context[19,20], it constitutes a valuable demonstration of how cognitive traits may confer advantages that vary with environmental and seasonal conditions.

DECLARATION OF INTERESTS

The author declares no competing interests.

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Symbiosis: Partners in crime

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Defensive symbionts protect their hosts against imminent threats. A new study uncovers a symbiosis whereby a fungus safeguards its beetle host from predation, but also exploits the beetle as a vector to help it attack plants and cause disease.

Symbiosis with microbes confers eukaryote hosts with many advantages, from the mycorrhizal fungi that provide nutrients to most land plants to the mitochondrial ancestor that supplies cells with energy. In short, symbionts can extend the arsenal of tools a host can use beyond those encoded by its own genome[1]. Some symbionts protect their hosts from natural enemies, forming a critical component of host defense[2]. Many insects harbor symbionts that confer such protection at the egg and larval stages, when there may be increased susceptibility to predators and parasites. In this issue of *Current Biology*, Berasategui *et al.*[3] demonstrate that a species of fungus (*Fusarium oxysporum*) can protect the pupal stage of the tortoise leaf beetle (*Chelymorpha alternans*). Moreover, these beetles can disperse this fungal symbiont to naïve plants, in which the fungus causes disease, making it a symbiont capable of spanning the mutualist–parasite continuum[4].

The tortoise leaf beetle spends its entire life cycle on plants belonging to the morning glory family, the leaves of which are a food source for larvae and adults[5]. As *C. alternans* larvae form their pupa, a filamentous substance forms a coat and remains at high abundance throughout pupation. Berasategui *et al.*[3] identify the substance as being a species of *Fusarium*. This is a surprising finding, given that this fungal genus is usually associated with plants, with some species and strains responsible for major crop damage[6]. The beetle host also differs from its close relatives in that it lacks typical defensive behaviors (such as fecal shields and maternal care) during the pupal stage. These findings led the researchers to hypothesize that *F. oxysporum* serves an anti-predator role.

To test this hypothesis, Berasategui *et al.*[3] conducted an elegant field

experiment in the beetle's range in the Republic of Panama. The researchers kept beetle pupae in cages in the presence or absence of their symbiont. The cages were then either sealed or exposed to the environment. Over four days, exposed pupae that had been kept without symbionts suffered increased predation, likely by ants. By contrast, pupae harboring *F. oxysporum* and those in sealed cages exhibited higher survival rates. Genomic analysis revealed that, like other strains of *Fusarium*, this *F. oxysporum* strain possesses genes encoding products with insecticidal properties, specifically metabolites with cytotoxic and deterrence effects toward insects, making them prime candidates for the mechanism underpinning pupal protection. It is likely that the beetles have developed tolerance to their fungal symbiont's insecticidal properties, but this remains untested. These findings ultimately illustrate the importance of symbiont-mediated protection, a phenomenon that has been understudied for the pupal life stage of holometabolous insects.

All symbioses occur in communities of interacting species. The researchers looked beyond the focal protective interaction and found that, as adult beetles emerge, the symbiont on the pupal casing is picked up and carried to another plant. How is this transportation beneficial for the fungus? Dispersal allows the symbiont to utilize other resources, colonize unoccupied niches, and escape competition or a turbulent environment[7,8]. Thus, in return for protection during a vulnerable life stage, the beetle reciprocates the benefit by vectoring the fungus to a new morning glory plant where it establishes a systemic infection. Importantly, Berasategui *et al.*[3] discovered a dual role for *F. oxysporum*: a protective symbiont for the beetle, and a plant pathogen. The researchers also showed that beetle-associated *F. oxysporum* consistently caused wilt disease in the sweet potato plant — one of the native host plants of the beetle.

Such partners in crime are not uncommon. The beetle–*Fusarium* association is one of several reciprocal mutualisms whereby one or both species causes harm to other organisms in the community (Figure 1A).

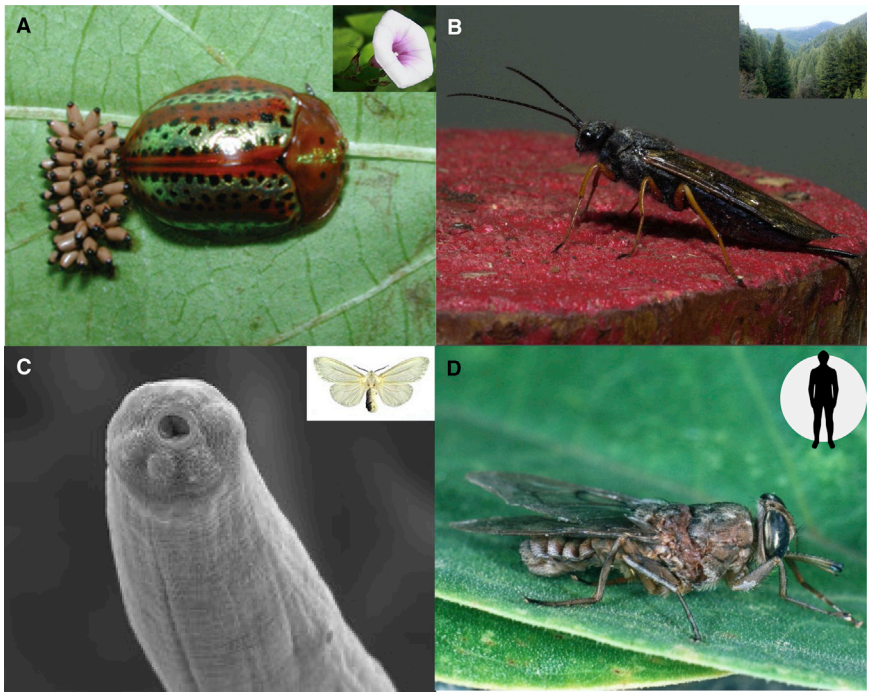

Figure 1. Symbiotic partners in crime.
Examples of destructive symbioses in nature with the target of damage shown as insets in the upper-right corners. (A) Tortoise leaf beetle (*Chelymorpha alternans*), shown here with its eggs, harms plants in the morning glory family through feeding, while the fungal symbiont (*Fusarium oxysporum*) causes wilt disease. Image reprinted with permission from Oxford University Press: inset, Franz Xaver/Wikicommons (CC BY-SA 4.0). (B) *Sirex* woodwasps cause direct damage to conifers while dispersing fungi that decay wood. Image credit, Toter Alter Mann (CC BY-3.0): inset, Eric Guinther/Wikicommons (CC BY-SA 3.0). (C) *Steinernema carpocapsae* nematode teams up with *Xenorhabdus nematophila* bacteria to kill insects. Image credit, Mirayana M. Barros/Wikicommons (CC BY-SA 4.0): inset, TampAGS/Wikicommons (CC BY-SA 3.0). (D) Tsetse flies (*Glossina* spp.), which vector African trypanosomes, require *Wigglesworthia glossinidia* bacteria to develop properly. Reprinted with permission from Springer Nature.

Woodwasps and their fungal symbionts represent another plant-killing duo (Figure 1B). *Sirex* woodwasps cause damage to conifers by boring holes into the wood. Along with its eggs, the woodwasp deposits spores of white rot fungi, which act as a direct food source for the wasp larvae and as decomposers of plant materials[9]. *Caenorhabditis elegans* nematodes also harm the environment they inhabit with their associated bacteria — the pair is responsible for major mushroom yield decline[10]. Another nematode, *Steinernema carpocapsae*, conducts lethal teamwork with *Xenorhabdus nematophila* bacteria by weaponizing them to parasitize insects (Figure 1C). Inside a host, the nematodes release these bacteria, which then multiply, kill the insect, and break down the cadaver, providing nematodes with nutrients[11]. Likewise, the parasite *Babesia microti* infects human red blood cells, but conversely improves the larval survival rate of its tick vector, *Ixodes trianguliceps*[12].

Genomic analysis of *F. oxysporum* reveals interesting aspects of its biology in symbiosis. The fungus possesses genes involved in plant perception and cell-wall degradation, but, by contrast, cellular-motility and extracellular-structure genes are underrepresented[3]. This finding suggests that using beetles as vectors may have reduced the need for the symbiont to disperse without assistance. Moreover, the beetle-associated strain has one of the smallest genomes of the *F. oxysporum* species complex, a pattern consistent with symbionts that have long-term associations with hosts[13]. Despite the size of its genome, *F. oxysporum* can still inflict damage to plants, both directly through its own gene products

and indirectly by improving the survival of beetle pupae. Small genomes need not prevent microbial symbionts from having large impacts. The bacterium *Wigglesworthia glossinidia* has one of the smallest genomes of any living organism. It resides within tsetse flies (Figure 1D), the vectors of trypanosome parasites causing sleeping sickness in humans. The tiny bacterial genome encodes nutrients that supplement the fly's poor blood diet; without the symbiont, tsetse flies are sterile and do not grow well[14].

Overall, the new study by Berasategui *et al.*[3] highlights the power of symbiosis in communities: interactions between mutualists can have major effects — bad ones — on other species outside the partnership. While beetles and fungi can be independent perpetrators of plant destruction, together they can escalate the crimes being committed.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Sensory integration: Time and temperature regulate fly siesta

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Temperatures outside the preferred range require flies to acutely adjust their behavior. A new study finds that heat-sensing neurons provide input to fly circadian clock neurons to extend the daytime siesta, allowing flies to sleep through excessive daytime heat.

As a human child, Goldilocks could tell that the bears' porridge was too hot (or too cold) relative to her own internally controlled body temperature. As ectotherms, *Drosophila* body temperature is highly dependent on ambient temperature, so they must instead be able to discriminate absolute temperature to find that 'just right' environment. But just right for what? Daily fluctuations in temperature prompt flies to distribute various behaviors around the day to maximize environmental fitness. To accomplish this, flies have separate sensory circuits for temperatures above and below their preferred temperature. Temperature information is then relayed to higher brain circuits and integrated with additional sensory inputs to guide behavioral changes that occur on varied timescales. One such behavior is sleep, which is regulated by multiple internal and external factors including temperature, circadian time, and sleep homeostatic pressure due to elapsed waking time.

Shifts in ambient temperature alter the timing of fly sleep, likely helping them conserve energy and avoid desiccation in