

is why we need to focus on the start of the food chain. Insects could make up the protein shortfall without requiring us to acquire dramatic new tastes in food.

Insects can be a sustainable alternative to soy and fishmeal in particular. Not only are insects already part of the natural diet of cattle, pigs, poultry, and fish, but insects deliver an important source of high-quality protein and polyunsaturated fats.

Farming insects is also hugely cost-efficient and suitable for many climates. I first began breeding *Molitor*/mealworm larvae at *Ynsect*, the company I co-founded in 2011, and discovered just how energy efficient it was. Insects require very little water, can be grown in the dark all year round, have no impact on sea or freshwater biodiversity, and even lead to improvements in land use productivity.

Specialists and scientists have known about the *Molitor* species for a long time. The mealworm (the larval form of the *Tenebrio molitor* beetle) is comprised of more than 70% protein and is a natural source of nutrients for a wide array of animals, including fish, poultry, pigs, dogs, and cats.

It is also the insect species most suited to industrial development. It is a naturally gregarious, nocturnal species, which, from a practical standpoint, makes breeding easier. It brings real added value to the market for alternative protein sources thanks to its nutrient-packed content and unique health benefits for plants and animals.

Our chosen technology and insect species allow us to fully focus on sustainable development: to do more with less; to use fewer resources to feed plants and animals; to use fewer antibiotics and pesticides; to reduce our physical footprint.

Given its intrinsic qualities, the *Molitor* is perfectly placed to promote a circular economy. The mealworm consumes all sorts of organic matter, even low-grade materials. It grows quickly and requires less space, less earth and less water than other animal protein sources. It also releases less ammonia and fewer greenhouses gases than other premium animal proteins. The entire production system is modelled on a circular economy with zero-waste. The *Molitor* protein is produced using fewer antibiotics and chemical fertilizers and the final product is 72% protein, with proven nutritional and health benefits for aquaculture and pets. With two billion more people to feed within a matter of 30 years and fish being the fastest-growing source of protein for human consumption globally, insect protein can play a pivotal role in closing the gap.

I envision a time when insect protein is at the start of the food chain for almost everything consumers eat. And even our plants will be supercharged with fertilizers derived from insects applied to increase yields.

Putting insects back to their rightful place at the start of the food chain will give our planet much more breathing space than misguidedly trying to force everyone to give up meat and dairy. With insect farming, we are creating a new and highly sustainable agrifood industry, backed by extremely innovative tried-and-tested production facilities. Hopefully, the big brand beasts at the top of the global food chain will soon realize this, and will back the logical solution to the protein crisis rather than simply jumping on the popular bandwagon.

**Disclosure of interest** The author declares that he has no competing interest.

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## The impact of climate on the winter strategies of insects

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Life-history traits within ecological communities can be influenced by two opposite pressures, the first one being community-wide density-dependent processes like competition (internal filters), and the second regional environmental conditions (external filters). While species belonging to a guild may present contrasting traits as a means of niche differentiation, allowing coexistence whilst exploiting the same resources, traits in a regional context may converge to a narrow range of values because of environmental filtering [1]. As ectotherm organisms depend strongly on temperatures, convergent winter strategies could be expected in insects of the same area. In temperate areas, insects can escape the stressful winter conditions either by (i) migration, (ii) diapause (i.e. arrest of development), or (iii) remaining in activity by producing cryoprotectant molecules. Concerning the diapause strategy, it was shown that temperature is both a selective pressure and a modulator of the diapause expression in insects. Thus, with climate warming, and especially winter warming, which acts at the community level, a convergent alteration of the response to seasonal changes is expected for the ectotherms, either through genetic adaptations to novel climatic conditions or through phenotypic plasticity.

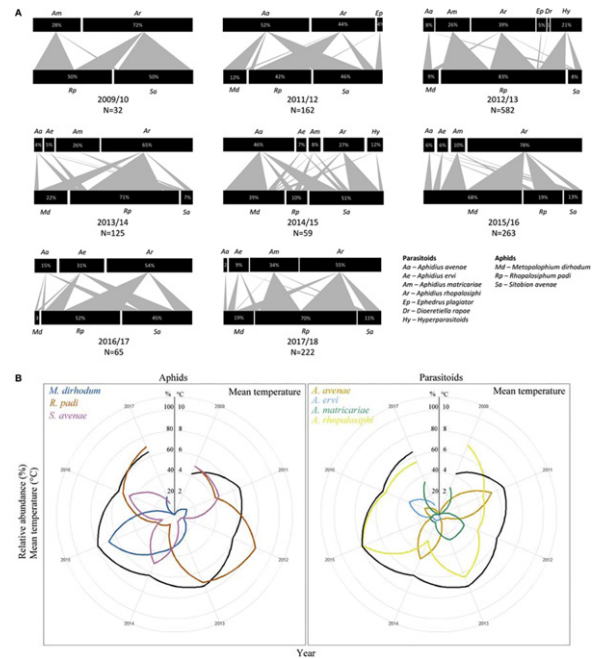
In a first study [2], we observed the loss of diapause strategy in two species of an aphid-parasitoid community. Since the 1980s in western France, the winter guild of aphid parasitoids (Hymenoptera: Braconidae) in cereal fields has been made up of two species: *Aphidius rhopalosiphi* and *Aphidius matricariae*. The recent activity of two other species, *Aphidius avenae* and *Aphidius ervi*, during the winter months suggests that a modification of aphid parasitoid overwintering strategies has taken place within the guild. In this study, we first performed a field survey in the winter of 2014/2015 to assess the levels of parasitoid diapause incidence in agrosystems. Then, we compared the capacity of the four parasitoid species to enter winter diapause under nine different photoperiods and temperature conditions in the laboratory. As predicted, historically winter-active species (*A. rhopalosiphi* and *A. matricariae*) never entered diapause, whereas the species more recently active during winter (*A. avenae* and *A. ervi*) did enter diapause, but at a low proportion (maximum of 13.4 and 11.2%, respectively). These results suggest rapid shifts over the last three decades in the overwintering strategies of aphid parasitoids in Western France, probably due to winter warming. This implies that diapause can be replaced by active adult overwintering. The mechanism behind the change of overwintering strategy seems to be more a decrease in responsiveness to environmental signals rather than a genetic loss of diapause. This plasticity allows non-diapausing individuals to increase their progeny production. A meta-analysis dedicated to animals has shown that most of the responses to environmental changes involved phenotypic plasticity rather than genetic evolution. Moreover, when genetic changes or shifts in demography, distribution or phenology occurred, these were generally preceded by a modification involving phenotypic plasticity. Thus, behavioural plasticity appears important in explaining the variation in the success of species to resist to environmental changes.

We confirmed this evolution of winter strategy in our aphid-parasitoid system, by using a nine-year dataset to build trophic webs. We confirmed that the community structure and composition that prevailed before 2011 have recently shifted toward a more diversified community, with the presence of the two new braconid parasitoid species studied before

(*Aphidius ervi* and *Aphidius avenae*), but also a few hyperparasitoid species and one aphid species (*Metopolophium dirhodum*). Modifications in minimal winter temperatures and frequency of frost events across the years partially explain observed community changes, although no clear climatic trend can be emphasized. Strong bottom-up effects from the relative abundance of aphid species also determine the relative abundance of parasitoid species each winter. Strong compartmentalization in parasitoid preference for host is reported. We confirmed the recent modifications in parasitoid community composition to be linked to shifts in diapause expression (reduction or arrest of the use of diapause strategy) and to host availability throughout the year. This increase of winter activity has cascading consequences on community structure and ecosystem functioning. These consequences include an increasing competition between species and an increasing complexity of trophic web structures.

Outside our particular model, the species of a community can respond to winter warming, as to any other environmental changes, through plasticity or genetic evolution. The environmental changes generally impact negatively the species. However, some species cope well with them and their populations increase to a point where they become themselves a threat to other species. In our aphid–parasitoid system, the species that do not more express diapause are favoured in a first approach compared to the other species that do not change their phenology and that probably suffer from more competition, as their relative abundance in the system is decreasing during the last years. In both cases, the species have responded to changes (winter warming for some species and competition for the others) by plasticity. One remaining question is whether the plastic responses are sufficient to prevent long-term population decline and extinction. This research field is still in its infancy, and examples are scarce for insects. Most of the rare studies showed that behavioural responses are insufficient, but still improve survival, which could facilitate evolutionary adaptation by providing more time for genetic changes. This is especially likely in species with short generation time, as suggested for many pest and disease vectors.

In a last study [3], we highlighted the implications of these community changes for natural biological control in cereal fields. In agrosystems, the increase in non-crop plant diversity by habitat management in or around arable fields contributes to improved conservation biological control. During winter, plant flowers are often used as monospecific ground cover and are expected to die before flowering, as a result of recurrent frost events. Decreases in minimal temperature due to climate change offer new possibilities for plants used in such sown cover crops to mature and blossom. Changes in plant phenology thus constitute an important environmental change, with expected consequences for ecosystem functioning, such as biological control. In Brittany, where winter agricultural landscape is dominated by a mosaic of cereal and sown cover crops, we assessed the consequences of mustard (*Synapis alba*) flowering cover crops on aphid parasitism and food web structure in plots adjoining cereal crops, in contrast to plots close to spontaneous non-crop plants of the same field. Overall, aphid parasitism rate at the field scale was strong (60–70%), being 13% higher adjacent to the mustard cover than closer to spontaneous vegetation. In addition, there was no change in food web structure between the two distinct zones, enabling us to hypothesize that mustard cover mostly constituted an alimentary patch. The positive effect on parasitism rate was significant but weak, as the floral nectar of mustard is known to be of poor quality for parasitoids. Our results highlight the potential advantages of adapting practices in response to actual changes in agrosystems. Increase floral diversity in sown cover crops could constitute a complementary method in management programs by providing more alternative food resources, alternative hosts, and climatic refuge to enhance the conservation biological control of parasitoid populations (Fig. 1).



**Fig. 1** (A) Quantitative food webs of parasitoid and aphid community composition during winters 2009/2010 to 2017/2018 (there were no insects in 2010/2011). Upper and lower bars represent the relative abundance (%) of parasitoids, including hyperparasitoids, and aphid species, respectively. The thickness of the arrow between bars is proportional to the interaction strength between a pair of species. The total number of individuals ( $N$ ) used to construct each food web is shown for each year. (B) Rank plots showing the relative abundances (%) of aphids (left panel) and *Aphidius* parasitoids (right panel) during each winter from 2009/2010 to 2017/2018. The mean winter temperature ( $^{\circ}\text{C}$ ) is shown in black. From [4].

**Disclosure of interest** The author declares that she has no competing interest.

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