



Kinship effects in quasi-social parasitoids II: Co-foundress relatedness and host dangerousness interactively affect host exploitation

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Foundress relatedness and host size

**Kinship effects in quasi-social parasitoids II: Co-foundress
relatedness and host dangerousness interactively affect host
exploitation**

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ABSTRACT

Sclerodermus brevicornis is a parasitoid that exhibits cooperative multi-foundress brood production. Prior work showed that the time lag to paralysis of small sized hosts is shorter when co-foundress relatedness is higher and predicted that the greater risks and greater benefits of attacking larger hosts would combine with co-foundress relatedness to determine the limits to the size of a host that a female is selected to attack as a public good. It was also predicted that the time to host attack would be affected by an interaction between host size and relatedness. Here we show empirically that both host size and kinship affect *S. brevicornis* reproduction and that they interact to influence the timing of host attack. We also find effects of co-foundress relatedness after hosts have been successfully suppressed. A public goods model using parameters estimated for *S. brevicornis* again suggests that selection for individual foundresses to attack and then, if successful, share hosts will be dependent on both size of the host and the foundresses' relatedness to any co-foundresses present. Females will not be selected to bear the individual cost of a public good when hosts are large and dangerous nor when their relatedness to co-foundress is low. We conclude that while reproductive behaviours exhibited by *Sclerodermus* females can be cooperative, they are unlikely to be exhibited without reference to kinship or to the risks involved in attempting to suppress and share large and dangerous hosts.

Keywords: Host size - host attack – kinship - public goods – *Sclerodermus brevicornis* – sociality.

INTRODUCTION

The evolution and maintenance of social systems has been considered in many animal taxa (e.g. Costa, 2006, 2018; Schenider & Bilde, 2008; Davies *et al.*, 2012; Tanaka *et al.*, 2018; Ågren *et al.*, 2019; Downing *et al.*, 2020). Among parasitoid wasps, an extremely speciose functional group (e.g. Dolphin & Quicke 2001; Davis *et al.*, 2010; Dale-Skey *et al.*, 2016; Whitfield *et al.*, 2018; Chen *et al.*, 2019), sociality is unusual and relatively little explored. *Sclerodermus* (Hymenoptera: Bethyridae) are among the most socially complex parasitoids known (Bridwell, 1920; Wheeler, 1928; Mamaev, 1979). Species in this genus are not members of the monophyletic group that contains most hymenopterans that have parasitoid life-histories (the Parasitica) but are aculeates ('stinging wasps'). Within the Aculeata, they are members of the Chrysoidea, which forms the sister group of all other aculeate taxa, including the ants, bees and vespid wasps in which eusociality has evolved (Peters *et al.*, 2017).

Female *Sclerodermus* do not only exhibit maternal care of their own offspring, but a group of 'foundress' females may cooperate to tend, apparently indiscriminately, a group of offspring produced collectively on a single host (Bridwell, 1920; Kühne & Becker, 1974; Casale, 1991; Hu *et al.*, 2012; Wu *et al.*, 2014). *Sclerodermus* are considered quasi-social as they exhibit cooperative brood care without generational overlap or apparent division of labour (Tang *et al.*, 2014; Costa, 2018). Tang *et al.* (2014) showed that co-exploitation of large hosts provides direct fitness benefits (in terms of average reproductive success) to individual females within *Sclerodermus harmandi* foundress groups and thus that quasi-sociality could be explained without reference to inclusive fitness benefits, an oft invoked factor in social evolution studies (Hamilton, 1964; Costa, 2006, 2018; Davies *et al.*, 2012).

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3 While Tang *et al.* (2014) showed that kin selection need not be required to explain
4 *Sclerodermus* sociality, a role for inclusive fitness effects in the reproductive cycle was
5 not excluded. Abdi *et al.* (2020) subsequently showed that, in *Sclerodermus*
6 *brevicornis*, kinship among foundress groups affects the timing of host attack:
7 paralysis of standard sized hosts was more rapid when co-foundress relatedness is
8 higher. Attacking hosts carries considerable mortality risks for *Sclerodermus* females,
9 especially when hosts are large (Kühne & Becker, 1974; Liu *et al.*, 2011; Tang *et al.*,
10 2014; Wei *et al.*, 2014) and, while females must ultimately access a host in order to
11 reproduce, they may be reluctant to take risks when reproductive benefits may be
12 shared with non-kin. Using data from several *Sclerodermus* species, Abdi *et al.* (2020)
13 employed a simple public goods model based on Hamilton's rule (Hamilton, 1964;
14 Cooper *et al.*, 2018) to explore how three parameters, the greater risks and greater
15 benefits of attacking larger hosts and co-foundress relatedness, could combine to
16 determine the size ranges of hosts that a female is selected to attack to provide
17 reproductive resources to co-foundresses as well as to herself. This suggested that
18 when foundresses are more closely related, larger hosts will be attacked by individuals
19 as a public good. It also suggested that, in general, effects of kinship would be least
20 marked when hosts are small and relatively safe to attack and may be greater when
21 hosts are large and dangerous to attack, and thus that co-foundress relatedness and
22 host dangerousness should interact to affect the timing of host attack.
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49 Here we test empirically the combined effects of host size and *S. brevicornis* co-
50 foundress relatedness. We hold foundress number constant, at two females, and vary
51 relatedness such that co-foundresses are either brood-mates or non-siblings. We
52 provide foundress pairs with a single host, drawn from a wide range of host sizes,
53 larger hosts being more dangerous to attack. We evaluate the timing and success of
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3 host attack behaviour and other aspects of reproductive success, and find effects of
4 kinship including an interaction between co-foundress relatedness and host
5 dangerousness. We also assay the success of single foundresses attacking hosts of
6 different sizes, the timing of attack and the probability of dying during attack,
7 confirming that larger hosts are more dangerous for individual females to attack. We
8 use our empirical estimates of the host-size dependent risks of host attack and on
9 offspring production on successfully suppressed hosts in a new model of host attack by
10 *S. brevicornis*. As with models for other *Sclerodermus* species, this suggests host size
11 and foundress kinship will interact to influence host attack behaviour and, specifically,
12 that individual *S. brevicornis* foundresses will be selected to attack and then share
13 hosts as a public good only when their relatedness to co-foundresses is high and the
14 host is neither large nor very small.
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35 MATERIALS AND METHODS

36 37 38 39 40 **INSECT CULTURING**

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42 *Sclerodermus brevicornis* (Kieffer) (Hymenoptera: Bethyridae) is a gregarious
43 ectoparasitoid wasp which is a parasitoid of European long-horned beetle larvae
44 (Coleoptera: Cerambycidae) (Kieffer, 1914; Lupi *et al.*, 2017) that can be reared on
45 several non-native, invasive cerambycids, including the larvae of yellow long-horned
46 beetle, *Psacotha hilaris hilaris* (Pascoe) (Lupi *et al.*, 2017) which was used as a host
47 in this study. Stocks of *P. h. hilaris* were maintained according to Lupi *et al.* (2017).
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Stocks of *S. brevicornis* were reared on late instar larvae of *P. h. hilaris*.

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3 All cultures and experiments were maintained in a climate chamber at $25\pm 1^\circ\text{C}$, and
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5 16H:8H L:D photoperiod and $60\pm 5\%$ relative humidity. To synchronize parasitoid and
6
7 host availability, newly emerged *S. brevicornis* adults were stored in a refrigerator at
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9 $5\pm 0.5^\circ\text{C}$ for a maximum of 7-10 days prior to use in experiments (following Abdi *et al.*,
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11 2020).
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17 **TWO-FOUNDRESS EXPERIMENT**

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19 The experiment followed a 2×3 factorial design, varying foundress relatedness and
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21 host size and holding foundress number constant. In each replicate, a larval host was
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23 placed individually into a plastic container (5 cm diameter and 4 cm depth) in which
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25 there was a thin layer (ca. 1.5 mm) of cork oak granules to maintain the relative
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27 humidity and to allow the parasitoids to access the part of the host which otherwise
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29 would be in contact with the container. Hosts were classified as small (mean weight =
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31 0.0476 g, range = 0.0213 to 0.0825 g, SD = 0.0197), medium (mean = 0.2851 g, range
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33 = 0.2142 to 0.3671 g, SD = 0.0415) or large (mean = 0.7020 g, range = 0.4921 to
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35 1.0522 g, SD = 0.1367); the weight of the host in each replicate, not just its size class,
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37 was also recorded. Note that our 'small' size class corresponds closely to the
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39 standardized sizes of the factitious host used by Abdi *et al.* (2020) and also to the
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41 'small' host size class of *P. hilaris* used by Lupi *et al.* (2017). Then two adult female *S.*
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43 *brevicornis* were added into each container. The relatedness between co-foundresses
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45 was varied such that foundresses were either brood-mates (often sisters) that had
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47 developed in the same brood or were non-siblings that had developed in different
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49 broods. To give adequate overall statistical power (Smith *et al.*, 2011), we set up 20
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51 replicates of each foundress relatedness and host size combination (20 replicates \times 2
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53 foundress relatedness levels \times 3 host size levels = 120 replicates overall).
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3 Replicates were left undisturbed for two days as observing the wasps within this
4 period has previously been found to disrupt their reproductive behaviours (D.L. & C.J.
5 pers. obs.). We then observed each replicate once per day until the 23rd day. At each
6 observation, we recorded whether the host had been paralysed, whether any
7 oviposition occurred, whether any foundresses had died and the number and sex of
8 adult offspring produced.
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17 **SINGLE-FOUNDRESS ASSAY**

20 The assay consisted of presenting single female *S. brevicornis* with a host of known
21 weight and varying host weight considerably across replicates (range = 0.0227 to
22 0.9408 g, mean = 0.3536, SD = ± 0.2723 , n=37). In each replicate, a larval host was
23 placed individually into a plastic container with cork granules, as described above.
24 Then a single adult female *S. brevicornis* was added into each container. The
25 container was covered with a white plastic cover and left undisturbed for 7 days. We
26 then observed each replicate once per day for a further 14 days. At each observation,
27 we recorded whether the host had been paralysed, whether any oviposition occurred,
28 whether the foundresses had died and whether dead foundresses had been bitten into
29 two parts by the host.
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44 **STATISTICAL ANALYSES**

46 Unless otherwise stated, significance was assessed by sequentially deleting terms
47 from initially complex models, and aggregating levels within factors, to achieve minimal
48 adequate models (Crawley, 1993; Wilson & Hardy 2002). All statistical tests were two
49 sided. All analyses were carried out using the statistical software package *GenStat*
50 (version 17, VSN International, Hemel Hempstead, UK).
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3 In the two-foundress experiment, the explanatory variable 'foundress relatedness'
4 was always fitted as a factor with two levels. In analyses of single-foundress and two-
5 foundress data, host size was fitted as a factor with three levels in some analyses and
6 as a continuous variable in others. The response variables were the parameters
7 recorded during the daily observations and at the end of the experiment.
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15 Binary data (on host paralysis, acceptance, foundress mortality and bisection) were
16 explored using logistic analyses assuming binomially distributed errors and a logit link
17 function; here the test statistic is change in deviance, G , which is approximately χ^2
18 distributed (Crawley, 1993). Other logistic analyses of proportional data with
19 denominators larger than unity (e.g. sex ratio) assumed quasi-binomial error
20 distributions and adopted a logit link function; the test statistic was the F -ratio
21 (Crawley, 1993; Wilson & Hardy, 2002). Logistic analyses comparing foundress
22 mortality during the successive stages of host handling (2-foundress experiment)
23 employed mixed models (GLMM and Wald χ^2 statistics), with replicate **identity** fitted
24 as a random factor. Integer data (e.g. number of offspring produced) were explored
25 using log-linear analyses assuming quasi-Poisson error distributions, adopting a log-
26 link function and generating F -ratio test statistics (Crawley, 1993). Data derived from
27 integers (e.g. offspring production per foundress) that were likely to be approximately
28 Poisson-distributed were also analysed using log-linear models (Faraway, 2006; Tang
29 *et al.*, 2014). Following logistic and log-linear analyses, we give the percentage
30 deviance explained (%Dev) as a descriptor analogous to r^2 .
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51 Time-to-event data on host paralysis, oviposition and foundress mortality were
52 analysed using parametric cohort survival analyses with censoring (Aitkin *et al.*, 1989;
53 Crawley, 1993). We first compared exponential models (constant hazard function)
54 against Weibull models (time dependent hazard function): in all cases, the Weibull
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3 models provided a significantly better description of the data. The influences of the
4 candidate explanatory factors (see above) were then explored by their inclusion into
5 the Weibull models (Aitkin *et al.*, 1989; Crawley, 1993). In one case, we used a non-
6 parametric log-rank test due to poor fit to parametric assumptions.
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12 As we performed many individual statistical tests, we controlled for possible Type
13 I errors using the false discovery rate (FDR) procedure to control for multiple
14 comparisons (Benjamini & Hochberg, 1995; McDonald, 2014). We treated the main
15 results from the two-foundress experiment (Table 1) as a ‘family’ of tests (including
16 evaluations of interactions (Cramer *et al.* 2016) and set the family-wide α -value to
17 0.05; thus adopting a more stringent criterion than in the accompanying, more
18 exploratory study (Abdi *et al.*, 2020). Similarly, we treated results from the single
19 foundress assay as a family of tests and used an FDR of 0.05. We report uncorrected
20 interpretations in the main text and the results of FDR procedures in the results
21 summary tables (Tables 1 & 2).
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39 **PUBLIC GOODS MODEL OF HOST ATTACK**

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41 We consider the selective forces that might combine to influence an individual female
42 *S. brevicornis* host attack decision by using a public goods model. Public goods
43 models consider situations in which a focal individual produces, at personal cost, a
44 benefit which is then shared between the individual and its social partners. Hamilton’s
45 rule asserts that a trait will spread if its fitness benefits to the recipients (b) multiplied
46 by the relatedness (r) between social partners is greater than the fitness cost (c) to the
47 actor ($rb - c > 0$) (Hamilton, 1964; Cooper *et al.*, 2018). As approaches to calculating
48 b and c are under ongoing debate (Gardner *et al.*, 2011; Abdi *et al.*, 2020), we proceed
49 heuristically in making use of our empirical estimates of the host size dependent
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3 probability of a foundress dying during host attack (cost, c) and of the fitness obtained
4 from a successfully paralysed host of a given size (benefit, b) to explore, qualitatively,
5 how co-foundress relatedness (r) might affect selection for host attack as a public
6 good. As benefits and costs are affected by host size, our proxies of b and c are in the
7 form of regression equations rather than being fixed values applied across all hosts.
8 Cost is expressed as a proportional response to host size and thus c takes values
9 between zero and unity. As the relationship between the benefits provided by a host
10 and the size of that host is domed (see below), we divided by the maximum value of
11 the polynomial regression equation to scale benefits as a proportion, b thus takes
12 values between zero and unity (following Abdi *et al.*, 2020). We use an open
13 formulation of Hamilton's rule in which the mechanism generating co-foundress
14 relatedness is undefined (Cooper *et al.*, 2018) and explore values of r ranging between
15 zero and unity.
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35 RESULTS

36 TWO-FOUNDRESS EXPERIMENT

37 Results of analyses reported in this section are summarized in Table 1.
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47 *Foundress mortality*

48 Approximately a quarter (23.75%, 57/240) of foundresses died by the twenty-third day
49 after presentation with a host. Foundresses that were brood-mates died earlier than
50 non-sibling foundresses (cohort survival analysis with surviving females treated as
51 censors: $G_1 = 5.7$, $P = 0.020$, %Dev = 1.98, Fig.1). In this analysis, the longevity of
52 each of the pair of foundresses was treated as if it were independent of the other; such
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3 pseudo-replication could have generated the significance. We therefore ran an
4 additional analysis using a non-parametric log-rank test on the mean longevity of
5 females in each replicate, thus analysing one observation per replicate: this also
6 indicated that brood-mates died earlier than did non-siblings ($z = 4.919$, d.f. = 1, $P =$
7 0.027). Time to death was not significantly affected by host size ($G_2 = 2.4$, $P = 0.301$,
8 %Dev = 0.88) or by its interaction with foundress relatedness ($G_2 = 2.9$, $P = 0.235$,
9 %Dev = 1.10).

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11 Similarly, the proportion of foundresses in a replicate dying (number dying/2) was
12 significantly higher when foundresses were brood-mates (logistic ANOVA: $G_1 = 5.23$,
13 $P = 0.022$, %Dev = 3.15, Fig. 2) but was not affected by host size ($G_2 = 1.14$, $P =$
14 0.321 , %Dev = 1.37) or its interaction with foundress relatedness ($G_2 = 1.52$, $P = 0.218$,
15 %Dev = 1.84). However, separate analyses within each host size class indicated that
16 mortality of brood-mate foundresses was significantly higher when presented with
17 medium sized hosts (logistic ANOVA: $G_1 = 7.62$, $P = 0.006$, %Dev = 12.71, Fig. 2) but
18 did not differ when hosts were large ($G_1 = 0.62$, $P = 0.430$, %Dev = 1.09) or small (G_1
19 = 0.08, $P = 0.774$, %Dev = 0.18).

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21 We further explored foundress mortality in relation to the successive host-handling
22 periods: pre-paralysis (host presentation to host paralysis), paralysis-to-oviposition
23 and post-oviposition (Fig. 3). The proportion of foundress that died differed significantly
24 according to relatedness (mortality was highest amongst brood mates, GLMM: Wald
25 $\chi^2 = 4.06$, d.f. = 1, $P = 0.046$) and between periods (post-oviposition mortality was
26 lowest, $\chi^2 = 17.29$, d.f. = 2, $P < 0.001$) but without significant interaction between
27 relatedness and period ($\chi^2 = 2.12$, d.f. = 2, $P = 0.348$). Host size affected mortality
28 through an interaction with period (size: $\chi^2 = 2.59$, d.f. = 2, $P = 0.279$; size \times period: χ^2
29 = 15.48, d.f. = 4, $P = 0.005$), with pre-paralysis mortality being lowest when
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3 foundresses were presented with small hosts. There was no significant interaction
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5 between relatedness and size ($\chi^2 = 2.81$, d.f. = 2, $P = 0.250$) or between all three main
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7 effects ($\chi^2 = 0.04$, d.f. = 3, $P = 0.998$).
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10 11 12 **Paralysis**

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14 The percentage of hosts that were paralysed by *S. brevicornis* foundresses was
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16 83.33% ($n = 120$). This proportion decreased significantly with an increase in host size
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18 (logistic ANCOVA: $G_1 = 15.90$, $P < 0.001$, %Dev = 14.70, Fig. 4) but was unaffected by
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20 relatedness ($G_1 = 0.20$, $P = 0.653$, %Dev = 0.19) or its interaction with host size ($G_1 =$
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22 1.55, $P = 0.213$, %Dev = 1.43).
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26 Among the 100 replicates in which host paralysis occurred, the time taken to
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28 paralyse the host ranged up to 22 days. The 20 replicates in which there was no
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30 paralysis observed were treated as censors in the subsequent cohort survival analysis.
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32 Time-to-paralysis was significantly affected by host size ($G_2 = 96.5$, $P < 0.001$, %Dev =
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34 37.36), with smaller hosts paralysed faster than larger hosts. Foundress relatedness
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36 also affected time-to-paralysis ($G_1 = 9.5$, $P = 0.002$, %Dev = 5.97) and there was a
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38 significant interaction between relatedness and host size ($G_2 = 9.5$, $P = 0.009$, %Dev
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40 = 7.80): for small hosts, paralysis was significantly more rapid when foundresses were
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42 brood-mates ($G_1 = 20.4$, $P < 0.001$, %Dev = 46.99), for medium sized hosts, paralysis
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44 by brood-mates was non-significantly earlier ($G_1 = 2.10$, $P = 0.147$, %Dev = 3.61) and
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46 for large sized hosts paralysis by brood-mates was non-significantly later ($G_1 = 0.1$, P
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48 = 0.752, %Dev = 0.16) (Fig. 5). We checked these results by repeating the analysis
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50 with host size fitted as a variate rather than as a categorical factor: the interpretation
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52 remained the same (Host size: $G_1 = 60.1$, $P < 0.001$, %Dev = 29.09; Relatedness: G_1
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54 = 4.3, $P = 0.038$, %Dev = 2.64; Interaction: $G_1 = 4.1$, $P = 0.043$, %Dev = 2.47).
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Oviposition

The percentage of presented hosts which were oviposited on was 73.33% ($n = 120$), excluding the 20 hosts that were not paralysed, the percentage was 88%. The probability of oviposition on paralysed hosts was not significantly affected by host size (logistic ANCOVA: $G_1 = 0.07$, $P = 0.791$, %Dev = 0.10, $n = 100$), relatedness ($G_1 = 1.36$, $P = 0.243$, %Dev = 1.86) or by an interaction between host size and relatedness ($G_1 = 2.41$, $P = 0.121$, %Dev = 3.29). Once a host was paralysed, time to oviposition was not affected by host size (cohort survival analysis with foundresses that did oviposit by day 20 treated as censors, $G_2 = 5.2$, $P = 0.074$, %Dev = 3.58) or by an interaction between host size and relatedness ($G_2 = 2.4$, $P = 0.301$, %Dev = 1.93) but non-siblings oviposited significantly earlier ($G_1 = 7.70$, $P = 0.006$, %Dev = 5.50). There was, however, no difference between non-siblings and brood mates in the time taken to oviposition when data were analysed from the time of host presentation ($G_1 = 0.2$, $P = 0.655$, %Dev = 0.10).

Brood size

The total number of adult offspring produced from a host which had been oviposited on ($n = 59$) ranged between 1 and 163. Total brood size had a significantly curvilinear response to increasing host size (log-linear ANCOVA including a quadratic term: host size: $F_{1,55} = 14.50$, $P < 0.001$, %Dev = 13.95, host size²: $F_{1,55} = 32.41$, $P < 0.001$, %Dev = 31.18, Fig. 6A) and was also affected by foundress relatedness via a significant interaction with host size (relatedness: $F_{1,55} = 0.356$, $P = 0.064$, %Dev = 3.43; interaction: $F_{1,55} = 6.42$, $P = 0.014$, %Dev = 6.18, Fig. 6A); non-siblings typically produced larger broods. Examining the same data in terms of mean per-foundress

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3 offspring production (brood size/number of foundresses surviving at the time of
4 oviposition) also found a curvilinear response to increasing host size (host size: $F_{1,55}$
5 = 10.08, $P = 0.002$, %Dev = 10.41; host size²: $F_{1,55} = 27.22$, $P < 0.001$, %Dev = 28.10)
6 and an interaction between foundress relatedness and host size (relatedness: $F_{1,55} =$
7 9.88, $P = 0.003$, %Dev = 10.20; interaction: $F_{1,55} = 11.40$, $P = 0.001$, %Dev = 11.77,
8 Fig. 6B); non-siblings typically produced smaller broods than brood-mate foundresses
9 when hosts were small but relatively larger broods when hosts were large.
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21 **Sex ratio**

22 Offspring brood sex ratios were strongly female biased: the mean proportion of
23 offspring that were male was 0.0339 (+S.E. = 0.0039, -S.E. = 0.0035, $n = 59$). Due to
24 the mortality of some foundresses before oviposition, broods were either produced by
25 a single surviving foundress from a sibling group; a single surviving foundress from a
26 non-sibling group; two surviving sibling foundresses or two surviving non-sibling
27 foundresses. The effect of varying foundress number at oviposition was explored by
28 fitting the number of foundresses as a 2-level factor along with relatedness and host
29 size in a 3-way logistic ANOVA. Sex ratios were less female biased when pairs of
30 foundresses oviposited together ($F_{1,58} = 4.08$, $P = 0.049$, %Dev = 7.19, Fig. 7) but were
31 not significantly affected by relatedness ($F_{1,55} = 0.00$, $P = 0.948$, %Dev = 0.01), host
32 size ($F_{2,57} = 0.40$, $P = 0.670$, %Dev = 1.42) or by any interactions between these main
33 effects (relatedness \times host size interaction: $F_{2,54} = 1.22$, $P = 0.304$, %Dev = 4.29).
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50 Sex ratios were not significantly affected by brood size (logistic regression: $F_{1,57} =$
51 3.08, $P = 0.085$, %Dev = 5.12). The number of male offspring produced increased
52 significantly with an increase of brood size (log-linear regression: $F_{1,58} = 25.39$, $P <$
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0.001, %Dev = 30.82, Fig. 8). No other measured variables or their interactions affected the number of males per brood significantly.

SINGLE-FOUNDRRESS ASSAY

Results of analyses reported in this section are summarized in Table 2.

Probabaility of paralysis and oviposition

Almost 60% (22/37) of hosts presented to a single *S. brevicornis* foundress became paralysed. The probabaility of paralysis decreased significantly with an increase in host size (logistic regression: $G_1 = 11.68$, $P < 0.001$, %Dev = 23.39, Fig. 9A). Once a host was paralysed, the probability that the foundress oviposited on it was also almost 60% (13/22) and was not affected by the size of the host (logistic regression: $G_1 = 0.00$, $P = 0.957$, %Dev = 0.01).

Foundress mortality

Typically, when a female *S. brevicornis* attacks a host, either the host is paralysed or the wasp is killed (Table 3). In three of the 37 replicates the female apparently did not attack the host within the 21 day observation period as neither the host was paralysed nor foundress died (Table 3); these were excluded from estimation of the probability of mortality as a consequence of attack (cost parameter, c , in the public goods model, see below). Among the remaining replicates, around 40% (14/34) of the foundresses died. In two cases, the foundress died and the host was paralysed (Table 3): in one of these the foundress was cut in half, suggesting the host killed it during wasp attack and in the other case the foundress died intact suggesting that the cause of death may

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3 have been unconnected to host attack. Whether or not these replicates were excluded
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5 from analysis, the probability of mortality increased significantly with an increase in
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7 host size (all data: $G_1 = 5.18$, $P=0.023$, %Dev = 11.25; excluding only the foundress
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9 that died intact: $G_1 = 7.03$, $P = 0.008$, %Dev = 15.54; excluding both females that died
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11 along with host paralysis: $G_1 = 8.22$, $P=0.004$, %Dev = 18.62; Fig. 9B shows the
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13 regression for the second case). We observed that some dead females had been
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15 severed into two parts, such as the head being separated from the rest of the body or
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17 the head and thorax separated from the abdomen. The probability that a dead female
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19 was bisected increased significantly with an increase of host size (logistic regression:
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21 $G_1 = 7.97$, $P=0.005$, %Dev = 43.67, $n=14$, Fig. 9C).
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31 ***Timing of paralysis and mortality***

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33 Among the 22 replicates in which host paralysis occurred, the time taken to paralyse
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35 the host ranged up to 19 days. Time-to-paralysis was significantly affected by host
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37 size, with smaller hosts being paralysed earlier than larger hosts ($G_1 = 18.4$, $P<0.001$,
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39 %Dev = 37.15); in this analysis replicates in which the foundress died before host
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41 paralysis, or both the foundress and the host were alive at the end of the experiment,
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43 were treated as censors. Time to foundress mortality also ranged up to 19 days but
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45 was unaffected by host size ($G_1 = 2.8$, $P=0.095$, %Dev = 5.34, females that did not die
46
47 were treated as censors). There was no relationship between time to foundress
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49 mortality and whether a female was bisected by the host (logistic analysis: $G_1 = 0.00$,
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51 $P = 0.947$).
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PUBLIC GOODS MODEL OF HOST ATTACK

An estimate of the host size dependent probability of a foundress dying during host attack (a proxy for cost, c) was obtained from the single-foundress assay (Fig. 9) and an estimate of how fitness benefits obtained from a successfully paralysed host (a proxy for benefit, b) are influenced by host size was obtained from the two-foundress experiment (Fig. 6). Following Abdi *et al.* (2020), these relationships were then used in Hamilton's rule ($rb - c > 0$, Hamilton, 1964) to explore how variation in *S. brevicornis* co-foundress relatedness (r) might affect selection for host attack as a public good (Cooper *et al.*, 2018).

The result (Fig. 10) suggests that selection for public goods attack should depend on a combination of host size and relatedness. Specifically, the model suggests that individual foundresses will be selected to attack and then share hosts as a public good only when the host is neither large nor very small (*i.e.* within the range *ca.* 0.1 to 0.7g) and further, only when their relatedness to co-foundresses is high ($r > 0.5$). The model also suggests that a wider range of host sizes will be attacked as a public good when inter-foundress relatedness is higher.

As the relationships between host size and benefits differ according to co-foundresses relatedness (Fig. 6) we constructed a version of model using the fitted quadratic log-linear regression for brood-mate foundresses when relatedness, r , is equal to 0.75 or 1, and the regression for non-sibling foundresses when $r = 0.0$ or 0.25. The form of the prediction was very similar to results shown in Fig. 10, but brood-mate females would be expected to carry out public good host attack on very small hosts and to have a slightly lower upper-host size that they should attack as a public good.

DISCUSSION

For *Sclerodermus* females, attacking a host is a challenging step in the reproductive cycle and yet, to be able to reproduce, a female parasitoid must gain access to a suppressed host. Our estimates indicate that, when presented with a healthy host, 25-40% of *S. brevicornis* foundresses die prior to host suppression (estimates from two foundress and single foundress cases respectively). Further, foundress mortality is related to host size, with larger hosts being considerably more dangerous to attack, as is also the case for other *Sclerodermus* species (Liu *et al.*, 2011; Wei *et al.*, 2014). The observation that many of the dead wasps in the single-foundresses assay were severed into two pieces indicates that hosts engage in active, and often successful, behavioural defence against parasitism, as also observed by Li and Sun (2011) and Liu *et al.* (2011).

A female may avoid the risks of host attack by utilizing a host that has been successfully attacked by another female ('free-rider' behaviour, Rankin *et al.*, 2007). *Sclerodermus* females have not been observed to defend paralysed hosts against usage by conspecifics (in contrast to some sub-social bethylids, Hardy *et al.*, 2013) and post-ovipositional brood care is cooperative, without apparent inter-foundress conflict (Hu *et al.*, 2012; Wu *et al.*, 2014): as such, the reproductive resource represented by a paralysed host is shared between co-foundress females. In *S. brevicornis* (this study) and *S. pupariae* (Wei *et al.*, 2014) there is a domed relationship between offspring production and host size while for *S. harmandi* larger hosts, once suppressed, provide a larger collective reproductive benefit for co-foundresses (Liu *et al.*, 2011; Tang *et al.*, 2014). Although there are several estimated forms of the relationship between host size and *Sclerodermus* brood size, in all cases the total

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3 reproductive benefits of host exploitation are host-size dependent (Abdi *et al.* 2020;
4 this study).
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8 While a female may avoid host attack risks by joining one or more conspecifics in
9 the exploitation of a previously suppressed host, the converse question concerns
10 whether a female should be prepared to attack a host to obtain a resource that will
11 then be shared with others. A guide to whether individuals should attack, and then
12 share, a host of a given size (with the associated risk of death and benefits of
13 successful suppression) is provided by the public goods modelling approach using
14 Hamilton's rule. A discussion of the caveats associated with using empirically obtained
15 parameter estimates **as proxies for parameters** in Hamilton's rule is provided by Abdi
16 *et al.* (2020) and we further note that defining fitness benefits, b , simply in terms of
17 numerical offspring production does not take into account that host size may affect
18 further components of fitness. One example is the size of female offspring (Wei *et al.*,
19 2014) which, in turn, may influence performance, including the ability to attack hosts
20 of a given size (affecting c). Using Hamilton's rule nonetheless suggests that both host
21 size and co-foundress relatedness will be important influences on a *S. brevicornis*
22 female's attack decision. When hosts are very small, the risks **associated with** host
23 attack are low but the benefits of host suppression are also small: even when the
24 relatedness of a female to any co-foundresses present is high, a female is unlikely to
25 attack a host as a public good because the personal fitness costs to the female
26 outweigh the fitness benefits. When hosts are medium sized, the risks during host
27 attack are intermediate and the benefits of success are large. Under these
28 circumstances, a female is expected to pay the private cost of providing a public good
29 but only if her relatedness to co-foundresses is high. Using empirically estimated cost
30 and benefit parameters suggests that inter-foundress relatedness of 0.75 (the
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3 relatedness of full sisters under haplo-diploid genetics, Hamilton 1964) is sufficient for
4 selection to favour public goods attack on medium sized hosts. When hosts are large
5 and very dangerous, such that most attacking females are killed, and the benefits of
6 successful host suppression are small, females are not expected to engage in public
7 goods attack. We note that we have implicitly considered host attack an individual
8 activity, carried out by one foundress while others present stand to benefit from her
9 actions, but it remains possible that multi-female *Sclerodermus* attack, whether
10 simultaneous or sequential, influences the probability of success.
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21 The public goods approach functions to indicate whether a *S. brevicornis* female
22 should attack and then share a host, rather than whether a female should attack a host
23 to support only her own offspring. Females that do not obtain access to a suppressed
24 host (whether shared or not) cannot reproduce and thus might be expected to attack
25 all sizes of hosts when there are no other options. Following Abdi *et al.* (2020), we
26 interpret the public goods model to suggest patterns in the latency of host attack, *i.e.*
27 how long a female encountering a dangerous host should wait for other females to
28 attack the host before eventually attacking it herself. We might expect a female's
29 reluctance to attack to be reduced by potential inclusive fitness benefits when other
30 females present are kin and, indeed, we found from the two-foundress experiment that
31 females tended to die both earlier and with a higher probability when they were with
32 brood-mates rather than non-siblings (in contrast to the lack of effect found by Abdi *et*
33 *al.* 2020, assessing attack on small hosts only).
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51 The models constructed by Abdi *et al.* (2020) for other *Sclerodermus* species and
52 the model constructed here for *S. brevicornis* all suggest that co-foundress
53 relatedness and host size will interact to influence the time that females wait before
54 host attack. We have found empirically that time-to-paralysis is affected by host size
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3 (in accord with Lui *et al.*, 2011, studying *S. harmandi*) by relatedness (in accord with
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5 Abdi *et al.*, 2020) and also by their interaction, as predicted. The time-to-paralysis raw
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7 data for *S. brevicornis* (Fig. 5A) suggest the greatest effect of relatedness when hosts
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9 are small, with hosts being paralysed more rapidly when co-foundresses relatedness
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11 is higher, whereas the fitted cohort survival model (Fig. 5B) and the public goods model
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13 (Fig. 10) both suggest greater effects for medium-sized hosts. When hosts are large,
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15 the time-to-paralysis data, the cohort survival model and the public goods model all
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17 suggest that relatedness has little effect on host attack rates. We conclude that using
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19 empirically estimated benefit and cost parameter's in Hamilton's rule provides a
20
21 broadly useful heuristic to understanding host attack in *Sclerodermus*.

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26 Following the successful suppression of a host, mortality among pairs of
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28 foundresses was common, especially during the period between paralysis and
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30 oviposition. We suggest that this mortality may result from inter-foundress conflict over
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32 resource exploitation, even though such conflict is not visually obvious. Further work
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34 is required to probe the apparently cooperative nature of post-paralysis behaviour and
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36 brood production in *Sclerodermus* (e.g. to test for disproportionate reproduction by
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38 some foundresses [reproductive skew]) and any mediating effects of co-foundress
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40 kinship. While we detected no effect of relatedness on foundress mortality after host
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42 suppression, we did find that brood-mate females produced slightly greater numbers
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44 of offspring on small hosts (as also found by Abdi *et al.*, 2020) and on larger hosts
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46 brood sizes were considerably larger when co-foundresses were not siblings. We
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48 suggest that *Sclerodermus* oviposition decisions may comprise a dynamic game
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50 between co-foundresses, involving a trade-off between brood-size and offspring
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52 fitness and a tragedy of the commons (TOC) scenario, whereby individual foundresses
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54 tend to selfishly add their own offspring, leading to broods being larger than the size
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3 that would optimise group fitness; we also expect that such behaviour would be
4 mediated by kinship (Rankin *et al.*, 2007; van Dijk *et al.*, 2014; Ferrari *et al.*, 2015;
5 Smith & Schuster, 2019). Further, as communal brood production in *Sclerodermus*
6 usually leads to some reproductive output, we suggest that a TOC would be a
7 'component tragedy' in which selfishness reduces average fitness partially but not
8 completely (Rankin *et al.*, 2007).
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17 Maturing offspring had extremely female-biased sex ratios, as previously observed
18 in *S. brevicornis* (Lupi *et al.*, 2017; Abdi *et al.*, 2020) and congeners (Kühne & Becker,
19 1974; Li & Sun, 2011; Liu *et al.*, 2011; Hu *et al.*, 2012; Tang *et al.*, 2014; Wei *et al.*,
20 2014; Gao *et al.*, 2016; Kapranas *et al.*, 2016). We detected no effects of co-foundress
21 relatedness on sex ratios but, in common with Tang *et al.* (2014), we found a slight
22 decrease in bias as foundress number increased. Sex ratio bias in *Sclerodermus* is
23 likely to be selected for by the advantages accrued by co-foundresses from communal
24 exploitation of hosts that are too large for single females to reproduce on alone (*i.e.*
25 mutually beneficial female–female interactions increase the reproductive value of
26 daughters, Tang *et al.* 2014; Kapranas *et al.* 2016); however, there are currently no
27 models of optimal sex allocation in *Sclerodermus* and therefore no formal predictions
28 concerning the likely influences of co-foundress relatedness.
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47 CONCLUSIONS

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49 This study set out to evaluate the importance of host size on the host attack and further
50 reproductive behaviour of *Sclerodermus brevicornis*. This followed a prior study (Abdi
51 *et al.*, 2020) which identified that co-foundress relatedness affects the timing of host
52 attack and suggested (using data on reproductive patterns in congeners and a public
53 goods approach), that host size should interact with relatedness and thus mediate the
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3 observed effect of kinship. We have shown that effects of both host size and kinship
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5 operate during several of the stages of *S. brevicornis* host attack and reproduction and
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7 that they interact to influence the timing of host attack, as predicted.
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10 A public goods model of host attack using parameters estimated for *S. brevicornis*
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12 gives broadly similar results to the previous models, again suggesting that selection
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14 for an individual foundresses to attack and then, if successful, share their hosts will
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16 depend on both size of the host and the foundress's relatedness to any co-
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18 foundresses present. We also found that co-foundress relatedness influences some
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20 reproductive behaviours following host suppression, and we suggest that future
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22 studies are likely to reveal further effects.
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26 Our overall conclusions are that females attune their behaviour to the risks involved
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28 in attempting to suppress large and dangerous hosts and that while reproductive
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30 behaviours exhibited by *Sclerodermus* females can be cooperative, they will not
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32 always be exhibited without reference to kinship.
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37 **CODA: COOPERATIVE REPRODUCTION IN THE GENUS *SCLERODERMUS***

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39 Tang *et al.* (2014) showed that it is to the direct fitness advantage of individual female
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41 *Sclerodermus* to exploit hosts as part of a multi-foundress group, provided that the
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43 host is not small. This is because individual females have very low probabilities of
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45 successfully suppressing and reproducing on medium and large sized hosts, while
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47 larger groups of foundresses have greater collective success and the mean per
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49 foundress production of offspring is higher than when females attempt to reproduce
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51 alone. However, Tang *et al.* (2014) did not assess variation in behaviour or success
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53 within foundress groups, nor did they control inter-foundress relatedness. Our new
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55 evidence from this study and from the accompanying study (Abdi *et al.*, 2020)
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3 suggests that individuals within apparently cooperative foundress groups may attune
4 their contributions to their own direct and inclusive fitness interests and thus that there
5 is conflict within cooperation, as noted in numerous other biological systems and
6 societies (Schenider & Bilde, 2008; West & Ghoul, 2019; Ågren *et al.*, 2019; Levin *et*
7 *al.*, 2020).

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10 We suggest that the current understanding of *Sclerodermus* cooperative
11 reproduction can be broadly summarized by considering inter-foundress relatedness
12 simply as 'high' or 'low' and hosts as 'small' or 'large', and by classifying cooperation
13 very simply in terms of inner conflict (Table 4); we note that when hosts are either
14 very small or very large, any selection for cooperation may break down (due to very
15 low benefits or very high costs of attack, respectively). Depending on the combination
16 of inter-foundress relatedness and host size, a female may be selected to attack a
17 host or to leave host attack to others, and also to share or to not share a successfully
18 attacked host. When hosts are small and attack incurs low cost, *Sclerodermus* may
19 share them with related females due to inclusive fitness benefits but attempt to
20 exclude non-relative females to maximise direct fitness gains from host exploitation
21 (as in sub-social bethylids, Hardy *et al.*, 2013), although aggressive inter-female
22 behaviour has not currently been reported in *Sclerodermus*. When hosts are large,
23 and attack incurs high cost, females may gain both direct and inclusive fitness from
24 sharing with relatives but will gain only direct fitness when co-foundresses are not kin.
25 In the latter case, cooperation may not be conflict free and is likely to be characterised
26 by forms of exploitation, manipulation and enforcement (Ågren *et al.*, 2019, 2020;
27 Engelhardt & Taborsky, 2020).

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30 *Sclerodermus* are aculeate parasitoids that have evolved quasi-sociality
31 (communal brood care) but no parasitoid hymenopteran has evolved the eusociality
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3 (further involving reproductive division of labour and overlapping generations) that is
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5 observed in some non-parasitoid aculeate sister taxa (Peters *et al.*, 2017). It seems
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7 unlikely that lineages of *Sclerodermus* could readily transition to eusocial
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9 reproduction, as generational overlap would necessitate multi-generational
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11 cooperative groups colonising fresh hosts in concert. Further, if foundress groups are
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13 commonly formed from mixtures of kin and non-kin, selection for greater social
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15 complexity, such as reproductive specialization, may be limited (Downing *et al.*, 2020).
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AUTHOR CONTRIBUTIONS

All authors designed the experiment. M.K.A., C.J. and D.L. collected the data. M.K.A. and I.C.W.H. analysed the data and wrote the manuscript. **I.C.W.H. revised the manuscript.** All authors discussed the work at all stages and approved the manuscript.

COMPETING INTERESTS

All authors declare that they have no competing interests.

DATA ACCESSIBILITY

The data generated in the experiments reported in this study are available from the corresponding author on reasonable request. On publication we will deposit the data in the Dryad Digital Repository.

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Table 1. Summarized main results from the two-foundress experiment*

Reproductive trait	Relatedness	Host size	Interaction
Foundress mortality (overall proportion)	Higher among brood-mate foundresses	NS ¹	NS
Foundress mortality (timing)	Brood-mates die earlier than non-siblings	NS	NS
Paralysis of host (proportion)	NS	Lower probability with larger hosts	NS
Paralysis of host (timing)	Brood-mates often paralyse hosts earlier than non-siblings but depends on host size	Smaller hosts paralysed earlier	Brood-mates paralyse smaller hosts earlier and larger hosts later than non-siblings
Oviposition on host (probability)	NS	NS	NS
Oviposition on host (timing)	Non-sibling foundresses oviposited earlier	NS	NS
Brood size (total)	Significance via interaction	Curvilinear response	Non-siblings produced larger broods than brood-mates except on small hosts
Brood size (per foundress)	Significant as main effect and via interaction	Curvilinear response	Non-siblings produce smaller broods than brood-mates on small hosts and relatively larger broods on large hosts
Sex ratio of offspring	NS	NS	NS

*All significant effects retained the same interpretation after multiple-comparisons correction using a false discovery rate of 0.05.

¹NS = No statistically significant influence detected.

Table 2 Summarised single foundress assay results*

Trait	Effect of increasing host size
Host paralysis	Probability of paralysis decreased
Oviposition on paralysed host	NS ¹
Foundress mortality	Probability of mortality increased
Bisection of dead foundress	Probability that a dead female was bisected increased
Timing of host paralysis	Smaller hosts were paralysed earlier than larger hosts
Timing of foundress mortality	NS

*All significant effects retained the same interpretation after multiple-comparisons correction using a false discovery rate of 0.05.

¹NS = No statistically significant influence detected.

Table 3. Outcomes of single-foundress interactions with hosts

Foundress status	Host not paralysed	Host paralysed but not oviposited on	Host paralysed and oviposited on
Foundress died (bisected)	8	1	0
Foundress died (intact)	4	1	0
Foundress lived	3	7*	13

*Six of these hosts may have been too small (0.0005–0.0592mg, mean=0.0287, SD=0.0215) to support offspring development.

Table 4. *Sclerodermus* reproductive strategy: a synthesis

	Small host	Large host
High relatedness	Attack and share host Conflict free cooperation	Attack and share host Conflict free cooperation
Low relatedness	Attack host but do not share host No cooperation	Avoid host attack but share host attacked by others Conflict within cooperation

FIGURE LEGENDS

Figure 1. The effect of relatedness on foundress survival over time.

Figure 2. Foundress mortality according to host size and relatedness. Bars represent standard errors of means and are asymmetrical due to back transformation from the logit scale. Differences between brood-mates and non-siblings on small or large hosts were not significant.

Figure 3. Foundress mortality according to relatedness (A) and host size (B) during the successive stages of host handling. Bars represent standard errors of means and are asymmetrical due to back transformation from the logit scale.

Figure 4. The effect of host size on probability of host paralysis.

Figure 5. The effects of co-foundress relatedness and host size on time to paralyse the host. The upper panel shows the cohort data from the six treatment combinations and the lower panel shows the fitted survival model, estimated from Weibull analysis with unparalysed hosts treated as censors. To avoid disruption of the females' behaviours no observations were taken during the first two days and the statistical model was fitted assuming no hosts were paralysed during this period. Foundress relatedness and host size interacted to influence time-to-paralysis: effects of kinship were significant only when hosts were small.

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3 **Figure 6.** Adult offspring produced according to relatedness and host size. (A) Total
4 brood size. (B) Per-foundress offspring production (C) Per-foundress offspring
5 production. Regression lines were obtained by log-linear ANCOVAs including a
6 quadratic term. Offspring production differed according to relatedness so separate
7 lines are shown for brood-mate and non-sibling foundresses. The regression line for
8 overall brood size on panel a is used as a the host-size dependent benefit, b , in the
9 public goods model: fitness benefits obtained from paralysed host = $\exp(8.82 \times \text{host}$
10 $\text{size} - 8.27 \times \text{host size}^2 + 2.261)$.

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23 **Figure 7.** Sex ratios of broods according to the number of foundresses surviving to
24 the time of oviposition. Bars represent standard errors of means and are asymmetrical
25 due to back transformation from the logit scale.

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33 **Figure 8.** The relationship between the number of males in a brood and brood size.

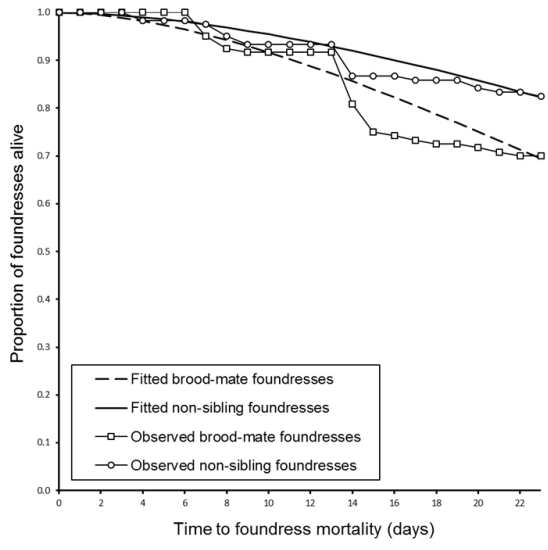
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37 **Figure 9.** Probabilities of host paralysis [n=37] (A), foundress mortality [n=34] (B) and
38 the foundress being bitten in half by the host [n=14] (C). The logistic regression line in
39 panel b is used as the host-size dependent cost, c , in the public goods model:
40 probability of death when attacking host = $1/(1+(1/(\exp((3.99 \times \text{host weight}) - 1.847))))$,
41 excluding the replicate where the female may have died after successful host attack.

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51 **Figure 10.** Public goods model of relatedness mediated host attack for *Sclerodermus*
52 *brevicornis*. The model combines the estimate of the host size dependent probability
53 of a foundress dying during host attack (cost, c), presented in Fig. 9B, with the estimate
54 of fitness benefits of successful attack (b), shown in Fig. 6, into Hamilton's rule ($rb - c$
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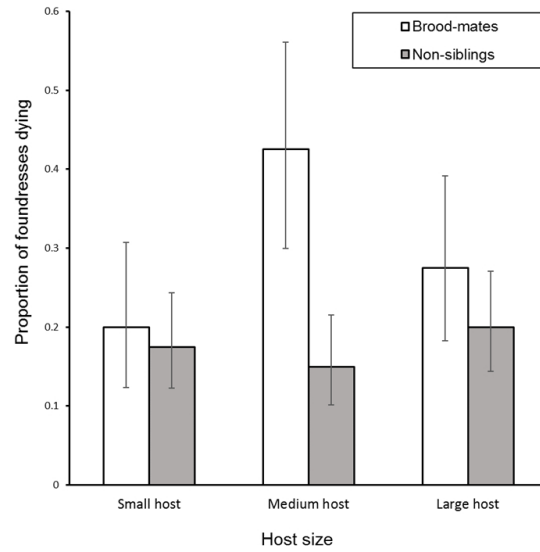
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3 > 0) to illustrate how co-foundress relatedness (r) might affect selection for host attack
4 as a public good. The model suggests that selection for public goods attack depends
5 on a combination of host size and co-foundress relatedness, and will be strongest
6 when hosts are mid-sized and relatedness is >0.5 . In **panel A** values from Hamilton's
7 rule are plotted against host weight and the benefit curve was scaled to a maximum
8 of 1, following Abdi *et al.* (2020). **Panel B** highlights the combinations of relatedness
9 and host weight when public goods attack is favoured.
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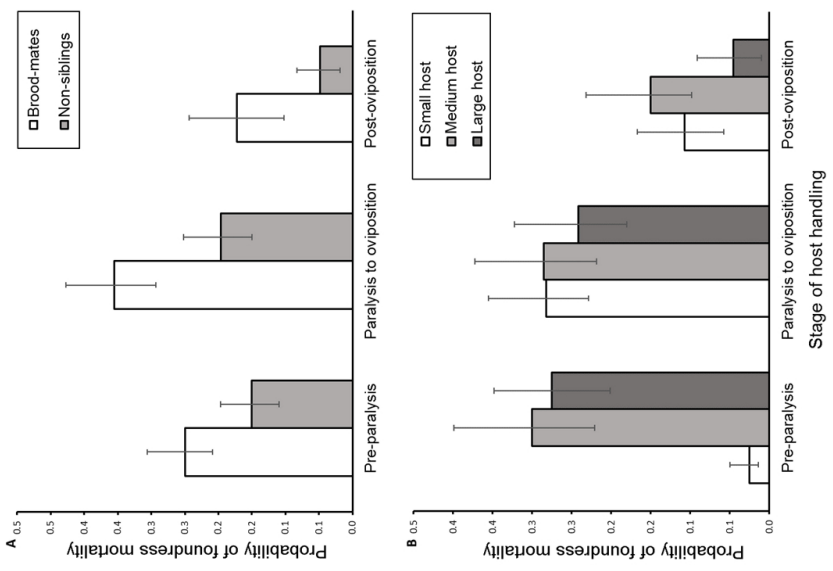


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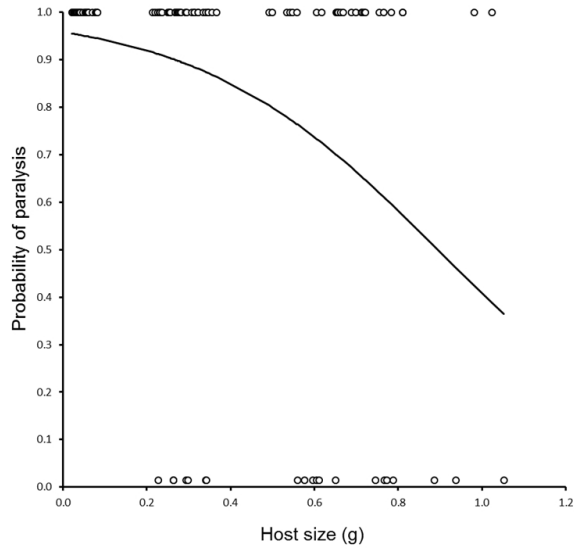


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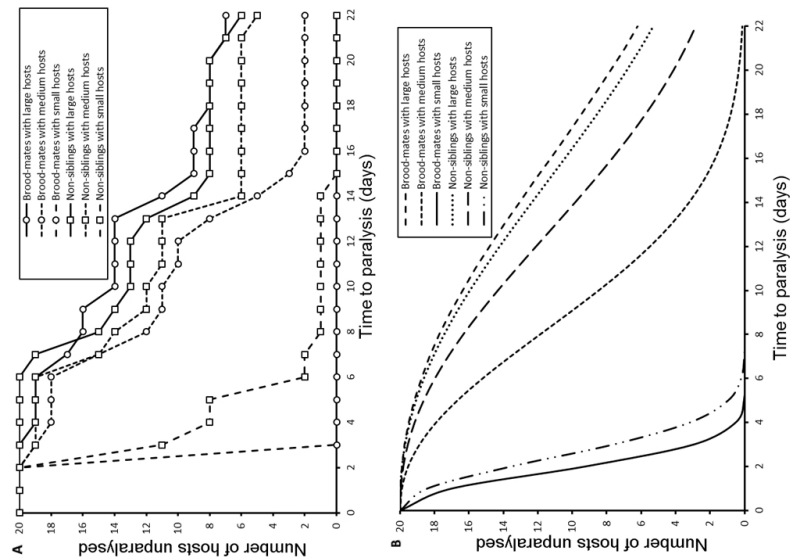


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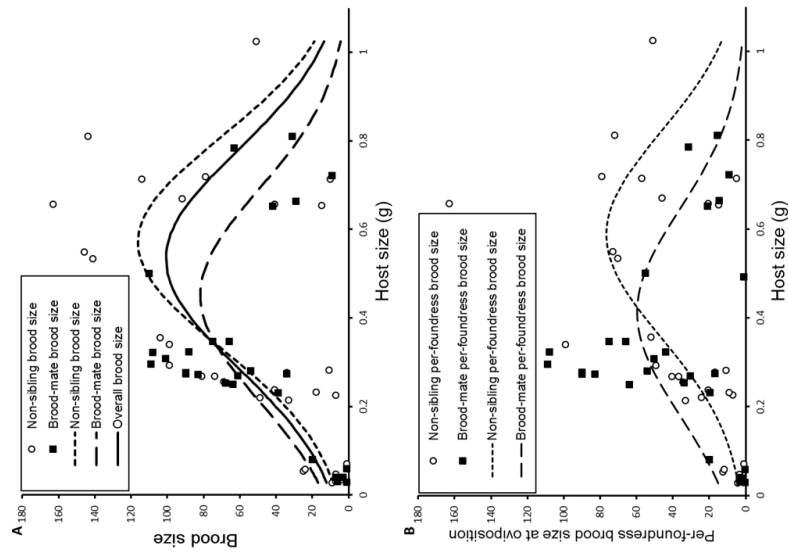


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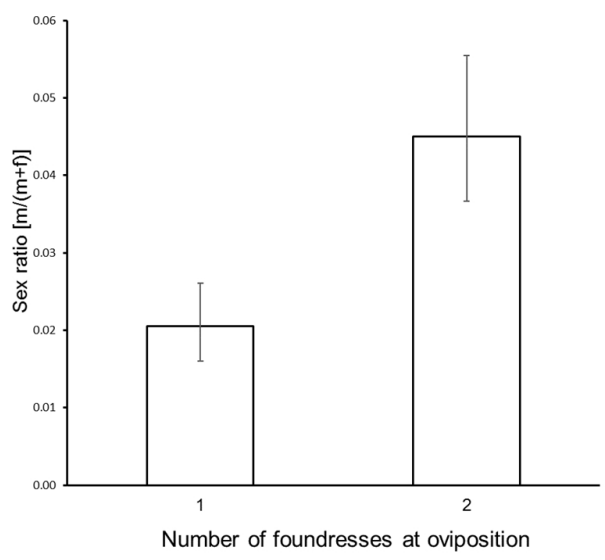


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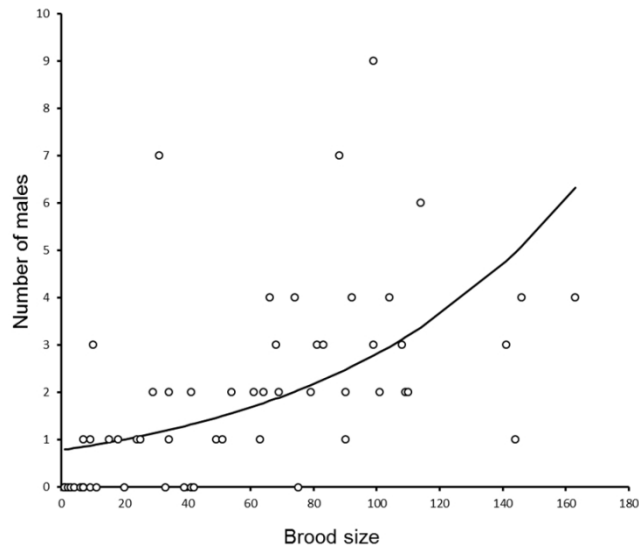
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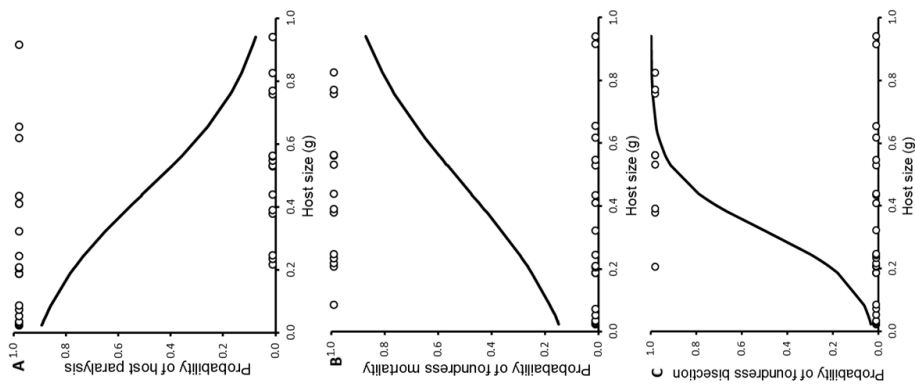
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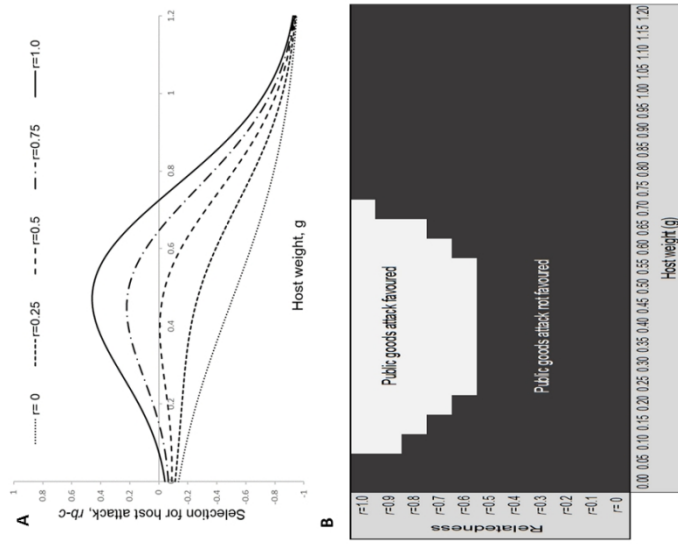
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