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CARABID BEETLES AS ENTOMOPATHOGENIC VECTORS: A REVIEW OF THEIR ECOLOGICAL ROLE AND POTENTIAL APPLICATIONS

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Abstract

As predators of phytophagous insects and potential vectors of pathogens, ground beetles (Carabidae) are vital in agroecosystems. In this work, their interaction with entomopathogenic fungi and bacteria is presented to highlight the dual role of ground beetles as biocontrol agents and pathogen vectors. This includes understanding how disease propagation and dispersion in multitrophic complexes interact with parasitism, predation, and competition. Integrated pest management (IPM) strategies that consider the potential of ground beetles are evaluated in terms of their ability to enhance biological control methods. The current state of knowledge regarding the long-term ecological consequences and the function of these strategies as vectors of organisms, however, limits their scope. This work underscores the necessity of understanding multitrophic interactions to inform the integration of ground beetles into pest control strategies.

Key words*: Carabidae, biological control, entomopathogens, multitrophic, IPM.*

INTRODUCTION

Ground beetles (Coleoptera: Carabidae) play a fundamental role in agroecosystems, acting as biological control agents of herbivore populations, facilitating nutrient recycling, and contributing to the overall ecological stability of agricultural environments (Lundgren & McCravy, 2011; Marrec et al., 2020).

As noted by Holland (2002), these insects are among the most frequently studied entomofauna groups due to their remarkable taxonomic and ecological diversity. Additionally, their interactions with other species allow them to influence ecosystem structure and function in meaningful ways.

The factors driving ground beetle population dynamics are diverse, ranging from environmental conditions such as temperature and humidity to soil properties and food resource availability.

Cividanes (2021) highlights how vegetation structure significantly impacts their distribution, determining both how these beetles spread across landscapes and their feeding behaviors. Changes in habitat composition influence their functional diversity, leading to variations in species distribution and ecological interactions.

Because they respond quickly to environmental fluctuations, ground beetles are widely recognized as reliable indicators of agroecosystem health. A study by Makwela et al. (2023) establishes a direct correlation between beetle biodiversity and farming intensity, demonstrating that modifications in habitat structure and increased agrochemical usage have a measurable impact on these insect communities. As a result, ground beetles are valuable tools for monitoring human-induced disturbances in agricultural systems, offering crucial data on ecosystem stability and resilience.

Entomopathogens are microorganisms, primarily fungi and bacteria, that can infect and cause lethal diseases in insects, playing a crucial role in the biological control of agricultural pests. These agents are widely used in Integrated Pest Management (IPM) due to their high specificity and minimal impact on non-target organisms (Deka et al.,2021).

According to Khan & Ahmad (2019), entomopathogens represent a fundamental component of biological control strategies, offering high host specificity, low impact on non-target species, and contributing to the ecological balance within agroecosystems. These microorganisms are commonly found in soil and other natural habitats, acting by infecting insect hosts either through the cuticle or via ingestion. Their infections often lead to epizootic outbreaks that significantly reduce pest populations.

Entomopathogenic fungi, such as *Beauveria bassiana* (Bals-Criv.) Vuill. and *Metarhizium anisopliae* (Metschn.) Sorokīn penetrate the insect cuticle, triggering a systemic and lethal infection. After the host dies, the fungi proliferate on the dead insect, releasing spores that contribute to the regulation of pest populations (Abbas et al., 2020; Ebani & Mancianti, 2021).

Entomopathogenic bacteria, such as *Bacillus thuringiensis* (Berliner, 1915) (Bt), produce specific toxins that disrupt the insect's intestinal epithelium, causing paralysis and eventual death. Unlike fungal entomopathogens, bacterial pathogens must be ingested by the host to be effective (Ebani & Mancianti, 2021).

By utilizing entomopathogens, dependence on chemical pesticides can be reduced, promoting sustainable agriculture while preserving biodiversity.

MATERIALS AND METHODS

This review aims to examine the role of carabid beetles in agroecosystems, emphasizing their dual function as both natural predators of pests and potential vectors of entomopathogens. Additionally, it explores the multitrophic interactions that shape their effectiveness in biological control. By synthesizing current research, the review assesses ecological and abiotic factors that influence carabid populations, compares their biocontrol efficiency with other methods, and identifies both the opportunities and challenges of integrating them into pest management strategies.

The study draws on peer-reviewed literature, scientific research, and other relevant sources published in English from the 1990s onward.

Through this approach, the review provides an integrated perspective on the contribution of carabid beetles to modern Integrated Pest Management (IPM) strategies, highlighting their advantages as well as the constraints they face in the context of agroecological and climatic shifts.

RESULTS AND DISCUSSION

Ecology and Diversity of Carabids

Carabids constitute one of the most diverse beetle families, comprising over 40,000 described species distributed across approximately 86 tribes (Lövei & Sunderland, 1996). Their remarkable diversity is reflected in a broad range of ecological adaptations, including active predators, phytophagous species, and opportunistic feeders. Taxonomic classification within this group is primarily based on distinct morphological features, such as antenna and leg structures, along with the presence of pygidial glands responsible for secreting defensive chemical compounds (Kotze et al., 2011). Advances in molecular and phylogenetic studies have further clarified evolutionary relationships, reinforcing the stability of the Carabinae subfamily, which consists mostly of large, ground-dwelling species. In contrast, members of Trechinae and Harpalinae exhibit a greater degree of ecological diversity (Kotze et al., 2011).

These beetles inhabit every continent except extreme desert regions. The highest species richness is found in tropical areas, yet research in these ecosystems remains relatively scarce, as most studies have focused on populations in the Northern Hemisphere (Avgın & Luff, 2010).

In Europe, *Carabus auronitens* (Fabricius, 1792) is frequently encountered in temperate forests, while in North America, *Pterostichus melanarius* (Illiger, 1798) is one of the most widespread species in agricultural environments (Niemelä, 2001). In colder regions, species such as *Nebria* spp. have adapted to harsh climatic conditions by reducing metabolic activity and developing resistance to low temperatures (Kotze et al., 2011).

Populations in temperate ecosystems display exceptional ecological flexibility, allowing them to thrive in a wide variety of habitats, from cultivated lands to mountain forests and wetlands. Studies on habitat fragmentation suggest that landscape changes significantly influence species distribution. While some are negatively impacted by habitat loss, others, particularly generalists, may benefit from environmental alterations (Niemelä, 2001; Thomas et al., 2002).

Ecological Factors Influencing Carabid Populations

Carabid populations are shaped by a range of ecological factors that influence their distribution, abundance, and ecological roles within agroecosystems.

Abiotic elements such as temperature, humidity, and habitat structure, alongside biotic interactions with other organisms, contribute to population dynamics and determine the success of these species across different environments (Murdoch, 1966).

The intensification of agricultural practices has led to substantial habitat alterations, impacting both species diversity and community composition. Research suggests that intensively managed farmland experiences a decline in larger carabid species, while opportunistic ones, better adapted to environmental disturbances, tend to thrive (Cole et al., 2002). In contrast, semi-natural areas and undisturbed habitats support higher biodiversity, providing essential resources for survival and reproduction (Gill & Garg, 2014).

Anthropogenic landscape modifications, including deforestation, urban expansion, and agricultural land conversion, reduce habitat connectivity, affecting the dispersal of carabid species.

Studies indicate that generalist species are more capable of persisting in fragmented environments, whereas specialists often experience significant population declines (Niemelä, 2001).

These shifts have direct consequences on the stability of carabid communities and their ability to contribute to biological control within agroecosystems (Murdoch, 1966).

Climatic variations further influence the life cycles and behavior of carabids, altering reproductive rates and feeding activity.

Research shows that higher temperatures enhance the activity of predatory species, while humidity plays a crucial role in sustaining populations in arid regions (Murdoch, 1966).

Additionally, climate change may lead to range expansions for certain species, potentially disrupting trophic structures and ecological balance in newly colonized areas (Koivula, 2011) (Figure 1).

Figure 1. Ecological network of an agroecosystem highlighting carabid beetles as predators and vectors of entomopathogens. Solid lines represent direct trophic interactions, while dashed lines indicate indirect effects. Carabid beetles regulate pest populations through predation and by vectoring entomopathogenic fungi and bacteria. Agricultural practices influence these interactions by altering vegetation structure, pest dynamics, and carabid behavior. Integrating biological control strategies can enhance ecosystem stability and reduce reliance on chemical inputs

Source: Adapted from De Heij, S. E., & Willenborg, C. J. (2020)

Multitrophic Interactions and the Role of Carabids in Agroecosystems

In agroecosystems, multitrophic interactions shape the complex relationships between predators, parasites, pathogens, and herbivores, directly influencing the structure and stability of food webs (Ivanković Tatalović, 2023). Ground beetles play a crucial role in these interactions, impacting pest population dynamics and enhancing biological control efficiency through their diverse ecological relationships (Ivanković Tatalović, 2023; De Heij & Willenborg, 2020).

As polyphagous predators, these beetles feed on a wide range of prey, including herbivorous insects, other predatory species, and even entomopathogens (Kamenova et al., 2017). Research suggests that carabid communities can be divided into two trophic groups: some species specialize in resources associated with cultivated plants, while others have a more flexible diet that adjusts to seasonal fluctuations in food availability (Kamenova et al., 2017). This dietary variation influences pest control efficiency depending on agricultural management practices and resource availability (Gill & Garg, 2014).

Carabids contribute to the natural regulation of pest populations, helping to maintain ecological balance and reducing the reliance on chemical pesticides (Winder et al., 2001). For instance, *Pterostichus melanarius* is known for its ability to significantly lower populations of aphids and lepidopteran larvae in cereal crops (Symondson et al., 2006). Moreover, studies emphasize that the effectiveness of these beetles as biocontrol agents is closely linked to the complexity of the food web and habitat characteristics (Gill & Garg, 2014; De Heij & Willenborg, 2020).
A key aspect of multitrophic interactions is the relationship between carabids and entomopathogens. These predators can act as vectors, aiding in the spread of fungal spores to susceptible hosts, but they can also reduce the effectiveness of entomopathogens by preying on infected insects before spores are released (Roy & Pell, 2000). Additionally, the presence of alternative prey may alter the efficiency of carabids as biocontrol agents, as they tend to diversify their diet and prioritize more accessible food sources, leading to seasonal variations in pest suppression (Symondson et al., 2006; De Heij & Willenborg, 2020).
The outcomes of these interactions are strongly influenced by agroecosystem conditions and agricultural practices. Pesticide applications, for example, can negatively impact both carabids and entomopathogens, disrupting natural food webs and reducing biocontrol efficiency (Ivanković Tatalović, 2023). On the other hand, habitat management strategies such as ecological field margins and uncultivated areas help support stable beetle populations and enhance their role in pest suppression (De Heij & Willenborg, 2020; Winder et al., 2001). In this context, conserving carabid diversity in agricultural landscapes emerges as a key strategy for maintaining ecosystem services and promoting sustainable farming practices.

Carabids as Predatory Insects and Biological Control Agents

Carabids are widely recognized as effective predators that contribute to the regulation of herbivorous insect populations in agricultural environments. Their role in pest suppression makes them essential components of sustainable farming systems.
Many species within this group exhibit polyphagous feeding behavior, preying on a broad range of agricultural pests, including aphids, lepidopteran larvae, and coleopteran eggs. Research indicates that larger species such as *Carabus nemoralis* (O.F.Müller, 1764) and *Carabus granulatus* (Linnaeus, 1758) are particularly effective in controlling slugs and harmful beetle larvae (SaccoKromp, 1999; Sacco-Martret de Préville et al., 2024).

Table1. Carabid Species and Their Contribution to Biological Pest Control in Agroecosystems.
Source: Kromp, 1999; Lang et al., 1999; Symondson et al., 2002; Hanson et al., 2016

Species	Description and comments	Selected references
Pterostichus melanarius	Commonly found in agricultural fields, has been extensively studied for its effectiveness in biological control, playing a crucial role in reducing aphid populations and other pests in wheat crops	Hanson et al., 2016
Harpalus rufipes	A key species in biological control, capable of reducing both harmful insects and weeds. Research indicates that it feeds on invasive plant seeds, helping to limit their spread in agricultural fields.	Kromp, 1999
Poecilus cupreus	An active predator in corn and soybean fields, playing a crucial role in regulating caterpillar and lepidopteran larval populations. Studies confirm its significant impact on pest control in cereal crops.	Lang et al., 1999
Carabus nemoralis	A large-sized species, highly effective in preying on slugs and harmful larvae in horticultural crops. Commonly found in orchards and gardens, it plays a vital role in natural biological control.	Symondson et al., 2002

In wheat and maize fields, *Pterostichus melanarius* (Illiger, 1798) and *Poecilus cupreus* (Linnaeus, 1758) are among the most prevalent predators targeting aphids and caterpillars. Experimental studies have demonstrated that these species significantly reduce populations of Cicadellidae and Thysanoptera, thereby mitigating crop damage caused by these pests (Lang et al., 1999) (Table 1).
Maintaining a diverse habitat has been shown to support stable carabid communities, enhancing their effectiveness in biological control. According to Hanson et al. (2016), variations in agricultural land use influence the distribution and abundance of these beetles, which can directly impact their ability to suppress pest populations.

Predation Mechanisms and Impact on Pest Populations

Ground beetles are opportunistic predators that employ various hunting strategies depending on habitat conditions, resource availability, and prey characteristics. Research indicates that larger species, such as *Carabus auratus* (Linnaeus, 1761) and *Pterostichus melanarius*, can effectively control pest populations in agroecosystems by preying on larger insects (Rouabah et al., 2013).

Carabids can be classified based on their body size and feeding preferences into surface-active predators, soil hunters, and specialists in seed or larval consumption. For instance, *Poecilus cupreus* and *Harpalus rufipes* (Degeer, 1774) are ecologically adaptable species with a significant impact on aphid and lepidopteran larvae populations (Williams et al., 2010). By consuming eggs, larvae, and adult insects, these beetles play a key role in natural pest suppression. Studies have demonstrated that large predatory species, including *Pterostichus melanarius*, can substantially reduce aphid and caterpillar numbers, providing an effective form of biological control (Hummel et al., 2012).

An important factor influencing predation efficiency is the relationship between beetle size and prey size. Rouabah et al. (2013) found that larger species are capable of consuming a broader range of pests, including sizable beetle larvae and caterpillars, which contributes to a significant decline in these pest populations. Predator-prey interactions are not solely determined by beetle abundance but are also influenced by competition among different predator groups. Studies in organic farming systems suggest that carabids compete for food resources with other natural enemies, such as predatory spiders and hemipterans (Kromp, 1989).

Additionally, intra-guild competition among carabids can affect their efficiency as biological control agents. Experimental research has shown that the presence of dominant and highly aggressive species, such as *Carabus auratus*, may lead smaller species like *Bembidion lampros* (Herbst, 1784) to alter their foraging strategies and reduce feeding activity to avoid direct encounters (Williams et al., 2010).

The functional diversity of carabids plays a crucial role in enhancing biological control efficiency. Experimental studies suggest that the coexistence of multiple species with varying sizes can improve predation success due to trophic complementarity, where different species target various pest developmental stages or trophic levels (Rouabah et al., 2013). Maintaining high carabid diversity in agroecosystems is essential for effective pest control and reducing dependence on chemical pesticides. Sustainable agricultural practices, such as maintaining vegetated field margins and implementing crop rotation, can help maximize the benefits provided by these insects in pest suppression (Hummel et al., 2012).

Comparative Efficiency of Carabids Versus

For a long time, conventional agricultural systems have relied heavily on insecticides to manage pest populations. However, research indicates that the presence of carabids in organic farming and no-till systems can effectively suppress pests without intensive chemical use, achieving agronomic results comparable to traditional pesticide applications (Prasifka et al., 2007; Koss et al., 2005). Their predatory activity contributes to reducing weed seeds and harmful insect populations, reinforcing the sustainability of biological control approaches (Prasifka et al., 2007).

The widespread use of broad-spectrum insecticides significantly affects the abundance and diversity of carabids and other natural predators, which may lead to secondary outbreaks of resistant herbivorous insect species (Kennedy et al., 2001). Additionally, exposure to chemical treatments such as pyrethroids initially increases predatory activity but eventually results in population declines due to high mortality rates and sublethal effects, including reduced reproductive success and diminished biocontrol efficiency (Prasifka et al., 2007; Koss et al., 2005).

A comparative assessment of fields treated with selective insecticides, broad-spectrum pesticides, and organic biocontrol strategies found that areas managed using selective insecticides and organic methods supported higher densities of carabids and other beneficial predators. This increase in natural enemy populations led to more effective pest suppression than in fields exposed to broad-spectrum chemicals (Koss et al., 2005). Consequently, integrating carabids into pest management strategies offers significant benefits, including lower pest densities, enhanced biodiversity conservation, and reduced reliance on synthetic insecticides. Long-term sustainability can be achieved through habitat management and natural predator conservation, providing efficient pest control while preserving soil health and agroecosystem biodiversity (Prasad & Snyder, 2004).

Ground beetles as Vectors of Entomopathogens

Carabid beetles host diverse bacterial communities that influence their physiology and ecological role. Research has identified specific bacterial strains within the digestive tracts of species such as Harpalus pensylvanicus and Anisodactylus sanctaecrucis. These microorganisms, including Serratia, Burkholderia, Hafnia, Phenylbacterium, Caedibacter, Spiroplasma, Enterobacter, and Weissella, contribute to nutrient digestion and trophic interactions within agroecosystems (Lundgren et al., 2007).

One notable entomopathogenic bacterium associated with carabids is Photorhabdus luminescens (Thomas & Poinar, 1979; Boemare et al., 1993), a symbiotic microorganism of entomopathogenic nematodes. This bacterium exhibits strong insecticidal properties, targeting key agricultural pests, and may indirectly influence carabid predation activity in farming systems (Muhammad et al., 2022). Entomopathogenic fungi also play a crucial role in regulating insect populations, with several species identified in association with carabids. *Beauveria bassiana* is among the most commonly reported fungal pathogens affecting these beetles, having been isolated from species such as *Bembidion lampros* and *Agonum dorsale* (Pontoppidan, 1763). While adult beetles show lower infection rates, larvae tend to be more susceptible (Riedel & Steenberg, 1998). Another relevant fungal pathogen, *Metarhizium anisopliae*, has been detected in agricultural soils and in carabids collected from pesticide-free fields. Frequently used in biological pest control, this fungus can be passively transported by carabids, potentially facilitating its spread to other insect species within agroecosystems (Steenberg et al., 1995).

Further studies have also recorded the presence of other fungal pathogens, such as *Paecilomyces farinosus* (Holmsk.; A.H.S.Br. & G.Sm.) and L*ecanicillium lecanii (*Zimm.; Zare & W. Gams, 2001). While their direct impact on carabid populations remains less understood, these fungi are known to affect agricultural pests and may contribute to ecological pest regulation (Steenberg et al., 1995).

A comprehensive review of carabid-fungus interactions, analyzing 200 years of literature, identified 3,378 unique associations between 1,776 carabid species and 676 fungal taxa. The findings suggest that most interactions involve ectoparasitic fungi from the order Laboulbeniales, whereas entomopathogenic fungi such as *Beauveria* and *Metarhizium* are less frequently recorded (Pozsgai et al., 2021).

Mechanisms of Entomopathogen Dispersal

Carabid beetles contribute significantly to the dissemination of entomopathogens by passively carrying fungal spores (*Beauveria bassiana*, *Metarhizium anisopliae*) and bacterial cells on their body surfaces, particularly on the cuticle and locomotory appendages. These spores can be transferred to other insects or soil substrates, facilitating pathogen spread within the agroecosystem (Steenberg et al., 1995; Meyling & Hajek, 2009).

Field studies indicate that fungal spores adhering to carabid cuticles can remain viable for extended periods, and their contact with other insects may lead to infection, exerting continuous pressure on pest populations (Meyling & Hajek, 2009) (Figure 2).

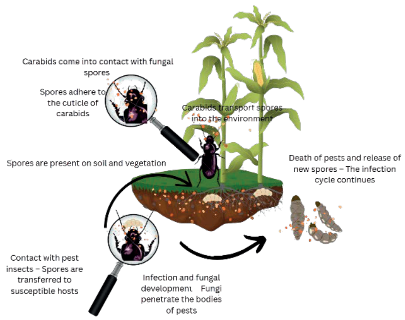

Figure 2. Carabid Beetles as Predators and Entomopathogen Vectors in Agroecosystems. Source: Adapted from Steenberg et al. (1995) and Meyling & Hajek (2009), own elaboration

Another significant pathway for entomopathogen spread is through the ingestion of infected prey. Carabid beetles can consume diseased insects and later excrete viable spores, facilitating pathogen dispersal within the agroecosystem (Wang-Peng et al., 2018). For instance, the consumption of prey infected with fungi such as *Beauveria brongniartii* (Sacc.; Petch, 1926) contributes to its propagation, as spores are expelled into the environment, a process documented in *Poecilus* species (Traugott et al., 2005).

Additionally, carabids can serve as intermediate hosts for entomopathogenic nematodes (*Steinernema*, *Heterorhabditis*), acting as vectors by coming into direct contact with contaminated soil or by consuming infected prey (Labaude & Griffin, 2018). Research indicates that certain nematodes have developed adaptive mechanisms that allow them to survive passage through the digestive tract of carabids, eventually being excreted into the soil, where they can seek out and infect new hosts (Jones et al., 2015).

Factors Influencing the Vector Efficiency of Carabids

The effectiveness of carabid beetles as vectors of entomopathogens is shaped by abiotic conditions such as temperature, humidity, and soil composition. Extreme temperatures and low moisture levels can negatively impact both fungal spore viability and the activity of entomopathogenic nematodes, thereby reducing the role of carabids in pathogen dissemination (Matuska-Łyżwa et al., 2024). Additionally, sandy soils enhance beetle mobility but decrease fungal spore persistence, whereas clay-rich soils retain moisture, creating favorable conditions for pathogen survival (Kamata, 2000; Tscharntke et al., 2007). Population density is another critical factor influencing vector efficiency, as a higher number of individuals increases the likelihood of encounters with infected insects and contributes to pathogen spread within the agroecosystem (Rosenheim, 1995). However, not all carabid species demonstrate equal efficiency in this process. For instance, *Poecilus cupreus* and *Harpalus rufipes* are recognized as effective vectors due to their high mobility and feeding behavior (Cividanes, 2021). The presence of other predators in agroecosystems can also affect the role of carabids in entomopathogen transmission. Intraguild predation, where carabids compete with other natural enemies for resources, may alter feeding strategies and influence the efficiency of pathogen dispersal (Kamata, 2000). Furthermore, habitat fragmentation impacts carabid distribution and their effectiveness in biological control, with more diverse agricultural landscapes supporting stable populations and enhancing their potential as pathogen vectors (Tscharntke et al., 2007).

Persistence and ecological impact of entomopathogens in carabid beetles

Entomopathogenic fungal spores can remain viable in the soil for extended periods, exerting continuous infection pressure on pest populations. Carabid beetles play a role in the redistribution of these spores, transporting them across considerable distances during their nocturnal activity, which enhances their ecological spread within agroecosystems (Meyling & Hajek, 2009).

Although most entomopathogens have minimal impact on adult carabids, some research suggests that prolonged exposure to fungi such as *Beauveria bassiana* may lead to decreased mobility and survival rates in certain species. These effects could alter population dynamics and potentially reduce their effectiveness as biological control agents (Steenberg et al., 1995).

Agricultural Practices and Their Influence on Carabid Vector Efficiency

The application of pesticides can significantly impact the ability of carabid beetles to transport and spread entomopathogens. Recent studies indicate that certain insecticides not only reduce carabid diversity but may also disrupt the transmission of entomopathogenic fungi by altering beetle behavior (Menalled et al., 2007; Matuska-Łyżwa et al., 2024).

Effects of Conservation Practices on Carabid-Mediated Pathogen Dispersal

Agricultural practices aimed at biodiversity conservation, such as implementing ecological field margins and crop rotation, can enhance the efficiency of carabids as vectors of entomopathogens. Cividanes (2021) highlights that agricultural landscapes incorporating natural habitats help sustain stable carabid populations, ultimately improving their role in pathogen dissemination.

Integrating Carabid Beetles into Integrated Pest Management (IPM)

Research highlights that sustaining carabid beetle populations in agricultural landscapes requires targeted strategies, such as ecological field margins and habitat management (Jowett et al., 2022).

A crucial factor in successfully incorporating carabids into IPM is the establishment of suitable habitats, including field borders and ecological corridors, which can significantly enhance their biocontrol efficiency. Studies indicate that these conservation measures lead to increased carabid density and diversity, contributing to a reduction in pest populations (Ameixa & Kindlmann, 2008).

Adopting an IPM approach that integrates carabid beetles can minimize reliance on insecticides and help prevent the development of pesticide resistance in pest species. Proper habitat management has been shown to improve the effectiveness of these beetles in controlling agricultural pests, particularly in cereal and vegetable crops (Labrie et al., 2003).

Certain agricultural practices for crop production and pest management can support beneficial organisms in maize fields. Research shows that conserving crop residue and reducing tillage enhance the survival of ground-dwelling predators, such as ground beetles and spiders, which naturally control maize pests (Chiriloaie-Palade et al., 2024).

Farmer perception of carabid benefits is another key factor influencing the success of IPM. Research suggests that farmers who recognize the ecological role of these beetles are more likely to adopt conservation-friendly practices, such as reduced tillage and the implementation of ecological field margins (Jowett et al., 2022).

The effectiveness of carabids as biocontrol agents varies depending on agricultural practices. For instance, the application of broad-spectrum pesticides can negatively impact their populations, diminishing their pest suppression capabilities. Conversely, IPM strategies that prioritize habitat conservation can enhance agricultural sustainability by maintaining robust carabid communities (Legrand et al., 2011).

Incorporating carabid beetles into IPM presents a viable approach to reducing pesticide dependence while maintaining ecological balance in agroecosystems. Conservation efforts and farmer engagement in biodiversity-friendly practices can position carabids as a key component of sustainable pest control strategies (Warner et al., 2000).

Challenges and Future Perspectives

Gaps in Current Knowledge

Although numerous studies have highlighted the role of carabid beetles in biological control, significant knowledge gaps remain regarding the specific mechanisms through which they influence pest population dynamics. Macfadyen et al. (2019) emphasize that there is a lack of direct studies correlating carabid abundance with actual reductions in pest densities, making it challenging to integrate them into evidence-based Integrated Pest Management (IPM) programs. Additionally, the extent to which ecological factors affect their efficiency as biocontrol agents is not yet fully quantified (Holland & Luff, 2000).

Another underexplored aspect is the relationship between carabids and entomopathogens. While interactions between these organisms may play a crucial role in spreading entomopathogenic diseases, research on the specific transmission mechanisms and their impact on pest suppression remains limited (Jowett et al., 2022). Furthermore, the incomplete taxonomic classification of certain carabid species in agroecosystems complicates efforts to determine the precise role of individual species in pest regulation (Macfadyen et al., 2019).

Long-Term Ecological Impact and Future Research Directions

Shifts in agricultural practices, such as intensive monocropping and widespread pesticide application, have negatively affected carabid beetle abundance and diversity, diminishing their effectiveness as natural pest regulators. The conversion of natural habitats into intensively farmed land has led to the loss of essential ecological refuges needed for maintaining stable beetle populations (Holland & Luff, 2000). Furthermore, climate change is altering carabid distribution and predatory efficiency, highlighting the need for Integrated Pest Management (IPM) strategies to adapt to evolving environmental conditions (Macfadyen et al., 2019).

To optimize the role of carabids in IPM, future research should focus on agroecological approaches such as ecological field margins and crop diversification, which have the potential to enhance their pest control efficiency (Jowett et al., 2022). Additionally, developing precise monitoring techniques using advanced technologies, such as DNA analysis of carabid gut contents, could provide insights into prey composition and feeding dynamics (Macfadyen et al., 2019). Long-term studies are also essential to assess the sustainability of carabids as biocontrol agents across different agroecosystems (Holland & Luff, 2000).

CONCLUSIONS

This study examined the complex role of carabid beetles as vectors of entomopathogens, highlighting their ecological importance and potential applications in integrated pest management (IPM). The findings suggest that these beetles not only regulate pest populations through predation but also play a role in spreading entomopathogens, thereby enhancing biological control efficiency. However, their effectiveness is shaped by various factors, including habitat conditions, pesticide exposure, and environmental variables.

To successfully integrate carabids into IPM systems, it is essential to implement strategies that sustain their presence and activity in agricultural landscapes. Agroecological approaches such as preserving semi-natural habitats, minimizing chemical inputs, and fostering biodiversity can contribute to maintaining stable carabid populations and optimizing their role in pest suppression. Effective habitat management is particularly important in maximizing their ecological benefits while reducing dependence on conventional pest control methods.

Further research is needed to deepen the understanding of the interactions between carabids, pests, and entomopathogens. Investigating how these beetles contribute to pathogen transmission could support the development of more targeted and sustainable pest management strategies. Additionally, adapting biocontrol methods to climate change and specific agroecosystem conditions may improve the long-term viability of these approaches.

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