Current Research Status on the Application of Predatory Ants in Biological Pest Control

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Abstract This paper reviews the historical application, primary species, and efficacy of predatory ants in pest management, and systematically elucidates their core mechanisms, including direct predation, non-lethal deterrence, and ecological regulation, as well as two application models: forest land introduction and farmland conservation. Meanwhile, the negative impacts on other arthropods, population diffusion, and management challenges in current applications are analyzed. Future research directions, such as precise assessment and risk control, integrated pest management (IPM) strategies integrating multiple technologies, and applications of molecular ecology, are clarified. The aim is to provide a reference for the in-depth research, promotion, and application of this type of natural enemy insect in sustainable IPM of agriculture and forestry.

Key words Predatory ants, Biological control, Integrated pest management (IPM), Ecological regulation, Natural enemy insects

1 Introduction

With the growing prominence of issues such as pest resistance, pest resurgence, and environmental pollution resulting from chemical pesticides, biological control has emerged as a central strategy for sustainable plant protection and has garnered unprecedented attention. Compared to traditional methods, biological control offers distinct advantages, including environmental friendliness, absence of pollution, and sustainability. Advances in science and technology have further enhanced its significance and role in pest and disease management. Consequently, the research and application of biological pest and disease control have become focal points within the field of plant protection, both domestically and internationally. The use of insects for pest control is an effective approach within the field of biological control. Predatory natural enemy insects play a crucial role in the prevention and control of diseases and pests[1]. In China, research on predatory natural enemy insects has primarily focused on parasitic wasps, predatory ladybugs, predatory mites, and predatory ants. Among these natural enemy groups, ants (Hymenoptera: Formicidae) are considered highly promising biological control factors due to their wide distribution, large population sizes, complex social behaviors, and strong predatory capabilities. Ants are social insects belonging to the family Formicidae within the order Hymenoptera and are distributed worldwide[2]. Certain ant species in China have been identified as predatory. The use of *Oecophylla smaragdina* for citrus pest control, originating from ancient practices, has evolved into contemporary ecological agricultural strategies that emphasize the conservation and utilization of native ant populations. Research on ants in pest management has progressed from empirical methods to scientifically grounded approaches, transitioning from extensive to more precise techniques[3]. The biological control of agricultural and forestry pests can be effectively implemented through the utilization of predatory ants as natural enemies, thereby enhancing the diversity of available natural enemy species and offering novel approaches for the development of biological control using predatory natural enemy insects. However, in China, the application of predatory ants as natural enemies remains limited, characterized by a narrow range of species and low abundance. Furthermore, research on predatory ants is relatively scarce. This article aims to review the current state of research on predatory ants as natural enemies, evaluate their potential applications and limitations, and explore future directions for the sustainable utilization of predatory ants in pest management.

2 Species and applications of predatory ants as natural enemies

The Antidae family exhibits considerable diversity. The majority of native ants and crowned ant colonies are predatory in nature. Predatory ants have been employed as natural enemies to manage agricultural pests for nearly a millennium. These ants occupy a wide range of ecological niches within ecosystems. Key agricultural pests targeted by these predatory ants include citrus psyllids, ladybug larvae, and aphids. Consequently, predatory ants play a

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crucial role in biological control[4-5]. The primary predatory ant species in China include *Formica beijingensis*, predominantly found in Beijing, Heilongjiang, Qinghai, and other regions; *Formica wongi* and *Anoplolepis gracilipes*, which are located in the southern provinces; and *Formica japonica* which is distributed throughout the country[3,6].

3 Biological and ecological habits of predatory ants

Predatory ant species are a subset of social insects. Investigating their biological and ecological habits provides insights into the mechanisms underlying their social organization and their ecological roles, with predatory ants being especially significant within these groups[7-8].

3.1 *Solenopsis invicta* *S. invicta* is classified within the order Hymenoptera, family Formicidae, subfamily Myrmicinae, and genus *Solenopsis*. This species exhibits a broad tolerance for temperature variations, diverse feeding habits, and a wide dietary range. Additionally, it is characterized by a large population size, high reproductive rate, strong competitive abilities, and rapid natural dispersal capacity. Atmospheric temperature significantly influences the activity patterns of *S. invicta*[9]. The life cycle of *S. invicta* comprises four developmental stages: egg, larva, pupa, and adult[10]. *S. invicta* typically constructs nests in open areas proximal to water sources and with ample sunlight exposure. When ambient temperatures fall below 8 ℃, disturbance of the nest surface does not elicit an exit response from soldier ants. However, at temperatures exceeding 12 ℃, tapping the nest prompts soldier ants to emerge. Foraging activity increases notably when temperatures rise above 21 ℃. Additionally, when daytime temperatures surpass 32 ℃, these ants predominantly engage in nocturnal foraging behavior.

S. invicta, as a social insect species, comprises winged males, winged females, queens, and workers (including both worker and soldier ants). The worker ants are wingless and primarily responsible for foraging, feeding, and caring for the larvae and the queen. Additionally, they perform tasks such as defending the nest, repelling intruders, and evacuating the queen in times of danger. The winged reproductive individuals reside within the nest and only disperse by flight when it is the appropriate mating season.

The mature nests of *S. invicta* are distinctly aggregated, forming soil mounds that range from 10 to 30 cm in height and 30 to 50 cm in diameter, with some extending to a depth of 60 cm. When the nest is disturbed, *S. invicta* rapidly exits to confront the intruders[11].

3.2 *Oecophylla smaragdina* *O. smaragdina* is classified within the order Hymenoptera, suborder Apocrita, family Formicidae, subfamily Formicinae, and genus *Oecophylla*. As a social insect, it exhibits characteristics such as cooperative behavior, hierarchical differentiation, and phototaxis[12]. This species prefers warm and humid environments, demonstrates limited cold tolerance, possesses a diverse diet, and is sensitive to chemical agents[13]. The minimum temperature for its activity is generally around 20 ℃, while its activity significantly diminishes when temperatures exceed 32 ℃[14]. The activity of *O. smaragdina* is significantly influenced by light conditions. Their activity levels are markedly higher in illuminated areas compared to shaded ones. This preference for light likely explains their predominance in diurnal activities. *O. smaragdina* is an arboreal ant species that constructs nests by binding leaves together with silk. There are two distinct types of worker ants in *O. smaragdina*. The first type is larger, measuring approximately 10 mm in length, and is primarily responsible for field activities such as foraging, hunting, guarding, and nest construction. The second type is smaller, with a body length of about 7 – 8 mm, and performs tasks within the nest, including caring for the queen and the brood[15]. During nest construction, worker ants induce older larvae to produce silk by biting them, which facilitates the binding and joining of plant leaves. Additionally, the nests are not permanent structures; new nests are constructed at regular intervals, while some older nests are subsequently abandoned[13,16].

3.3 *Anoplolepis gracilipes* *A. gracilipes* is classified within the order Hymenoptera, family Formicidae, subfamily Formicinae, and genus *Anoplolepis*[17]. This ant species inhabits diverse environments and exhibits a broad diet. It demonstrates agility in movement, active predatory behavior, and possesses a high reproductive capacity, resulting in large population sizes. Additionally, it displays a well-defined division of labor within the colony and is sensitive to environmental conditions. The optimal temperature range for its growth is between 25 and 44 ℃[18-19]. Individuals measure approximately 4 mm in body length, with a light yellow body coloration, a dark brown to black abdomen, and a smooth, glossy surface lacking prominent sculptures[17].

A. gracilipes is capable of forming supercolonies comprising multiple queens, with no observed mutual aggression among individuals within the same population. A single nest may contain 20 to 30 or more queens simultaneously, and the nest size can extend from 10 to 150 hm^2. Under favorable environmental conditions and abundant food resources, these ants can establish high-density populations. For example, in Seychelles, the number of individuals within a single nest can reach nearly 4 000[19].

As an efficient predator, *A. gracilipes* exhibits a broad spectrum of dietary preferences, capable of consuming nearly all living organisms, including trees. It is active during both diurnal and nocturnal periods, exhibiting activity in both aboveground and subterranean environments. Furthermore, it demonstrates considerable adaptability to a wide range of temperatures during foraging. The nesting sites of *A. gracilipes* are diverse, occurring beneath leaf litter on the forest floor of rubber plantations, on tree branches and trunks, within the interlayers of rain caps on cut surfaces, and in the soil. Additionally, this species possesses a remarkable reproductive capacity[20].

4 Pest control mechanism of predatory ants

Predatory ants as natural enemies exert significant control over pest populations[21]. Their pest management mechanisms primarily operate through three main approaches. The first approach involves direct predation. Ants are opportunistic, broad-spectrum predators capable of actively locating and preying upon the eggs, larvae, pupae, and adults of pests. Furthermore, their social behavior facilitates cooperative hunting via pheromone communication, resulting in highly efficient predation. The second approach is a non-lethal deterrent impact. The mere presence of ants can strongly deter pests. Pests detect ant activity through visual, olfactory, or tactile cues, leading them to reduce feeding and egg-laying or to avoid areas inhabited by ants. This "trait-mediated effect" often plays a more significant and enduring role in pest population control than direct predation. The third approach involves ecological niche competition and interference. Ants alter the community structure of their natural enemies by competing for food resources or directly attacking them, including species such as spiders and ladybugs. This effect has dual implications: on the one hand, it may diminish the pest control efficacy of other natural enemies; on the other hand, when ants become the dominant population, they can establish a stable predation pressure centered on themselves.

The application of predatory ants as natural enemies in agricultural or forest ecosystems necessitates the establishment of suitable survival conditions for these ants. Consideration must be given to their behavioral patterns, nesting site preferences, and the influence of their ecological niches on coexisting organisms within the surrounding environment. Additionally, research has demonstrated that environmental and biological factors, including climatic conditions and the adaptability of natural enemies, significantly influence the efficacy of natural enemy insects[22]. Consequently, it is essential to conduct a comprehensive assessment of the potential impacts of natural enemies present at the release site on the survival and reproductive success of predatory ants. In regions experiencing severe pest infestations, the native populations of natural enemy insects are often insufficient, thereby limiting the effectiveness of biological control strategies. The artificial breeding of large quantities of natural enemy insects, followed by their introduction into areas with high pest populations, can effectively control and reduce pest numbers, thereby providing a viable solution to this issue[23]. Given that ants are predominantly social insects that favor humid and warm environments, environmental factors significantly influence their population dynamics. Consequently, when relocating ant colonies, it is essential to select release sites that align with the ants' habits to minimize environmental disruptions to their normal growth and development.

In addition to directly preying on pests to regulate their populations, research has demonstrated that the non-lethal effects of predatory ants and predation-induced stress can also contribute to pest management[24]. For example, exposure to the odors or stress signals from natural enemies can influence the physiology, behavior, and life of pests. This interaction can impair the digestive and metabolic efficiency of pest larvae, and decelerate their growth rates, ultimately achieving the ecological effect of reducing the population density of prey. Although ants, as natural enemies, play a significant role in pest control, it is essential to evaluate their application not only from the perspectives of community ecological niches and food chains but also with regard to the safety of practitioners, including researchers and farmers. Studies have demonstrated that certain ants contain toxic alkaloids within their bodies, such as pyrrolizidine alkaloids found in the venom of ants belonging to the subfamily Myrmicinae[25]. This venom can affect plant pests; however, and also poses risks to human health by causing poisoning of the skin and bloodstream. Therefore, when selecting appropriate ants as natural enemies against crop pests, it is essential to exercise caution to ensure effective pest management while preventing any adverse effects on human health.

5 Application practices of predatory ants

Currently, the application of ants primarily encompasses two approaches. The first, introduced control, entails the introduction of ant species with notable pest control capabilities, such as *O. smaragdina*, into targeted environments like orchards. Techniques such as constructing ant bridges and supplying alternative food sources and nesting sites facilitate the establishment of stable ant populations[16]. Although this method demonstrates clear objectives and direct efficacy, it is associated with high costs and is limited to particular ant species and habitats. Current research and promotion efforts are primarily focused on conservation control. Enhancing agricultural management practices, such as minimizing the use of broad-spectrum pesticides, implementing crop cover, maintaining or establishing weed belts along field margins, and creating artificial ant nests, provides shelter, alternative food sources, and nesting resources for local predatory ants. These measures contribute to increasing the population size of predatory ants and improving their pest control efficacy within the farmland ecosystem. This approach aligns more closely with ecological principles and supports the restoration of the entire natural enemy community[13].

Various species of ants have been effectively utilized for pest control across diverse habitats worldwide. Notably, *O. smaragdina* is employed in Asian citrus and cashew nut orchards to manage pests including stink bugs, beetles, and caterpillars, demonstrating significant efficacy and enabling a reduction in pesticide usage by over 70%[26-27]. *Oecophylla longinoda*, a species within the genus *Oecophylla* native to Africa, is widely utilized for pest control in cocoa and coconut plantations, similar to *O. smaragdina*[28]. Although *S. invicta* is recognized as a notorious invasive species, its strong predatory capabilities allow it to effectively manage various subterranean and surface pests, including *Salvinia minima*, within agricultural ecosystems in its native South America and other regions such as sugarcane fields and pastures[29]. An increasing number of studies on locally dominant ant species emphasize the protection and enhancement of pest control services provided by native predatory ants in farmlands through ecological engineering approaches. For example, the establishment of ecological islands and the cultivation of attractant plants facilitate the natural migration of indigenous ant species, such as *Pheidole*, *Tetramorium*, and *Formica*, into farmlands to suppress pest populations. Empirical evidence indicates that both the introduction of exotic ant species and the conservation of native ant colonies can effectively reduce the density of target pest populations, mitigate crop damage, and consequently improve crop yield and quality.

The analysis of predatory pest species not only reflects the research focus on natural enemy insects within the field of biological control but also offers valuable guidance regarding the optimal selection of release sites and quantities for artificial release of natural enemies. Statistical data indicate that most predatory ants preferentially prey upon Lepidoptera, Hemiptera, Coleoptera, and their respective larvae. Commonly targeted pests include Lepidopteran species such as *Dendrolimus punctatus* (Lasiocampidae), *Agrotis ypsilon* (Noctuidae)—which are preyed upon by *Odontomachus monticola* and *Camponotus japonicus*—and *Ostrinia furnacalis* (Crambidae), which is preyed upon by *S. invicta*, thereby influencing its population dynamics. Hemipteran pests include *Nilaparvata lugens* (Delphacidae), *Cimex* spp. (Cimicidae), and *Anoplocnemis* spp. (Pentatomidae). Additionally, Coleopteran pests such as *Sympiezomias velatus* (Curculionidae) and *Platyrhopalopsis picteti* (Carabidae) are also commonly preyed upon[13,30-32]. These pest species suggest that predatory ants primarily target herbivorous insects. Relevant studies have demonstrated that predatory natural enemy insects frequently inhabit the same areas as herbivorous insects, with their population sizes positively correlated. This relationship underscores their significant role in regulating herbivorous insect populations[33]. Based on the analysis of the prey species of predatory ants, it can be concluded that their primary targets for biological control are harmful pests that damage woody, herbaceous, and climbing plants. Furthermore, a review of the literature indicates that various ant species frequently prey on *D. punctatus* at high predation rates[34]. *Crematogaster* sp., *Camponotus* sp., and other species are the dominant ant taxa within the *Pinus massoniana* forest. These species have adapted to the habitat of the *P. massoniana* forest and preferentially consume the body or parts of *D. punctatus*, thereby playing a significant role in the predation and population control of *D. punctatus*.

Furthermore, pests belonging to the Pyralidae family are frequently targeted by various predatory ants. For instance, colonies of *S. invicta* preying on *O. furnacalis* can reduce the number of pest egg masses by 50%. The predation of *S. invicta* on sugarcane borers contributes to enhanced control efficiency of these pests, thereby decreasing the incidence of pests and diseases in sugarcane crops[5,35]. *Nesodiprion zhejiangensis* is a significant defoliator of *P. massoniana*. Research conducted in the *P. massoniana* forest regions of Zhejiang has demonstrated that numerous predatory *A. gracilipes* collectively attack and prey upon this pest by moving vertically along the trees. Local forestry practitioners and researchers have scientifically leveraged this behavior and implemented related novel technologies, resulting in a substantial reduction in the affected area of *P. massoniana*. This approach has not only facilitated effective pest control and minimized timber loss but has also contributed to increased income for local farmers[36].

Predatory ants exhibit behavioral traits analogous to those of other predatory natural enemies, such as mites and ladybugs. They contribute to crop growth by preying on pests and reducing the incidence of diseases and pests in agricultural and forestry crops, thereby demonstrating significant potential in biological control. However, research and industrial development related to predatory ants in China remain insufficient, and have yet to achieve the capacity for artificial large-scale breeding and mass release of these predatory ants. Further in-depth investigation is required to optimize the utilization of their predatory behavior to enhance pest prevention and control efficacy.

6 Prospects

Despite its clear advantages, the application of ants presents several challenges. One significant concern is the negative ecological impact: invasive ant species, such as *S. invicta*, may prey upon non-target beneficial insects, including pollinating bees and other predatory natural enemies, thereby disrupting local biodiversity. Additionally, many ants engage in mutualistic relationships with homopteran pests, such as aphids and scale insects, which produce honeydew. Ants protect these pests from their natural enemies to obtain nectar, which consequently results in a population explosion. This represents a fundamental contradiction that must be carefully balanced and managed in practical applications. Additionally, challenges related to population spread and management arise: the introduced ant population may extend into non-target areas, thereby posing ecological risks. Simultaneously, maintaining the stability of the ant population and preventing its collapse due to environmental fluctuations is an urgent technical issue that requires resolution. The complexity of evaluating the effects of pest control by ants arises from the influence of multiple factors, including crop type, pest species, climatic conditions, and the overall structure of the biological community. These variables complicate the establishment of standardized assessment methods and the prediction of outcomes, unlike the more consistent effects observed with chemical pesticides.

Future research should prioritize the following areas: (i) precise assessment and risk management, employing molecular markers, stable isotopes, and other methods to accurately determine the nutritional role of ants within the food web and their actual contribution to pest control. Additionally, an ecological risk assessment framework should be developed for the introduction of ants, emphasizing the selection and application of locally dominant species that present minimal ecological risks. (ii) A multi-technology integrated pest management (IPM) strategy should be employed to investigate the compatibility and synergistic effects of ants in combination with parasitic wasps, pathogenic microorganisms, and other biological control factors for pest control. This research aims to regulate the interactions between ants and harmful symbiotic insects, such as aphids, through approaches including pheromone modulation and the establishment of physical barriers, with the objective of maximizing beneficial interactions, minimizing adverse effects, and enhancing overall pest control efficacy. (iii) Research in molecular ecology and behavioral mechanisms necessitates an in-depth analysis of the molecular foundations underlying ant olfactory recognition, foraging decision-making, and pheromone communication. Such investigations provide theoretical support for the development of effective behavioral regulators, the optimization of attraction and repellent strategies, and the enhancement of the directional regulation of ant behavior. (iv) Ecological engineering technology is optimized to design efficient and cost-effective farmland habitat management plans. It aims to create environmental conditions that facilitate the colonization and reproduction of target predatory ants by enhancing habitat structure, thereby promoting the widespread application and adoption of conservation control models.

Predatory ants as natural enemies represent a potent and multifaceted biological control resources. They exhibit significant potential for managing agricultural and forestry pests through various mechanisms, including direct predation, deterrence, and ecological regulation. The conceptual framework for their application has evolved from traditional introduction-based prevention and control methods to contemporary conservation-based ecological enhancement approaches. Although challenges remain, such as interactions with symbiotic pests and potential ecological risks, advancements in interdisciplinary research, precise risk assessments, and integration with IPM strategies are expected to enhance the role of predatory ants in future ecology-oriented sustainable plant protection.

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