Original Article

Social dynamics drive selection in cooperative associations of ant queens

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Social dynamics, the emergent effects of interactions within structured groups, play a key role in shaping social phenotypes and fitness. We examined the potential positive and negative effects of social dynamics in simple groups, by creating social groups of harvester ant queens with 2 alternate nest-founding strategies, solitary versus cooperative. We compared social interactions, survival, and nest productivity of pairs containing queens from the cooperative founding population, the normally solitary founding population, or mixed pairs of the 2 types. Expressed social phenomenotypes of queens in pairs depended strongly on the lineage of the other queen. Two behaviors, aggression and brood care, showed simple social dynamical effects. Aggression escalated in pairs of normally solitary queens, whereas queens in cooperative pairs coordinated brood output, leading to more efficient worker production. These dynamics had context-based fitness consequences, such that cooperative queens gained a survival advantage in cooperative pairs, but neither type of queen experienced an advantage or disadvantage in “mixed” associations. The interplay between social dynamics and fitness in these associations provides an empirical example of social selection. It captures a likely scenario of the transition to and the early evolution of cooperative living, in which cooperative individuals interact with solitary individuals who lack a priori strategies for cooperation or cheating.

\textit{Key words:} ant foundress associations, cooperation, interacting phenotypes, pleometrosis, social dynamics, social phenotype, social selection.

\section*{INTRODUCTION}

The phenotypes of both animals in social groups and the groups in which they live are shaped by the interactions of individuals within the group (Moore \textit{et al.} 1997; Wolf \textit{et al.} 1998; Agrawal \textit{et al.} 2001; Fewell 2003; Bijma \textit{et al.} 2007; McGlothlin \textit{et al.} 2010). \textit{Social dynamics} are nonlinear or self-organizational effects that amplify (or in some cases, dampen) the expression of social phenomenotypes (Camazine \textit{et al.} 2001; Fewell 2003). Population evolution models designed to capture relationships between phenotype and selection rarely consider that social dynamics can generate emergent effects on social phenotype, with potentially profound effects on fitness. This has produced a mismatch between theoretical expectations for the evolution of cooperation and empirical data, especially for social systems such as communal groups, where relatedness cannot be used as an explanatory basis for the evolution of cooperation. A series of discussions on social selection have emphasized that social dynamics should be incorporated into models of social environment effects on phenotype and fitness, for example, as indirect genetic effects (West-Eberhard 1979; Moore \textit{et al.} 1997; Wolf \textit{et al.} 1998; Agrawal \textit{et al.} 2001; Bijma \textit{et al.} 2007; Bleakley and Brodie 2009; McGlothlin \textit{et al.} 2010). However, doing so requires proximate analyses of how social environment can influence individual phenotype (Linksvayer 2006; Danielson-François \textit{et al.} 2009; Wilson \textit{et al.} 2009; Chenoweth \textit{et al.} 2010; Teplitsky \textit{et al.} 2010).

In this study, we demonstrate that simple social dynamics within cooperative groups generate predictable nonlinear (nonadditive) effects on social phenotype, with outcomes for both individual- and group-level fitness, thus influencing social evolution. Individual and group behaviors become a product of social dynamics when 1) the behavior of one individual changes the likelihood of performance by others and 2) these interactions generate feedback loops in which social effects on behavioral phenotypes are amplified (Moore \textit{et al.} 1997; Wolf \textit{et al.} 1998; Fewell and Page 1999; Camazine \textit{et al.} 2001). Such effects can be quite simple algorithmically but with potentially large impacts on behavioral outcomes. These types of nonlinear interaction effects have been considered primarily in the context of escalated social conflict, including aggression, competition, and dominance (Agrawal \textit{et al.} 2001; Danielson-François \textit{et al.} 2009; Wilson \textit{et al.} 2009), but more recently, these have been examined in the context of social cooperation, group coordination, and cohesion (Fewell 2003; Linksvayer 2006; Bleakley and Brodie 2009; Linksvayer \textit{et al.} 2012), suggesting

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that they have the potential to influence social relationships more broadly. If so, social dynamics could inform evolutionary models of cooperation by increasing the expected likelihood of individual and group success for cooperative behavior, even in groups of unrelated individuals (Santos and Pacheco 2006; Bleakley and Brodie 2009; McGlothlin et al. 2010).

The present study provides empirical evidence of both positive and negative effects from social dynamics on individual behavior and fitness, by comparing the effects of different social environments on the behavior, survival, and group productivity of queens from 2 different populations of harvester ants (*Pogonomyrmex californicus*). In 1 population, newly mated queens form cooperative associations to initiate nests (pleometrosis), whereas in the other, queens found nests solitarily (haplometrosis). Pleometrotic associations in this species comprise simple groups of unrelated individuals (Bernasconi and Strassmann 1999; Johnson 2004). Selection based on survival during early nest formation is intense; such a small proportion of foundresses survive that variation in survival for this phase of their life cycle represents a critical component of lifetime fitness (Holldobler and Wilson 1990; Cole 2009). Unlike for most ant species (Bernasconi and Strassmann 1999; but see Helms and Helms Cahan 2012), the cooperative associations formed by pleometrotic *P. californicus* queens continue into colony adulthood and production of reproductive offspring (Johnson 2004); thus, they represent stable social associations that persist across the life of the resulting colony. The 2 populations are contiguous, with low levels of gene flow (Overson 2011).

Population differences in nest-founding behavior persist even when adult queens are placed together in a common environment, suggesting that the differences between the 2 populations have a genetic component (Helms Cahan and Fewell 2004; Johnson 2004; Jenson and Fewell 2008; Overson et al. 2013). The potential genetic basis allows us to consider the interacting effects of genotype (as lineage or population of origin) and social environment in shaping the expression of social phenotypes. Haplometrosis is the most common nest-founding strategy within the genus and is probably the ancestral state (Johnson 2004). Classic models of social evolution consider noncooperation as a “social” strategy in which “defecting” individuals gain advantage (as per Maynard Smith 1964, 1982). However, we do not expect haplometrotic queens, as solitary and in the ancestral state, to have any a priori social strategy. Thus, our experimental context reflects conditions of early social evolution in which cooperative individuals enter a population of noncooperative individuals, but wherein noncooperators have not necessarily evolved mechanisms for social manipulation or cheating.

**MATERIALS AND METHODS**

**Queen collection**

Two sets of experiments were conducted in 2 successive years to observe queen behavior and survival in pleometrotic, haplometrotic, and mixed associations. All queens for both years were collected from San Diego County, CA, USA, immediately following mating flights in July. Collected queens had shed their wings and were walking on the ground or had just begun nest excavation. At the collection sites, queens were placed into individual ventilated 1.3-ml Eppendorf tubes and remained cool and moist during transfer to Arizona State University for experiments; queens were introduced into laboratory nests within 5 days from collection. In the laboratory, queens were weighed to the nearest 0.1 mg and marked on the abdomen with paint (hot fuel-proof dope; Midwest AeroGloss) before placement into vertical observation nests. Nests consisted of 2 panes of glass (12.5 X 17.5 cm) separated by thin (0.32 cm) nylon strips and were filled with moist soil from one of the collection sites (Cibbet Flats, see below). Nest temperatures were maintained at approximately 28°C and fresh seeds (Kentucky blue grass) and dead *Drosophila melanogaster* were provided ad libitum.

On 1 July 2005, 278 pleometrotic queens were collected from the Cibbet Flats campground (Rissing et al. 2000), located 4 km north of the Cameron Fire Station (32°46'45"N, 116°25'36"W). Haplometrotic queens were collected from 3 areas within a contiguous haplometrotic population: Lake Henshaw, 4 km north of Moretis Junction, on 3 July (36 queens; 33°14'22"N, 116°45'46"W); Warner Springs, at the entrance to the Cleveland National Forest, on 1 and 2 July (16 queens; 33°17'07"N, 116°39'42"W); and the Oak Grove campground, on 2 July (4 queens; 33°23'16"N, 116°47'21"W). Queens from these 3 areas have not been observed to form foundress associations (Johnson 2004; Clark RM and Fewell JH, personal observation). The centers of the haplometrotic and pleometrotic populations are approximately 50 km apart, with patchy distributions in between. Nest site mapping and genetic analyses indicate a likelihood of low levels of gene flow between populations (ST = 0.144 based on 5 microsatellite loci; Overson 2011). In 2005, laboratory nests were created by pairing queens with another queen of similar mass from either the same population (pleometrotic–pleometrotic or haplometrotic–haplometrotic pairs, termed PP or HH, respectively; 51 and 17 nests, respectively) or the 2 different populations (pleometrotic–haplometrotic or “mixed” pairs, termed PH, 23 nests).

In the period 1–3 July 2006, 140 pleometrotic queens from Cibbet Flats and 140 haplometrotic queens from Lake Henshaw were collected. Queens were randomly assigned to 1 of 3 nest types: paired nests containing queens from the same population (PP pairs, 39 nests; and HH pairs, 40 nests) or paired nests containing queens from the 2 different populations (HP or “mixed” pairs; 39 nests). In this set of replicates, a subset of queens was also placed solitarily into nests (P or H; 20 nests of each). Queens were not paired by mass in 2006 to allow for a direct test of how size differences influence survival probability.

**Survival, behavior, and nest productivity**

Behavioral observations began immediately after introduction of queens into nests. Queen survival was noted daily up to the end of the observation period (20 days in 2005, and 45 days in 2006). Queen behavior was observed 8 times per day for 20 days in 2005 and for 5 days in 2006, with a minimum of 45 min between successive observations. During each observation, each nest was briefly scanned to note the occurrence of social interactions between queens (2006 only), all task-related behaviors, or inactivity. Types of social interactions included 1) nonantagonistic interactions, such as antennation of the other individual, allogrooming, or other contact (maintaining a distance of less than 1 body length away) and 2) antagonistic interactions, such as biting or dragging (grasping the other individual and walking or carrying her). Task-related behaviors consisted of 1) foraging (grasping or manipulating a seed or fly in the mandibles), 2) excavation (using mandibles to loosen or carry soil to the nest surface), and 3) brood care (laying an egg, manipulating brood, or standing over the brood pile). In 2006, nest productivity was additionally estimated by monitoring egg production and worker emergence up to day 30. Queens began to lay eggs on the second to third day after placement in nests. Beginning on the

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fourth to the sixth day, all eggs present in each nest were counted, every 2 days, up to day 14, after which the eggs began hatching into larvae.

Data analysis
Queen survival was analyzed in SAS (version 9.1.3) by generating Kaplan–Meier survival curves, using a log-rank test to check for an overall treatment effect. Posthoc pairwise comparisons between treatments used Bonferroni-corrected log-rank tests. The influences of body size and excavation frequency on survival were assessed via t-tests in R (version 2.15.3; R Core Team 2013), by comparing the mean initial masses or excavation frequencies of surviving queens to queens that died by the end of the observation period (day 20 in 2005; day 45 in 2006). The excavation comparison used total excavation frequencies across the first 5 days of the observation period and excluded queens that died during the first 5 days. Within-treatment comparisons were subjected to Bonferroni correction.

Aggressive behavior, characterized by overt biting and stinging, was observed infrequently; therefore, the nests were classified according to whether any aggression had been observed, and the incidences of aggressive versus nonaggressive nests were compared across the 3 paired treatments (HH, HP, and PP) in 2006 by chi-square analysis. The remaining nonagonistic behavioral observations were converted to arcsine square-root-transformed proportions and compared across treatments with analysis of variance (Anova) in R. Egg and worker production levels were compared across social contexts with Anova in R.

RESULTS
Social context and survival
Survival curves for queens in haplometrotic (HH), pleometrotic (PP), and mixed pairs (HP) were compared for 20 days in 2005 and 45 days in 2006. Social environment significantly influenced queen survival in both years (Figure 1; for 2005, overall log-rank $\chi^2 = 1.56, P < 0.0001$; for 2006, log-rank $\chi^2 = 35.24, P < 0.001$; see Table 1 for Bonferroni-corrected pairwise comparisons). Individual queens in PP associations consistently had the highest individual survival rates, whereas queens in HH associations had the highest mortality. Individual queen survival in mixed (HP) pairs was not significantly different from that in pleometrotic pairs for 2005 and was intermediate between PP and HH in 2006. Individual haplometrotic and pleometrotic queens within HP pairs had similar survival rates. In the 2006 experiment, haplometrotic and pleometrotic queens were also placed alone in nests; survival rates for these queens were similar to each other and to survival of queens in HP pairs (Figure 1).

Differences in queen survival across social contexts were not explained by body size. In 2005, queens from the haplometrotic population were heavier than the pleometrotic queens ($\bar{m}_{hap} \pm$ standard error of the mean = 14.5 ± 0.2 mg; $\bar{m}_{pleo} = 12.5 \pm 0.1$ mg; $t = 7.71, N = 450, P < 0.0001$). However, initial mass did not predict survival ($t = 0.621, P = 0.536$). In 2006, haplometrotic and pleometrotic queens were similar in initial mass ($\bar{m} = 13.77 \pm 0.13, t = 1.75, N = 274, P = 0.081$). Although the surviving queens across treatments were heavier than the queens who died by day 45 ($\bar{m}_{surv} = 14.2 \pm 0.2$ mg, $N = 105$; $\bar{m}_{inc} = 13.5 \pm 0.2$ mg, $N = 169$; $t = 2.49, P = 0.014$), survival rates did not differ by body mass within treatment groups and, in particular, did not predict which queen survived in mixed pairs (Table 2).

<table>
<thead>
<tr>
<th>Year</th>
<th>Comparison</th>
<th>Log-rank $\chi^2$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Overall</td>
<td>19.56</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td></td>
<td>HH versus HP</td>
<td>7.42</td>
<td>$P = 0.0064$</td>
</tr>
<tr>
<td></td>
<td>PP versus HP</td>
<td>0.4874</td>
<td>$P = 0.4851$</td>
</tr>
<tr>
<td></td>
<td>HH versus PP</td>
<td>19.6508</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td></td>
<td>Within HP, H versus P</td>
<td>0.6582</td>
<td>$P = 0.4172$</td>
</tr>
<tr>
<td></td>
<td>HH versus H within HP</td>
<td>2.9028</td>
<td>$P = 0.0884$</td>
</tr>
<tr>
<td></td>
<td>PP versus P within HP</td>
<td>0.0002</td>
<td>$P = 0.9898$</td>
</tr>
<tr>
<td>2006</td>
<td>Overall</td>
<td>33.24</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td></td>
<td>HH versus HP</td>
<td>8.16</td>
<td>$P = 0.0043$</td>
</tr>
<tr>
<td></td>
<td>PP versus HP</td>
<td>9.0639</td>
<td>$P = 0.0026$</td>
</tr>
<tr>
<td></td>
<td>HH versus PP</td>
<td>34.0824</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td></td>
<td>Within HP, H versus P</td>
<td>1.8952</td>
<td>$P = 0.1686$</td>
</tr>
<tr>
<td></td>
<td>HH versus H in HP</td>
<td>8.3892</td>
<td>$P = 0.0038$</td>
</tr>
<tr>
<td></td>
<td>PP versus P in HP</td>
<td>12.5997</td>
<td>$P = 0.0004$</td>
</tr>
<tr>
<td></td>
<td>Solitary P versus P in HP</td>
<td>0.1882</td>
<td>$P = 0.6644$</td>
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<tr>
<td></td>
<td>Solitary H versus H in HP</td>
<td>0.7296</td>
<td>$P = 0.3950$</td>
</tr>
<tr>
<td></td>
<td>HH versus Solitary H</td>
<td>2.5304</td>
<td>$P = 0.1117$</td>
</tr>
<tr>
<td></td>
<td>PP versus Solitary P</td>
<td>7.1182</td>
<td>$P = 0.0076$</td>
</tr>
</tbody>
</table>

Table 1: Pairwise comparisons of survival rates between social contexts

Comparisons that are significant after Bonferroni correction are in bold (<0.01).

$^a$Survival comparisons across days 1–20.

$^b$Survival comparisons across days 1–45.

Figure 1
Queen survival patterns. Survival curves for queens paired with other queens from the same population (HH or PP), queens paired with others from an alternate population (HP), or queens maintained by themselves (H, P). (a) Survival across the first 20 days of colony founding in 2005. (b) Survival across the first 45 days of colony founding in 2006. Survival differed across different treatment groups (refer to text and Table 1 for full statistical comparisons).
Table 2
Pairwise comparisons of initial masses of queens that survived versus queens that died in different social contexts during the early stages of nest founding (up to day 45 of nest establishment)

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>Mass (mg) ± standard error (sample size)</th>
<th>t</th>
<th>df</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH</td>
<td>13.3 ± 0.3 (63)</td>
<td>1.13</td>
<td>20.7</td>
<td>0.27</td>
</tr>
<tr>
<td>HP</td>
<td>13.7 ± 0.3 (48)</td>
<td>1.67</td>
<td>53.5</td>
<td>0.10</td>
</tr>
<tr>
<td>PP</td>
<td>13.7 ± 0.4 (31)</td>
<td>0.56</td>
<td>49.3</td>
<td>0.56</td>
</tr>
<tr>
<td>H</td>
<td>12.3 ± 0.6 (13)</td>
<td>1.17</td>
<td>11.6</td>
<td>0.27</td>
</tr>
<tr>
<td>P</td>
<td>14.6 ± 0.3 (14)</td>
<td>0.15</td>
<td>6.3</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Agonistic interactions and survival

Social interactions were monitored in the 2006 replicates to determine whether agonistic or cooperative behaviors were influenced by social context and whether social phenotype was related to survival. Although overt aggression was infrequent (a total of 27 queens in 21 nests), it was not randomly distributed (Figure 2; \( \chi^2 = 21.03, P < 0.0001 \)); the majority of aggressive incidents occurred in HH nests (19 queens in 14 nests). We observed only 7 queens behaving aggressively among the mixed pairs (4 pleometrotic and 3 haplometrotic queens in 6 nests) and only 1 aggressive event in a PP pair. Almost all cases of overt aggression were followed by the death of at least 1 queen (20 of 21 nests).

Potential nonagonistic effects on survival

Nonagonistic social contact rates were similar across the 3 pair types (2006 data only; Anova on arcsine square-root-transformed proportions of observations: \( F = 1.25, \) degrees of freedom \( df = 2, 231, P = 0.29 \)). Queens spent an average of 32 ± 1% of all observations in contact with each other (allogrooming, antennating, or in close proximity), and in all nests, they maintained a single, shared brood pile. Differential mortality was not explained by differences in task performance. In previous experiments, excavation had been associated with increased mortality (Fewell and Page 1999; Helms Cahan and Fewell 2004; Jeanson and Fewell 2008). However, queens from both years who survived up to day 20 actually performed more excavation bouts in the first 5 days (when almost all excavation occurs) than queens who died during this time, although this trend was not significant for 2006 (Figure 3; for 2005, \( t = 2.15, P = 0.037 \); for 2006, \( t = 1.50, P = 0.14 \)).

Foraging occurred infrequently and was not associated with individual survival probability. There were no differences in foraging rates across treatments in 2005 (Anova on arcsine square-root-transformed observations: \( F = 1.55, df = 4, 147, P = 0.19 \)). In 2006, however, foraging rates did vary, but posthoc analyses showed only weak differences between treatments (\( F = 3.33, df = 4, 224, P = 0.011 \)). Solitary pleometrotic queens foraged the least (0.9 ± 0.3 times), whereas solitary haplometrotic queens foraged the most (2.7 ± 0.9 times); paired queens in all 3 treatments foraged at intermediate levels (1.9 ± 0.2 for HH, 2.0 ± 0.3 for HP, and 1.3 ± 0.2 for PP). Initial foraging frequencies did not predict who survived and who died by the end of 20 days in either year (for 2005, \( t = 0.208, df = 20, P = 0.84 \); for 2006, \( t = 1.09, df = 114, P = 0.20 \)).

Nest productivity and social context

In 2006, initial worker production and egg production (number of eggs produced in days 1–14) were compared across social contexts. Worker production per nest across social treatments was compared only for those cases in which at least 1 of the 2 queens survived (\( n = 25, 21, \) and 14 for PP, HP, and HH, respectively). Although worker numbers varied, there was no significant effect of nest type on the number of workers produced by day 50 (Figure 4; \( F = 1.57, df = 2, 57, P = 0.217 \)). Note, however, that sample sizes were too small by day 50 for sufficient power to definitively test this question. Time from nest initiation to the emergence of the first workers was constant across nests, including pairs and single queens, suggesting this component of productivity is not socially flexible (\( F = 1.746, df = 4, 71, P = 0.1494, n = 76, \) mean = 40 days).

To measure group investment in worker production, initial egg production was compared across treatments for pairs in which both...
ant queens that employ 2 distinct social strategies, forming cooperative associations of unrelated individuals versus initiating nests solitarily (Rissing et al. 2000; Johnson 2004; Helms Cahan and Fewell 2004). Our results demonstrate that social context can act as an important driver of social phenotype and fitness and that self-organizational social dynamics can mediate such effects at both the individual and the group levels.

Foundational game theoretical models of social evolution make the explicit assumption that noncooperation provides an individual fitness advantage, whereas cooperation benefits the group as a whole (Axelrod and Hamilton 1981; Maynard Smith 1982). The behavioral outcomes and consequent fitness advantages in our groups deviate from these fitness payoffs, especially in the mixed associations. Models of cooperation (even when incorporating contingent strategies) generally assume that individual payoffs for cooperators will decrease below those of noncooperators in mixed associations (Taylor and Nowak 2007; Brown and Vincent 2008; Antal et al. 2009). However, the survival payoffs for queens in our mixed associations were neutral relative to other pairs—lower than those for pleometrotic pairs, equivalent to the solitary condition, for both queen types. Queens in groups where both members had a cooperative evolutionary history (PP) had survival rates 2 times higher than those in normally noncooperative pairs (HH). The high survival in pleometrotic groups was also coupled with more efficient brood production, such that individual and group payoffs were maximized when both group members cooperated. Because the 2 queen types survived equally well alone, we suggest that in pairs, the differential survival outcomes were driven primarily by the social partner.

Why do our results deviate from such a key expectation of social evolution? Most models of the evolution of cooperation treat both cooperation and noncooperation as social strategies, by assuming that noncooperators have the social tools in place to evaluate and respond to social contingencies. However, at the transition from solitary to social living, normally solitary individuals are unlikely to have a priori mechanisms in place to cheat or win in a social context. If so, this changes our theoretical consideration of noncooperation from a scenario in which noncooperation is an advantage to one in which nonsocial individuals can be taken advantage of.

**Amplification of social phenotype: conflict escalation**

The survival and productivity outcomes for foundresses across social contexts were driven proximately by self-organizing social dynamics. Self-organizational effects on social behavior have usually been considered as they relate to group-level behavior in complex societies (Camazine et al. 2001; Jeanson and Deneubourg 2009). However, nonlinear effects of social interactions also shaped individual behavior in these simple groups. Aggression, in particular, manifested as conflict escalation and was dependent on the behavior of social partners. Conflict escalation is a good fit with simple self-organizational models of reinforcement by positive feedback (Camazine et al. 2001; Jeanson and Deneubourg 2009) and is similar in interaction effects to social selection models of dominance (Agrawal et al 2001; Moore et al. 2002).

**Social regulatory mechanisms for behavioral coordination and cheating**

Social selection can also act to enhance behavioral coordination, and thus cooperation, if social interactions generate individual and/or group benefits. This seems to have occurred for brood production,
where queens in pleometrotic pairs were able to produce the same number of workers while investing in fewer eggs. This suggests that pleometrotic queens have evolved some mechanism for social regulation or policing, in which they adjust production and/or consumption of brood relative to production by other queens (Holman et al. 2010).

If so, this adjustment could provide a critical benefit to both the queen and the group. Brood production in ants is metabolically expensive (Wheeler and Buck 1995), and *P. californicus* queens have low fat stores relative to other *Pogonomyrmex* species (Hahn et al. 2004). Queens only produce sterile workers during colony initiation and early development, so brood production at this stage represents a cost for individual queens and a benefit to the group as a whole. We know from direct observation (across multiple experimental contexts and video capture) and from genetic data (Fewell JH, in preparation) that both queens in *P. californicus* associations produce eggs and that eggs are consumed by their own mothers, other queens, and their sibling larvae, allowing opportunities to socially regulate brood production.

This sets up the somewhat ironic situation in which “cooperative” behaviors can become “cheating” with different social partners. Pleometrotic queens who regulate brood output can potentially take advantage of haplometrotic partners who lack similar regulatory mechanisms. In support, previous work on *P. californicus* found that pleometrotic queens in mixed pairs are more likely than haplometrotic queens to engage in brood care and to remain near the brood (Jeanson and Fewell 2008). Also consistent with this scenario, haplometrotic *Messor pergandei* queens placed in associations with pleometrotic queens have higher relative weight loss and mortality (Helms Cahan 2001). These data emphasize that if we define cooperation as behaviors with ultimate benefit for individuals and social partners, cooperation becomes dependent on social context.

### The social environment as an indirect genetic effect

Our findings are compatible with recent models emphasizing the role of indirect genetic effects on selection of social traits (Wolf 2003; Linksvayer 2006; Bijma et al. 2007; Bijma and Wade 2008; McGlothlin et al. 2010). Social group composition can have a profound and heritable influence on an individual’s phenotype; thus, it can be considered a source of indirect genetic effects that influence social evolution (Moore et al. 2002; Wolf 2003; Bijma and Wade 2008; McGlothlin et al. 2010). Recognition of this can enrich theoretical models of social evolution from fixed effects to contingencies that incorporate social context in more realistic ways.

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