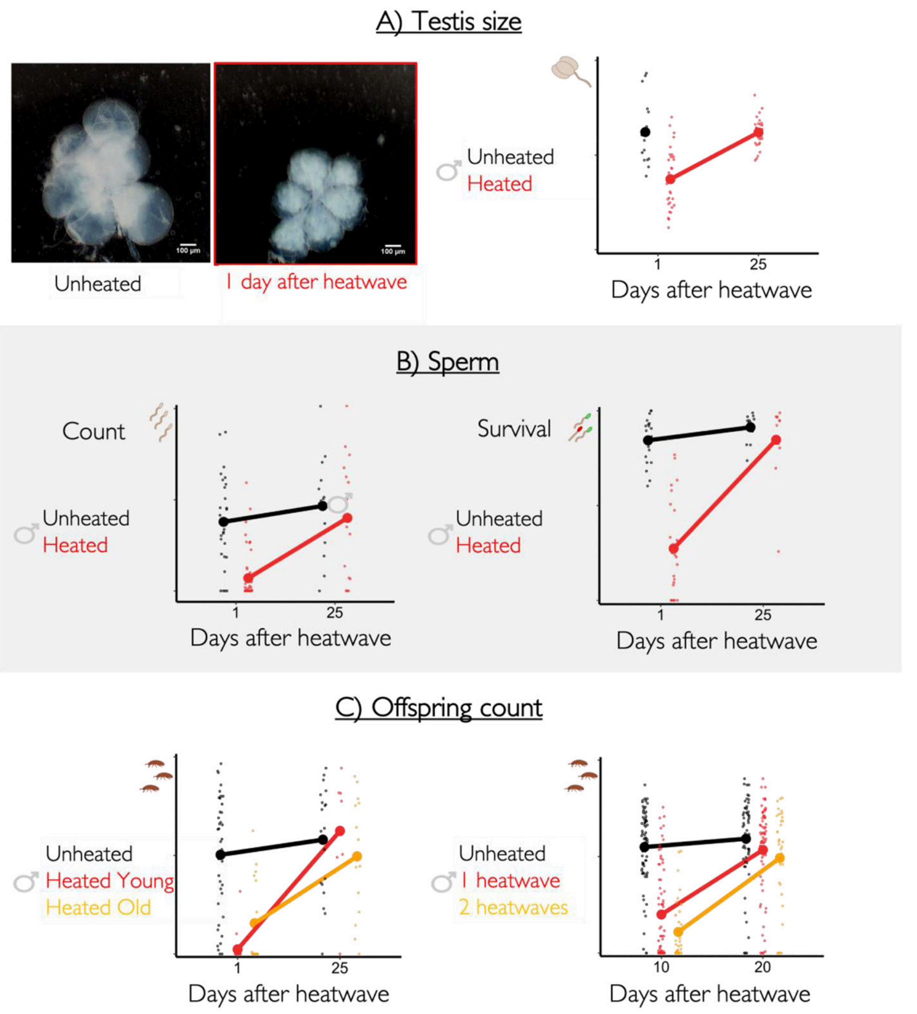


Figure 3

Figure 3

The reproductive functions of male beetles can recover after heatwave damage. Recovery takes, at most, 25 days of rest. **(A)** A heatwave can shrink testes by almost half, but they can return to normal. **(B)** Heatwaves can temporarily reduce sperm counts and sperm survival to less than half of expected. **(C)** Previously heated males do not show protective hardening when they are exposed to a second heatwave; their offspring production is still damaged. However, neither male age or hardening status affect the recovery of males' offspring production. Small dots show datapoints, and large dots are averages.

in a warmer world [4]. For example, females were more likely to mate with healthy males after mating with heat-damaged males.

WHAT DO OUR FINDINGS MEAN FOR THE FUTURE?

Our experiments demonstrate that the high temperatures currently seen in nature can kill young insects, reduce male reproduction, and cause damage that lasts across generations. We found that damage increases with higher temperatures and longer heatwaves. Since we used a beetle species in our studies, it is likely that our results are similar to what would happen in the wild. Recently, studies have found that males of other insects, like moths, bees, and flies, are also vulnerable to heat. Moreover, research combining data from multiple studies found that temperatures at which male insects are fertile (rather than temperatures at which they can survive) are better predictors of where those species live [5]!

As global warming and heatwaves worsen, natural populations will shrink over time because fewer individuals survive and reproduce. This could explain some local extinctions that have already been witnessed. Importantly, the vulnerability of insect species has knock-on effects up the food chain, because the birds and animals that normally eat insects could starve in the absence of insect populations. Although this loss of insects and biodiversity is concerning, there is still hope since it seems possible for life forms to recover from and adapt to heat. Humans can help by conserving their present habitats, giving them access to cooler areas, and doing our best to limit climate change.

ACKNOWLEDGMENTS

The study was supported in the UK by a Natural Environment Research Council (NERC) project grant (NE/K013041/1) and NERC EnvEast DTP studentship (Award Ref: 1540234). We dedicate this paper to Prof. Matthew J. G. Gage, who started and supervised this research, which now continues in his memory.

ORIGINAL SOURCE ARTICLE

Sales, K., Vasudeva, R., and Gage, M.J.G. 2021. Fertility and mortality impacts of thermal stress from experimental heatwaves on different life stages and their recovery in a model insect. *R. Soc. Open Sci.* 8:201717. doi: 10.1098/rsos.201717

REFERENCES

1. Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evo. Syst.* 37:637–69. doi: 10.1146/annurev.ecolsys.37.091305.110100

2. Cahill, A. E., Aiello-Lammens, M. E., Fisher-Reid, C. M., Hua, X., Karanewsky, C. J., Yeong Ryu, H., et al. 2013. How does climate change cause extinction? *Proc. Biol Sci.* 280:20121890. doi: 10.1098/rspb.2012.1890
3. Sales, K., Vasudeva, R., Dickinson, M. E., Godwin, J. L., Lumley, A. J., Michalczyk, Ł., et al. 2018. Heatwaves damage sperm function and cause transgenerational fitness decline in a model insect. *Nat. Commun.* 9:4771. doi: 10.1038/s41467-018-07273-z
4. Vasudeva, R., Dickinson, M., Powell, S., Sutter, A., Sales, K., and Gage, M. J. G. 2021. Polyandry protects females against heatwave-induced male infertility. *Anim. Behav.* 178:37–48. doi: 10.1016/j.anbehav.2021.05.016
5. Parratt, S. R., Walsh, B. S., Metelmann, S., White, N., Manser, A., and Bretman, A. J. 2021. Temperatures that sterilize males better match global species distributions than lethal temperatures. *Nat. Clim. Change* 11:481–4. doi: 10.1038/s41558-021-01047-0

SUBMITTED: 26 January 2022; **ACCEPTED:** 24 January 2023;
PUBLISHED ONLINE: 10 February 2023.

EDITOR: John T. Van Stan, Cleveland State University, United States

SCIENCE MENTOR: Malgorzata Lagisz

CITATION: Sales K, Gardner J, O'Neill LG and Vasudeva R (2023) Why Insects Cannot Stand the Heat of Climate Change. Front. Young Minds 11:863219. doi: 10.3389/frym.2023.863219

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

MELODY, AGE: 12

Melody is a young activist and climate justice warrior with hopes to change the world 1 day. She has lived in Europe and Australia, and enjoys reading and writing. Melody also enjoys playing and talking to her siblings and friends.

AUTHORS

KRIS SALES

Kris is a natural scientist interested in climate change, evolution, reproduction, and aging. Kris was born in Brighton, England. He studied in Norwich for a decade, earning a Ph.D. there (https://bit.ly/31IpQyG). Kris mainly experimented with insects (https://bit.ly/3woE7Po) and roundworms (https://bit.ly/39DShT5) in the laboratory. Kris loves teaching about animal behavior, woodlands, and statistics (https://bit.ly/3dAGsxW). Recently, Kris has been a marine biologist in Norway (https://bit.ly/3jflVU8) and a teacher in Morocco (https://bit.ly/3ujoGWL). Currently, he is a forest scientist in England (https://bit.ly/3vXyQg8). *krisreynardsales@gmail.com

JESSIE GARDNER

Jessie is a polar marine ecologist studying the consequences of climate change on life within and beneath sea ice. She is originally from the UK, where she spent time at the British Antarctic Survey and the University of East Anglia investigating the impact of ocean acidification and warming on pteropods (sea snails that swim with their foot) in the Southern Ocean. Currently, she is a postdoctoral researcher at UiT—The Arctic University of Norway and part of an international project that froze an icebreaker (Polarstern) into the Arctic sea ice for an entire year (https://follow.mosaic-expedition.org/). Jessie enjoys exploring remote and extreme places.

LOUIS G. O'NEILL

Louis is a behavioral ecologist and a passionate conservationist. He is originally from the UK, where he spent much of his time studying bird behavior and volunteering with various conservation organizations. His research interests have taken him to various countries to study their species and environments, including Iceland, where he studied goose behavior for his M.Sc. He has been living in Australia since 2016, where he is now completing his Ph.D. studying chestnut-crowned babbler (pictured) behavior. In his spare time, he is a wildlife rescuer/carer and as active as ever with environmental charities.

RAMAKRISHNAN VASUDEVA

Ram is an evolutionary ecologist (https://ramvasudev.wixsite.com/ramakrishnanvasudeva) currently working on understanding how changing conditions (e.g., constant temperature, heatwaves) affect reproduction in insects, including the evolution of reproductive systems and the selection pressures at play. He completed his master's degree and Ph.D. in the UK and has since worked as a researcher studying the role of thermal environments in the evolution of gamete form and function. Ram enjoys reading, traveling, and cooking. His other hobbies include studying the ecology of venomous snakes and understanding snakebite deaths within rural communities using long-term datasets.