BIO Web of Conferences **111**, 03006 (2024) https://doi.org/10.1051/bioconf/202411103006
ICBB 2024

Adaptability and Strategy of Ant Society: Analysis of Cooperation and Defense Behavior

Yijia Ji[1,2*]

[1]Malvern College Qingdao, Qingdao, Shandong Province, 266000, China
[2]EDP Sciences, Production Department, 91944 Les Ulis Cedex A, France

Abstract. The behavior and ecology of social insects have always been one of the important directions of biological research. Ants are typical true social insects. Through the study of their social behavior, we can not only reveal the adaptability and strategy of social insects, but also provide enlightenment for the interaction between human society and nature. However, there remains a significant gap in understanding the complex interactions and underlying mechanisms that govern the adaptability and strategic behaviors of ant societies, particularly in the context of rapidly changing environmental conditions and anthropogenic influences. Therefore, this paper deeply studies the adaptability and strategy of ant society, focusing on its cooperation and defense behavior. This paper first outlines the unique position of social insects in ecosystems, and then discusses in detail the social structure of ants, including the roles of soldiers, workers and queens. In terms of internal cooperation behavior, the tacit cooperation between ant individuals, as well as the care of larvae and the maintenance of nests were analyzed. In terms of external defense mechanisms, it highlights the diversity strategies of ant society against external threats. This comprehensive study provides a new perspective for understanding the behavior and ecological characteristics of social insects. By examining the adaptability and strategic behaviors of ant societies through a comprehensive lens, this study provides critical insights into the mechanisms of social cohesion and resilience in insect colonies, which have important implications for the broader field of biological research.

1 Adaptability of social insects

Typical true social insects such as bees, ants, wasps, and termites account for about 10% of the total weight of animals on Earth. They exhibit three main characteristics: adult individuals caring for juveniles, generation overlap, and reproductive division.[1] Social insect groups commonly consist of a fertile king or queen and non-fertile workers, forming a division of labor between breeding and non-breeding individuals [2-3].

The famous ant scientist Edward Wilson once imagined the ecological model of insects on the earth, that is, social insects live in the center of insect ecology, while solitary insects live on the edge of ecology to fill the gaps left. The successful evolution of social insects is attributed to their extremely socialized nature that goes far beyond humans, because they form solutions that ignore the existence of individuals, in contrast to social creatures such as humans, and guide altruism to the entire group rather than the individual itself, thus achieving success at the group level. This social system keeps the individuality of individual members to a minimum, ensuring the reproduction and evolution of the group.

The complexity of ant social structure has constantly attracted the attention of biology, behavior and ecology. Through in-depth study of their cooperation and defense mechanisms, we can better understand the interdependence and social synergy in this ecosystem. The purpose of this paper is to reveal the ways of cooperation among members of different levels in ant society and their responses to external threats, so as to provide fresh insights into social biological systems and ecosystem dynamics. The research promises to broaden our understanding of social insects and ecosystem interactions, and provide some suggestions for the relationship between human society and the natural world. This study not only contributes to a deeper understanding of the intricate social behaviors and ecological roles of ants but also offers novel insights into the complex mechanisms that underpin their adaptability and strategic responses to environmental challenges. Our findings on the cooperative and defensive behaviors of ant societies provide valuable knowledge for the development of more effective models of social organization and highlight the importance of considering non-human actors in the management of ecosystems.

2 The social structure of ants

In social insects, the social structure presents an extremely complex organizational structure, which allows them to survive and thrive in different environments. Ants are social insects, and the social

* Corresponding author: zhenzhenxu@126.com

structure of ant colonies generally includes different grades, such as queen ants, worker ants, and soldier ants, with each grade assuming specific roles and responsibilities. Ants' social structure and grade differentiation are intertwined to form a deeply coordinated social structure.

2.1 Soldier ant

Soldier ants are specialized individuals who undertake combat tasks in ant society, and they play a key role in protecting nests, food and resources in ant colonies. Soldier ants have developed upper jaws, and the entire body structure has been specialized for better combat. Their specialized forms and behaviors completely meet the specific task requirements, making them the claws of this super-individual. Some species of soldier ants blindly pursue strength in structure, which has evolved a huge head and a developed palate full of muscles that are perfectly out of proportion to their bodies, but this also makes their mobility generally poor, and the developed palate of the soldier ants also hinders their feeding, then ordinary worker ants take on the role of feeding the soldier ants.

Soldier ant differentiation mainly includes two categories: soldier ant monotype and soldier ant differentiation (Table 1). Soldier monotypes are common in some Macroceps, and their soldiers have no obvious differentiation, only slight differences in body size. The differentiation of soldier ants is also common in the species of Eciton, Dorylus and Carebara diversa. The soldier ants have essential differences in the ratio of head to body, with different grade differentiation, so that they have various body types of soldier ants. And some species also have the head width considerably higher than the queen, and the huge size of the specialized soldiers, so that they have the ability to threaten minor mammals.

2.2 Ergate

Worker ants constitute the majority of ant society, and their large numbers engage in a highly diverse range of tasks, so there is a variety of forms and functions in their internal. They go through the development process from egg to larva to pupal stage, and finally become mature worker ants. Although worker ants and queens are females, their ovaries are mostly underdeveloped and cannot reproduce, which results in different functional divisions between workers and queens.

The differentiation types of worker ants mainly include worker differentiation, worker soldier differentiation and worker monotypy (Table 1). In the differentiation of worker ants, different body types of worker ants (such as large, medium and minor worker ants) perform their respective responsibilities, such as digging, foraging, fighting, nursery, cleaning and so on. This differentiation is common in some ant species, such as Camponotus and Messor. However, the differentiation of workers normally appears in Pheidole and Carebara, which have two grades of worker and soldier ants. In contrast, the worker ants monotype is mainly found in the original ant species, such as the Ponera, the worker ants are not differentiated, and the difference between the queen and the ant is minor. This diversity in form and function provides a guarantee for the cooperation and division of labor in ant society.

Table 1. Common differentiation types of worker and soldier ants.

Grade	Differentiation type	Common variety
Worker ants	large, medium and short worker ants	Camponotus, Messor, etc.
	worker and soldier ants	Pheidole, Carebara,etc.
	monotype: no differentiation	Ponera, Myrmecia, etc
Soldier ant	soldier ants of different body types	Carebara, Eciton, etc.
	Monotype: no differentiation	Pheidole, etc.

2.3 Queen ant

The queen ant is the core of the colony, commonly the only fertile female, and the heart of the superorganism, the mother of the entire ant society. The reproductive right of the queen ant is the supreme right in ant society. The development of the queen ant begins with special ant eggs, hatching larvae that receive a richer supply of nutrients and hormones, and eventually develop into a queen ant with reproductive organs and reproductive functions. Every year, a group of winged breeding ants are cultured in the nest. They leave the nest at a specific time to find male or female ants in different nests for mating. This process is called wedding flight. In general, the marriage flight time of ants of the same species in the same area is the same, ensuring that breeding ants of the same species from different nests can meet. The mating site of ants is generally fixed, the males first gather in the air, then the females come, and this mating cluster site may be used by ants for numerous years.

The mating patterns of ants can be divided into female calling syndrome and male aggregation syndrome. The male ant colony model was proposed by Herdobler and Baez [4-5]. It means that the male ant gathers in the air and then the female ant comes to mate, which is also the mating method adopted by most ant species. The calling pattern of female ants is common in the genus of ants, such as ants, and its winged reproductive ants do not have the ability to fly, so they will release pheromone the surface to attract male ants to mate. Female ants generally mate with multiple males to ensure the genetic diversity of their offspring. After the wedding flight, the female ants will fall to the ground, remove their wings, and find a suitable place to nest, lay eggs, and feed the larvae. This process is full of crisis and the success rate is extremely low, but the surviving queen will start a different round of ant life cycle [6-8].

2.4 The social organization of ants

Ant societies exhibit a distinct way of organization, in which members' different body structures create different divisions of tasks. And the knowledge and behavior of ant individuals are inherited through inheritance rather than traditional learning, which enables each individual to distinctly understand his/her responsibility when he/she comes out of the cocoon. Without dictating, this self-organizing can form a nicely-ordered super-individual. Ant colonies form super clusters through elevated socialization, which has a huge advantage in resource acquisition and territorial competition. However, in this seemingly harmonious society, there is also competition for power, and worker ants also challenge the authority of the queen at all times, and they can kill or eat larvae they don't like at will, which also reflects that worker ants are the most direct and effective intervention to affect the development of larvae. In order to improve the survival rate, the larvae form a reciprocal relationship with the workers through the secreted liquid pheromone. Moreover, in some ant species, worker ants have the ability to reproduce, and with the aging of the queen ant, worker ants will compete for reproductive opportunities, leading to internal competition and fierce infighting. This reveals that despite the seemingly orderly cooperation in the ant society, there are constantly power games and competition for reproductive opportunities [9].

2.5 The social system of ants

The social system of ants can be divided into monogamy, strict monogamy, polygamy, no-monogamy, and parthenogenesis. Single queen system: There is usually only one queen in a colony, but multiple queens can also be found, such as the Camponotus japonicus. Strict single queen system: there is only one queen in the ant colony, and it does not accept the situation of numerous queens, such as Lasius alienus. Multiple queens: There are normally multiple queens in the ant colony, and some species can even have millions of queens at the same time, such as Formica yessensis. No queen: It loses the rank of queen ant and reproduces only through the mating of worker ants, such as Dinoponera. Parthenogenetic reproduction: It also does not have the caste of queens, but each worker can reproduce without mating, such as Ooceraea biroi.

3. Internal Cooperation and External Defense Behavior of Ant Colony

In the ant society, grade differentiation as a significant feature shapes the structure and function of the entire group. Different grades of ants play a particular role in the group, forming a close cooperative network. At the same time, this kind of division of labor also provides the group with an efficient foreign defense mechanism. In this chapter, we will look at the mechanisms of information transfer, cooperation and coordination among different members of ant groups, and how they respond to external environments, to gain insight into how these tiny groups of organisms respond to changing ecological challenges with extraordinary adaptability.

3.1 Internal cooperative behavior

3.1.1 The queen's epimeletic behavior

The queens show the behavioral characteristics of feeding larvae in the original late stage. This includes two main lifestyles: full seclusion and semi seclusion. In the completely reclusive type, the queens of most ant species meet the needs of the larvae by storing nutrients in the abdomen.

The semi-concealed ant species cannot store a large amount of nutrients in the abdomen after they are unfamiliar, therefore they will go out to hunt during the current period to feed the larvae. Primitive ant species, such as the Ponera and the Myrmecia, typically have the following characteristics:1) The body structure of the queen ant is similar to that of the worker ant, and the ability to fight and act is similar.2) All the members have a strong single combat ability, so the queen has the ability to hunt.3) Retain the characteristics of stinging needles, some species of stinging needles are extremely toxic, such as the Pogonomyrmex maricopa and Myrmecia pilosula.4) The abdomen of queens or workers typically cannot store nutrients in large quantities. The larvae mainly obtain nutrients by eating insect carcasses, rather than ingesting liquid food, which is different from the way in which most ant larvae ingest liquid food.

3.1.2 Ergate

Larval care, nest maintenance and foraging. Worker ants are responsible for the care of the larvae in ant society, nourishing the larvae by either digesting liquid food or prey carcasses entirely. This process is crucial to the development of the entire ant society. Worker ants undertake key nesting tasks, including digging, repairing and defending nests. They use jaws and forelimbs to excavate complex underground structures, maintain the structure of the nest, wash up debris, and maintain the health of the nest. Workers also participate in defense tasks, patrol the territory, resist foreign enemies, and ensure that the nest is free from threats. Workers participate in extremely coordinated foraging behavior. They form teams to search for food resources. Once they find resources, they will release pheromones to guide other ants, form an orderly handling team, and quickly transport food back to the nest. This efficient foraging strategy helps meet the nutritional needs of the entire ant colony (Warburg et al. 2017).

Trophallaxis. The trophallaxis behavior of ants is a social feeding behavior. When workers obtain food resources, they will return to the nest and share food with other ants through trophallaxis behavior.This behavior is a key way to maintain the collaboration and mutual assistance of the entire ant community.In the ant society, each ant is equipped with a special organ called the social stomach.The social stomach allows ants to store food and share it with other members. When ants obtain food resources or are hungry, they can feed other ants by mouth-to-mouth feeding. This trophallaxis behavior is essential for the survival and reproduction of ant societies. It helps to meet the nutritional needs of all members of the nest, especially for queens and larvae that cannot directly obtain food. In addition, through trophallaxis, ants are able to build stronger social bonds in their nests and enhance the cohesion of the entire group.

Physical contact. Worker ants exhibit powerful social behaviors through physical contact. In some primitive ant species, such as Ponera, due to the limited degree of socialization, their workers can not carry out complex communication. When workers find food or resources that their peers cannot understand or follow, they use a direct and effective way of biting their peers' mouthparts or bodies and dragging them to their destinations. In addition, ant species such as Camponotus and Myrmecocystus also showed similar behavior. When in danger in the nest, worker ants may bite the queen's mouthparts and drag her to safety. And some ants such as Pogonomyrmex californicus, Acromyrmex octospinosus in the nest are threatened, workers take a more direct approach, that is, bite the neck of the ant, the ant directly lifted, and quickly transferred to a safe zone, to protect the entire ant colony. This behavioral strategy of physical contact plays a key role in communication and defense in some ant species.

Voice communication. The worker ants play a role in calling for help and early warning by making sounds. In the Atta and Acromyrmex, workers can communicate with their peers by rubbing the abdominal somites. The ants such as the Camponotus nicobarensis, when in danger, will knock on the ground through the abdomen to generate vibrations to warn their peers. By using sound as the medium of communication, signals between ants become more efficient.

3.1.3 Soldier ant

Large-scale attack and defense. The large-scale attack and defense of ants is one of the crucial combat strategies in ant society. Soldiers normally patrol around and inside the nest or gather in specific nests. When the ants are threatened or encounter hostile ants, the soldiers will respond quickly and form a large-scale offensive team. This attack is generally organized and coordinated. Soldiers and ants coordinate their actions by releasing pheromones, and use their powerful jaws or stings to launch joint attacks against enemies to defend their nests and resources. This shows the strong degree of organization and adaptability of ant society.

3.2 External defense behavior

3.2.1 Ant queen

The external defense of queens depends on the cooperation of workers and soldiers. The worker ants are responsible for cleaning up the surrounding environment, maintaining the nest, and assisting in defense. Soldier ants are expert fighters who gather near their nests, respond quickly to threats, and execute effective defenses. This cooperative combat ensures the security of the whole ant society.

3.2.2 Worker ants and soldier ants

Boxing. Many ants display boxing behavior in battle. When two equally strong groups of ants from different nests engage in a fierce confrontation, they transform their fierce fighting into a more civilized form of boxing.This phenomenon is manifested in the fact that workers from different nests stand up and use their forelimbs to push each other to determine the outcome. Behind this boxing behavior reflects that only a stronger ant dynasty can cultivate stronger fighters. This behavior shows a relatively mild and efficient solution to the resource competition in the ant society in order to effectively preserve the living forces.

Ejection defense. In the case of the Odontomachus, its high, sharp upper jaw can open up to 180 degrees and remain open for quite a long time. When the attack is launched, the upper jaw can be closed instantaneously, and the speed is only 0.13 milliseconds, which is 2300 times faster than the blink. The ants' jaw closing speed can produce an impact equivalent to 100,000 times the force of gravity, giving them a powerful impact when defending the hole. Faced with such a quick and powerful jaw, it is highly difficult for the invaders to enter the nests of the ants.

Blocking the hole. Taking Cephalotes as an example, this arboreal ant will dig holes in the tree. The head of the soldier ant becomes huge, flat and smooth, which can be used to block the hole. The ants that block the door are exposed to the hole, and their heads are usually covered with dust, forming a excellent protective color. It is as difficult for an intruder to pull a doorstopper out of a hole as it is for an intruder to pull a stopper out of a bottle with little or no stopper showing. Faced with such defenses, the invaders could only attempt to enlarge the opening, but this required a powerful palate and a lot of time, making the attack very difficult. This also reflects the advantages of Cephalotes living on trees, because this special skill allows them to protect their nests and survive in a very competitive environment in South America.

Physical attack. The maxillary structure of ants is diverse among different species and has been specialized to varying degrees according to their ecological adaptation and offensive needs [10-14]. For example, the Myrmecocystus and Formica have a thin and sharp upper jaw, similar to two blades, which can easily bite wounds on prey or enemies with thin body walls. Soldier ants of the Atta have nearly the strongest bite force in the ant world, and can easily cut the enemy 's body, even cutting leather and biting off plastic pipes. Soldier ants such as Pheidole and Carebara have a strong axe-like upper jaw. Although they are not as sharp as other species, they can easily cut the enemy 's chitin shell and even bite off the heads of different ants through strong bite force. Some ants have lengthy and curved upper jaws, and the ends are as sharp as hooks, which can easily pierce the enemy 's body, such as the soldier ant of Eciton in South American or Polyergus. Another kind of ants have pince-like upper jaw with sharped saw-tooth in the end, both sharpness and strength, such as Odontomachus, Daceton armigerum, which can easily break through the enemy 's body wall with great impact. The different type of ants have a slender and powerful upper jaw, covered with serrated teeth, which can be used to fix prey, such as the Myrmecia and Harpegnathos. This diverse jaw structure reflects the adaptation of ants to different ecological environments and lifestyles during evolution.

Chemical attack. The ants' real killer lies in chemical attacks, including tailsting toxins, formic acid jets and secretions. Nearly all ants have chemical weapons, so that they can threaten enemies that are several times larger than their size, or even a hundred times larger than their size, and become a magic weapon for ants to win. Partial members of the Myrmicinae and the original ant species adopt a similar attack method to bees, namely tail spine attack. Its venom components mainly include formic acid, polypeptides and enzyme molecules, and it is a powerful neurotoxin. The stingers of different species of ants have different toxicity. For example, high-toxic ant species such as Paraponera clavata, Pogonomyrmex maricopa, and Myrmecia pilosula can easily kill tiny to medium-sized mammals. The tails of most of the higher ant species have degenerated, replaced by the powerful weapon of antacid. Formic acid can be squirted by the tails and produce atomization effect through cilia. Compared with tail pin attack, it can carry out more extensive large-area attack, so as to win more with less. Although the effect of ant acid attack on other insects such as ants is significant, the threat to large animals is limited due to the limited number and power of antacid. However, ants generally do not fight alone, but rely on the entire group, and group warfare is their greatest advantage. Thousands of ants spray antacid at the same time, which can diffuse a strong sour taste throughout the air, form a strong deterrent, and even be able to drive away large predators such as brown bears.

4. Conclusion

The very orderly superorganism are formed in ant society through caste differentiation and behavioral division. The queen is responsible for fertility as a core member, and its fecundity directly affects the survival and reproduction of the entire ant colony. The worker ants serve as the main body to complete various tasks and ensure the normal operation of the ant colony. Soldier ants play a key role in defense, their specialized morphology and behavior play a part in resisting external threats. Ant societies adapt through efficient cooperation and strong defenses. Worker ant differentiation demonstrates flexible adaptability to a variety of tasks. The specialization of the ants underscores the strategic importance of facing external threats. The structure of ant society gives it an advantage in competitive ecology. Anarchism is characterized by extremely ordered group behavior, which has become a highlight of ecology and behavioral research. Overall, ant society provides a profound insight into understanding social insects and organizational behavior, and has significant reference value for building a more effective organizational structure in human society.

References

1. Wilson E.O. The insect societies. The Belknap Press of Harvard University, Cambridge, MA, 1971.
2. Robinson G.E. Regulation of division of labor in insect societies. Annu. Rev. Entomol. **37** (1992): 637–665.
3. Zhang H., Liu Q., Huang X. Research progress on class types and behavioral differentiation mechanisms of social insects. Biodiversity Sci. **029** (004) (2021): 507-516.
4. Hölldobler B., Bartz S.H. Sociobiology of reproduction in ants. In: Hölldobler B., Lindauer M. (Eds.) Experimental Behavioral Ecology and Sociobiology. Sunderland, MA: Sinauer Associates, 1985, pp. 237–257.
5. Yang R., Nakamura A. Nest of ants tend to settle near the artificial light propagation. J. Biol. Divers. **30** (8) (2022): 10.
6. Boomsma J.J., Baer B., Heinze J. The evolution of male traits in social insects. Annu. Rev. Entomol. **50** (2005): 395–420.
7. Cong Y., Xiao H., Li F. Insect genome size and its evolution. J. Appl. Insects. **56** (6) (2019): 8. DOI: CNKI: SUN: KCZS. 0.2019-06-009.
8. Dawkins R., Lu Y., Zhang D., et al. The Selfish Gene. Golden Age: Second Half **6** (2019): 1.
9. Shik J.Z., Kaspari M. Lifespan in male ants linked to mating syndrome. Insect. Soc. **56** (2009): 131–134.
10. De Biseau J.C., Schuiten M., Pasteels J.M., et al. Respective contributions of leader and trail during recruitment to food in Tetramorium bicarinatum. Insectes Sociaux **41** (1994): 241-254.
11. Buckley R.C. Ant-plant interactions: a world review. Ant-plant interactions in Australia. Dordrecht, Netherlands: Springer, 1982, pp. 1-141.
12. Wang L., Zhang J., Li Z., et al. Of mutual symbiosis of ants and plant research progress. J. Southwest For. Univ.: Nat. Sci. **40** (1) (2020): 8. DOI: CNKI: SUN: YNLX. 0.2020-01-025.
13. Zhao Y., Zhao M., Mao W., et al. Research progress on the role of ants on grassland plants and animals and soil. J. Yunnan Agric. Univ. (Nat. Sci.) 2019.
14. Ma F., Li A. Effects of artificial intervention of ant and cotton aphid cooperative symbiosis on yield of Zanthoxylum. Gansu Sci. Technol. **050** (008) (2021): 7-9,15.