

Chemical deterrent enables a socially parasitic ant to invade multiple hosts

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Social parasites are involved in a coevolutionary arms race, which drives increasing specialization resulting in a very narrow host range. The *Formicoxenus* ants are a small group of social parasites with a xenobiotic lifestyle. *Formicoxenus quebecensis* and *Formicoxenus provancheri* are highly specialized ants using chemical mimicry to blend into their respective *Myrmica* ant host colonies. However, *Formicoxenus nitidulus* is unique in being able to survive in over 11 different ant host species. We observed that when live or dead *F. nitidulus* adults are seized by their host they are immediately dropped undamaged, despite possessing a cuticular hydrocarbon profile that differs markedly from its host. Hexane extracts of the *F. nitidulus* cuticle made previously acceptable prey items unattractive to their *Formica* host, indicating a chemical deterrent effect. This is the first time that a social parasite has been shown to exploit the generalized deterrence strategy to avoid host aggression over long periods of time. This supports the idea that coevolved and generalist diseases or parasites require fundamentally different defence mechanisms. We suggest that *F. nitidulus* uses its cuticular chemistry, possible alkadienes, as a novel deterrent mechanism to allow it to switch hosts easily and so become a widespread and abundant social parasite.

Keywords: *Formicoxenus nitidulus*; chemical deterrent; alkadiene; cuticular hydrocarbons; coevolution

1. INTRODUCTION

All parasites are locked into a coevolutionary arms race with their host as their interests are diametrically opposed. Overcoming complex recognition systems has led to increasing specialization and narrow host ranges. This is not only exemplified by the bird cuckoos (Brooke & Davies 1988; Marchetti *et al.* 1998), but also occurs in insects that parasitize social insect colonies (Lenoir *et al.* 2001). In the vast majority of cases in social insects where two unrelated species inhabit the same colony, the cuticular hydrocarbon (CHC) profiles, which encode the recognition signals (Howard & Blomquist 2005), are similar, leading to the conclusion that ‘chemical mimicry is responsible for mutual tolerance’ (Lenoir *et al.* 1997). Integration into a host colony by a social parasite occurs by two different methods: ‘chemical camouflage’, where the parasite acquires the colony odour from the host species or the nest surroundings by allogrooming, or ‘chemical mimicry’, where the intrinsic biosynthesis of host CHCs by the parasite actively reproduces the host’s odour profile (Dettner & Liepert 1994). This may explain why most social parasites are exceedingly rare in comparison with their hosts (Elmes *et al.* 1999; Thomas *et al.* 2006).

The small genus of *Formicoxenus* ants are xenobionts rearing their brood within the host colony and stealing its resources such as food and space. The brood of xenobionts are reared in separate chambers where the host workers cannot physically enter due to their small

size. The *Formicoxenus* ants represent one of the best examples of chemical mimicry through odour acquisition since *Formicoxenus provancheri* and *Formicoxenus quebecensis* are strongly attracted to their respective ant hosts, *Myrmica incompleta* and *Myrmica alaskensis*, and spend up to 45% of their time licking the host adults and larvae, earning them the name ‘shampoo ants’ (Errard *et al.* 1997). This behaviour allows them to directly acquire their hosts’ colony odour (Lenoir *et al.* 1997). This results in a strong host specificity since strong inter-species aggression between all ants inhibits social parasites moving between species (Holldobler & Wilson 1990). However, in Europe, *Formicoxenus nitidulus*, the only *Formicoxenus* species, is unusual in that it has been recorded from nine mound-building species of *Formica* wood ants (*Formica rufa*, *Formica polyctena*, *Formica pisarskii*, *Formica lugubris*, *Formica aquilonia*, *Formica pratensis*, *Formica truncorum*, *Formica uralensis* and *Formica exsecta*; Holldobler & Wilson 1990; Busch 2001) as well as *Polyergus rufescens* and *Tetramorium caespitum* (Wilson 1971). Despite strong colony recognition between the wood ant species, *F. nitidulus* colonies are well integrated into their host colonies and adults are able to switch freely between mound-building *Formica* species when they occur in the same area. Unlike the shampoo ants, *F. nitidulus* appears to have very little direct interaction with its hosts and is largely ignored (Stumper 1918), but when they are seized by a host worker they are dropped rapidly and left unharmed (Robinson 2005). Stumper (1949) concluded that *Formicoxenus* must have a special odour whose perception does not elicit any hostile response. The system employed by *F. nitidulus* to avoid being killed or

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damaged by the host must not be error prone since although encounters appear rare, they do occur and since *F. nitidulus* is continuously exposed to the hosts during its lifetime, it must survive being attacked on many occasions. This is a fundamentally different problem faced by social insect parasites that invade and usurp host colonies.

We hypothesize that some characteristic of the *F. nitidulus* cuticular chemistry deters a fully aggressive response in the *Formica* host workers. We investigated the CHC chemistry of *F. nitidulus* and used laboratory and field bioassays to investigate the behaviour of *Formica* hosts towards *F. nitidulus*.

2. MATERIAL AND METHODS

(a) Sample collection

During August 2005, samples of adult *F. nitidulus* ants and their *Formica* hosts were collected from Ballater, Aberdeenshire (*Fo. lugubris*), Ashness, Cumbria (*Fo. lugubris*), Arnside, Lancashire (*Fo. rufa*) and Sheffield, South Yorkshire (*Fo. lugubris*). A total of 3 winged queens (gynes), 11 workers and 28 male *F. nitidulus* ants were collected over the four sites, along with 5 host *Formica* workers from each colony. During August 2006, we collected approximately 200 *F. nitidulus* adults (workers and males) from the Sheffield site, for use in the bioassays. In *F. nitidulus*, workers and males are very similar in appearance, cuticular chemistry and behaviour, so in the bioassays we did not discriminate between the sexes and refer to them collectively as adults. Furthermore, all bioassays used *Fo. lugubris* workers from the Sheffield population, which is parasitized by *F. nitidulus*.

(b) Interaction bioassays

Direct interactions between *Fo. lugubris* and *F. nitidulus* adults were rarely observed in the field. We therefore created an artificially high encounter rate in the laboratory by placing one *Fo. lugubris* adult in a 50 mm diameter Petri dish containing 10 live *F. nitidulus* adults. If the *Fo. lugubris* worker seized an *F. nitidulus* adult, picked it up and then immediately dropped it, then this was classified as 'dropped', whereas it was classified as 'carried' if it was picked up and carried off. As soon as a behavioural interaction was observed, the *Fo. lugubris* was replaced with a new individual. The behaviour of 20 different *Fo. lugubris* individuals were observed with each trial lasting between 1 and 5 min. To exclude the possibility of avoidance behaviour, we introduced 20 freshly killed *F. nitidulus* adults individually onto a 50 mm² piece of white paper placed near a busy foraging trail of a *Fo. lugubris*. We then recorded the number of dead *F. nitidulus* that were either dropped or carried. We then tried to remove or at least reduce the amount of CHC from *F. nitidulus* adults by washing 10 dead *F. nitidulus* adults in HPLC-grade hexane for 10 min and recorded whether they were carried or dropped using the foraging trail bioassay just described.

Owing to the large number of foraging host workers, all bioassays were completed within a 5 to 10 min period and it is unlikely that the behaviour of the same host worker was recorded more than once.

(c) Formicoxenus extract bioassay

A CHC extract of *F. nitidulus* was prepared by placing 50 adults in 300 µl of HPLC-grade hexane for 10 min. Fifteen microlitres of extract were then applied via a Hamilton syringe to each of 20 fruitflies (*Drosophila pseudoobscura*) that

Table 1. Behaviour of *Fo. lugubris* workers towards *Drosophila* fruitflies that had been treated with a hexane control or a hexane extract of the cuticular hydrocarbons of *F. nitidulus*.

	flies carried	flies dropped
hexane only	17	3
hexane + <i>F. nitidulus</i> CHC extract	4	16

had previously been washed in hexane for 10 min to remove their own CHC profile. The application of 15 µl of extract to each fruitfly is roughly equivalent to one ant, as the dry weight of an *F. nitidulus* ($1\text{--}2 \times 10^{-3}$ g) is two to three times lower than that of a fly. A further 20 washed flies were treated only with 15 µl of hexane and used as the control. The flies were offered to *Fo. lugubris* workers using the same methodology as the dead *F. nitidulus* ants and their behaviour towards the two groups of flies was recorded as dropped or carried.

(d) Chemical analysis

Individual *F. nitidulus* or *Fo. lugubris/rufa* ants were placed into vials containing 30 or 50 µl of hexane, respectively. After 10 min, the ants were removed, hexane evaporated and the vials sealed and stored at 5°C. Prior to analysis, 30 µl of hexane was added to the vial and the sample analysed on an HP 6890 GC (equipped with an HP-5MS 30 m column) connected to an HP 5973 MSD (mass spectrometer). The oven was programmed from 70 to 200°C at 40°C min⁻¹ and then from 200 to 320°C at 15°C min⁻¹ and held for 2 min at 320°C. CHCs were characterized by the use of standard MS databases, diagnostic ions and their Kovats indices. Double-bond positions were determined by DMDS derivatization of a pooled extract of 10 *F. nitidulus* adults.

(e) Data analysis

The peak area for each compound was calculated for each ant and then normalized by calculating the percentage abundance of each compound in the sample, i.e. as a proportion of all compounds present. For each group (queens, workers or males) at each location, an average profile was calculated by taking the mean percentage for each compound across all the ants in that group. These data were later collated with the published data (73 CHCs) for *F. provancheri* and *F. quebecensis* and their *Myrmica* hosts (Lenoir *et al.* 1997) in order to investigate the wider relationships between *Formicoxenus* and their hosts. To determine the level of similarity of the CHC profile of the three *Formicoxenus* spp. and their hosts, we used hierarchical cluster analysis (Euclidean distances, Ward's method) to construct a single linkage dendrogram (SPSS v. 14) using all 77 CHCs described from this study and published data (Lenoir *et al.* 1997).

3. RESULTS

(a) Bioassays

Our field studies confirm previous observations (Robinson 2005) that all adult *F. nitidulus* ants (queens, males and workers) are largely unmolested by their much larger hosts but if seized by a *Fo. lugubris* or *Fo. rufa* worker they are rapidly dropped unharmed. In both our laboratory and field bioassays, we found that in all encounters between *Fo. lugubris* workers and *F. nitidulus* adults, living (20 out of 20 cases) or dead (20 out of 20 cases), resulted in *F. nitidulus*

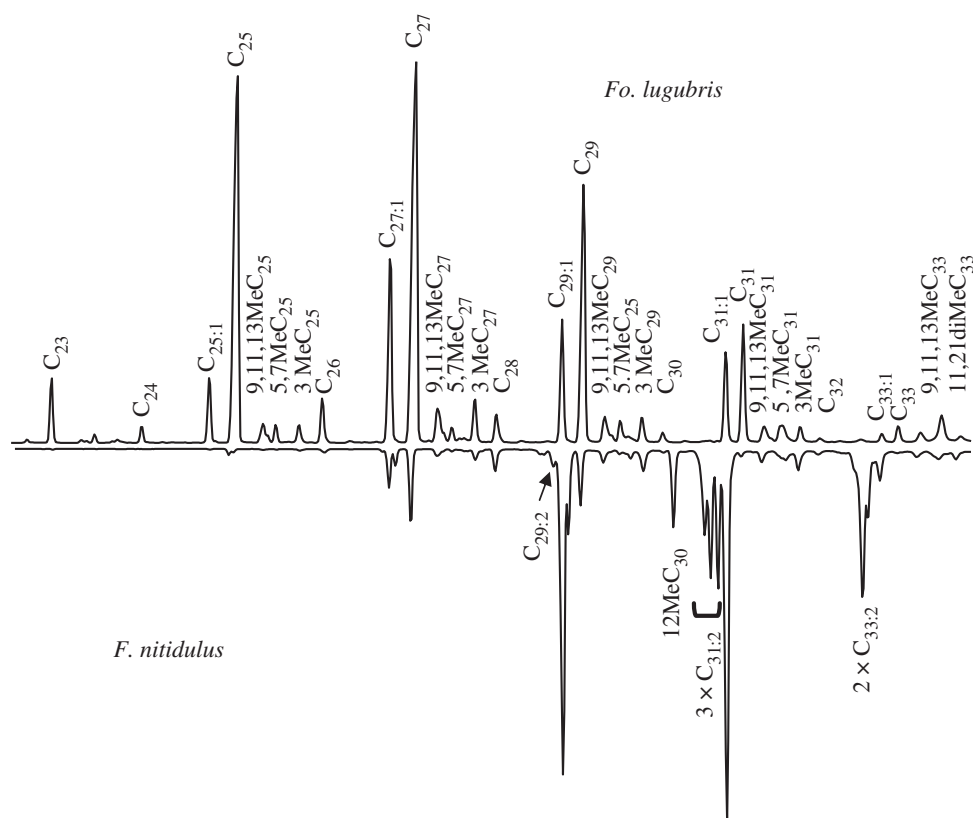


Figure 1. Comparison of typical total ion chromatograms for a *Fo. lugubris* host worker and *F. nitidulus* worker from the same colony. The compounds present are identified as alkanes (C_{23} – C_{33}), alkenes ($C_{25:1}$ – $C_{33:1}$), alkadienes ($C_{29:2}$ – $C_{33:2}$) and methyl-branched alkanes (e.g. 3Me C_{25}). See the electronic supplementary material for proportions of each cuticular hydrocarbon (CHC). The 12Me C_{30} was not detected consistently in all *F. nitidulus* ants (see electronic supplementary material).

being immediately dropped. This indicates that *F. nitidulus* possesses a strong and effective deterrent that remains functional in the absence of other behaviours. We were able to transfer this effect to prey items. The application of *F. nitidulus* cuticle extract to fruitflies significantly decreased (χ^2 -test with Yates correction: $\chi^2_1 = 14.44$, $p = 0.001$, $n = 40$) their attractiveness to *F. lugubris* foragers. Only 15% of control flies were dropped compared with 80% of the *F. nitidulus* extract-treated flies (table 1). Furthermore, by washing *F. nitidulus* adults in hexane for only 10 min, we were able to partially remove the deterrent effect, since the number of *F. nitidulus* ants picked up and carried away increased significantly (χ^2 -test with Yates correction: $\chi^2_1 = 10.7$, $p = 0.001$, $n = 60$) from 0 out of 50 cases (untreated) to four out of 10 cases (washed).

(b) Comparison of hydrocarbon profiles

The CHC profile of *F. nitidulus* and their *Formica* hosts was strikingly different (figure 1; electronic supplementary material). The CHC profile of all adult *F. nitidulus* ants ($n = 42$) were similar irrespective of sex ($n = 2$), caste ($n = 2$), host ($n = 2$) or location ($n = 4$), and always contained a high proportion (16–43%) of alkadienes ($C_{29:2}$, $C_{31:2}$ and $C_{33:2}$), a type of hydrocarbon completely absent in their UK *Formica* hosts (electronic supplementary material) or in any other recorded *Formica* hosts so far studied (Martin 2007, unpublished data).

The chemical dissimilarity between *F. nitidulus* and their *Formica* hosts became very clear when we included *F. provancheri*, *F. quebecensis* and their *Myrmica* hosts in the analysis. Our dendrogram (figure 2) shows that *F. provancheri* and *F. quebecensis* have an almost identical CHC profile to

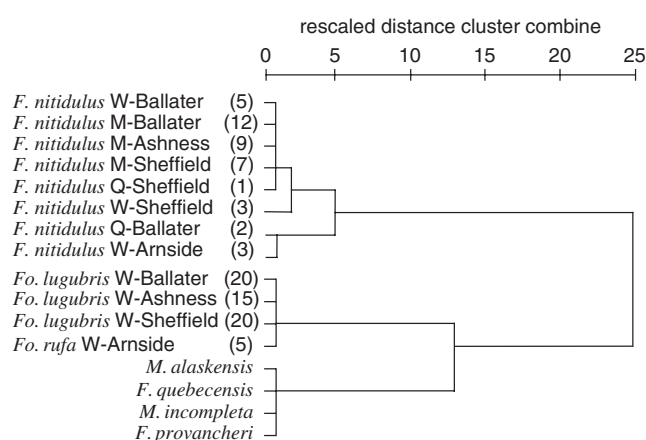


Figure 2. Hierarchical cluster analysis (single linkage, Euclidean distances, Ward's method) of the CHCs of *F. nitidulus* and their hosts *Fo. lugubris* and *Fo. rufa* (this study) from four locations in the UK combined with the data on *F. provancheri* and *F. quebecensis* and their hosts *M. incompleta* and *M. alaskensis* (Lenoir *et al.* 1997). The number of individual ants analysed is given in parentheses. W, worker; M, male; Q, queen.

their *Myrmica* hosts, while the *F. nitidulus* profiles are strikingly dissimilar from their *Formica* hosts. In fact, the CHC profile of *F. provancheri* and *F. quebecensis* more strongly resembles that of *Formica* than of *F. nitidulus* (figure 2).

4. DISCUSSION

In contrast to previous studies of social parasites, including that of the closely related species *F. provancheri* and *F. quebecensis*, we found the CHC of *F. nitidulus* and their

Formica hosts to be strikingly different. This strongly suggests that chemical mimicry is not being used by *F. nitidulus* and explains the lack of chemical congruency found between *F. nitidulus* and *Fo. rufa* (Lenoir *et al.* 2001). The results of our bioassays confirm previous observations that when *F. nitidulus* is seized by a *Fo. rufa* (Robinson 2005) or *Fo. lugubris* (this study) worker, it is rapidly dropped unharmed. Our study shows that this deterrent effect is probably attributable to a chemical cue found on the cuticle, because dead *F. nitidulus* ants are dropped on contact rather than simply avoided. Furthermore, we were able to transfer the deterrent effect via a hexane CHC extract of *F. nitidulus* to make previously attractive prey (fruitflies) unattractive. This suggests that the flies were not simply ignored but had become distasteful. If flies or *F. nitidulus* ants had been ignored, there is a possible interpretation that *F. nitidulus* is chemically insignificant (Lenoir *et al.* 2001), but this was clearly not the case. In contrast to previous studies of social parasites, including that of the closely related species *F. provancheri* and *F. quebecensis*, we found the CHC profile of *F. nitidulus* is dominated by alkadienes and alkenes (figure 1; electronic supplementary material). Alkenes are known to be used as recognition cues in insects (Lockey 1988; Akino *et al.* 2004; Howard & Blomquist 2005) and so we reiterate that it is highly unlikely that *F. nitidulus* are chemically insignificant to their hosts.

The presence of large amounts of normally rare alkadienes (Akino 2006) in the CHC profile of all *F. nitidulus* adults makes them good candidates for further investigation of their deterrent effect. Many social wasps (*Polistes*, *Vespa* and *Stenogastrinae*) also secrete substances that protect their colonies against attack from ants (Jeanne 1970; Martin 1991). These ant repellents are also composed of hydrocarbons (Sledge *et al.* 2000; Dani *et al.* 2003), although the specific hydrocarbons that act as deterrents have yet to be determined. Although we cannot completely rule out other compounds such as esters and fatty acids, which have also been suggested to act as ant repellents (Henderson & Jeanne 1989), their absence from all *F. nitidulus* GC traces (figure 1) makes it unlikely.

We confirm that two very different strategies have evolved within the *Formicoxenus* genus, which enables them to survive within their respective host colonies (Lenoir *et al.* 2001). First, the socially parasitic shampoo ants, *F. provancheri* and *F. quebecensis*, closely mimic the chemical profiles of their respective ant hosts (*M. incompleta* and *M. alaskensis*), and so are obligately associated with their host species (Lenoir *et al.* 1997) and accordingly cannot survive within *Formica* colonies (Buschinger 1976). In contrast, the chemical deterrent used by *F. nitidulus* allows it to inhabit at least nine mound-building species of *Formica* wood ants as well as *Polyergus rufescens* and *Tetramorium caespitum*. *F. nitidulus* can also survive in laboratory-maintained *Leptothorax acervorum* nests (Buschinger 1976). This suggests that the natural restriction of *F. nitidulus* to mound-building *Formica* species may be a function of its ecology rather than its chemistry. However, *L. acervorum*, a species closely related to *Formicoxenus*, is unusual in possessing a CHC profile similar to *F. nitidulus*, i.e. one dominated by the same alkadienes and alkenes (Kaib *et al.* 1993), so chemical mimicry could also explain the mixed laboratory nests of *L. acervorum* and *F. nitidulus*. The evolution of a chemical deterrent in some *Formicoxenus* species may have

occurred prior to their invasion of into Europe and Asia, since the Nearctic species, *Formicoxenus diversipilosus* and *Formicoxenus hirticornis*, also inhabit the thatched mounds of several *Formica* spp. (Francoeur *et al.* 1985) and share a similar biology to *F. nitidulus* (Alpert & Akre 1973).

Although queens of social parasitic ants (D'Ettorre *et al.* 2000; Ruano *et al.* 2005) and bumble-bees (Zimma *et al.* 2003) use chemicals as a repellent or deterrent, these are short lasting propaganda substances produced by the Dufour's or poison gland, which allow the parasite to invade and usurp the host colony or steal its brood (Lenoir *et al.* 2001). Therefore, the use of a cuticular ant deterrent by *F. nitidulus*, which allows it to survive within the host nests over long periods of time, is a novel strategy among social parasites. Such a strategy has clear advantages for exploiting a wide host range, but this is at odds with the apparent rarity of this strategy. Clearly, deterrence is a successful strategy for *F. nitidulus*, which is a widespread and abundant social parasite, with some host *Formica* mounds parasitized by over 100 *F. nitidulus* colonies (Buschinger *et al.* 1994). However, this is in stark contrast to the specialized chemical mimicry of *F. quebecensis*, which is regarded as a rare species, occurring in only a few locations (Buschinger *et al.* 1994). These findings lend weight to the idea that coevolved and generalist diseases or parasites require fundamentally different defence mechanisms (Boomsma & Franks 2006). The use of chemical deterrents to avoid predation is widespread among insects, but this is the first time it has been recorded in any of the predicted 10 000–20 000 species of insects that have evolved as social parasites of ants (Thomas *et al.* 2006). However, it is possible that other generalized xenobionts of ants use a similar mechanism, such as the *Myrmecophila* crickets (Holldobler & Wilson 1990).

It is usually assumed that chemical mimicry is responsible for mutual tolerance in most social insect parasites (Lenoir *et al.* 1997, 2001), and when an ant species becomes an obligate parasite it seems to evolve quickly into a state of abject dependence on its host (Wilson 1971). However, our findings reveal another mechanism of social parasitism that allows the exploitation of multiple host species. We suspect that the use of cuticular-based deterrents by insect social parasites may be a more widespread strategy than previously thought.

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NOTICE OF CORRECTION

The author names are now presented in the correct form.

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