



Beetles (Insecta: Coleoptera) as Bioindicators for the Assessment of Environmental Pollution

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ABSTRACT

Environmental pollution poses a significant threat to global ecosystems and human health, creating an urgent need for effective biomonitoring tools. Coleoptera, representing the most diverse insect order, has emerged as a valuable taxon for pollution assessment due to its ecological versatility and sensitivity. This comprehensive review synthesizes current knowledge on the use of beetles as bioindicators for a spectrum of environmental pollutants, including heavy metals, pesticides, microplastics, and the cascading effects of climate change. Methods: We analyzed a wide range of studies employing beetles to monitor pollution levels across different ecosystems, examining evidence from accumulation patterns, behavioural and physiological changes, and community-level shifts. Research demonstrates that beetles effectively indicate pollution intensity through measurable responses. Ground beetles (Carabidae) show pollution intensity-dependent metal accumulation, while other families provide insights into emerging contaminants and climatic shifts. Their ecological traits, such as trophic position and habitat specificity, make them powerful sentinels. Beetles provide a reliable, cost-effective means for environmental assessment. However, the standardization of methods, a deeper understanding of long-term implications, and the integration of modern genetic tools are critical areas for future research. Their formal inclusion in monitoring frameworks offers a promising pathway for comprehensive environmental health evaluation.

Keywords: Bioindicator, Environmental pollution, Ecological assessment, Ecosystem health, Sentinel species. Jewel beetles, Insect biomarkers.

INTRODUCTION

Environmental contamination, from localized heavy metal deposition to global-scale climate change, is a defining challenge of the Anthropocene, affecting every terrestrial and aquatic ecosystem on Earth (Steffen *et al.*,

2015). The assessment and monitoring of these pollutants require sophisticated approaches that can detect both overt and subtle ecological changes, moving beyond mere chemical quantification to understanding biological impacts. In this context, bioindicators—species or groups of species whose function, population structure, or physiological status reflects the abiotic or biotic state of an environment—have become indispensable tools in environmental science (McGeoch, 1998; Gerhardt, 2002). These organisms provide invaluable insights into habitat quality, ecosystem health, and the impacts of anthropogenic activities, often revealing integrated effects that discrete chemical sampling alone cannot capture (Hodkinson & Jackson, 2005).

Among potential bioindicators, insects have proven particularly valuable due to their ecological dominance, high reproductive rates, and pronounced sensitivity to environmental changes (Samways *et al.*, 2010). Coleoptera, the insect order comprising beetles, represents approximately 400,000 described species—nearly a quarter of all known animal life (Stork, 2018). This remarkable diversity, coupled with their varied life history strategies and near-global distribution across virtually all non-marine

ecosystems, makes beetles exceptionally well-suited for environmental monitoring (Kotze *et al.*, 2011). Beetles occupy nearly every trophic level in food webs, functioning as herbivores, predators, scavengers, and parasitoids, thus providing multiple pathways for assessing pollutant impacts and transfer through ecosystems (Lövei & Sunderland, 1996).

The concept of using beetles as bioindicators is not new; carabid beetles, for instance, were recognized as potential indicators of human impact decades ago (Thiele, 1977). However, recent research has substantially expanded our understanding of the specific physiological, behavioural, and ecological mechanisms through which beetles reflect environmental conditions (Buteler *et al.*, 2023; Tózsér *et al.*, 2019). This review synthesizes the current state of knowledge on beetles as bioindicators, focusing on their applications in assessing heavy metal pollution, emerging contaminants like microplastics and pesticides, and the complex effects of climate change. We also critically examine the challenges and limitations associated with beetle bioindication and propose key future directions for research and application in a rapidly changing world.



Photo plate: Indian Jewel Beetle

Credit: Vishal jadhav

2. BEETLES AS BIOINDICATORS: ECOLOGICAL PRINCIPLES

The effectiveness of beetles as bioindicators stems from a combination of intrinsic ecological characteristics that make them particularly responsive to environmental changes. Understanding these underlying principles is crucial for their appropriate application and for the accurate interpretation of monitoring data.

2.1 Criteria for Effective Bioindicators

For any organism to serve as a reliable bioindicator, it must meet specific ecological and practical criteria. An ideal bioindicator should possess: a well-established taxonomy and ecology, a widespread and abundant distribution, specialized habitat or resource requirements, known sensitivity to environmental changes, and should be relatively easy to survey and cost-effective to monitor (McGeoch, 1998; Caro & O'Doherty, 1999). Furthermore, a robust bioindicator should provide an early warning of change and respond in a manner that is representative of the responses of other taxa or ecosystem processes (Noss, 1990). Many beetle families satisfy these criteria exceptionally well. Ground beetles (Carabidae), for example, are among the most studied invertebrate bioindicators, with their ecology and response to disturbance being well-documented across the Northern Hemisphere (Kotze *et al.*, 2011; Koivula, 2011).

The selection of appropriate beetle species or groups for monitoring programs is highly dependent on the specific assessment goals. Species with narrow ecological tolerances (stenotopic species) are excellent for monitoring specific environmental parameters or

habitat types, while community-level approaches that examine species richness, abundance, and functional trait composition may be more appropriate for assessing overall ecosystem health or the impact of broad-scale stressors like climate change (Rainio & Niemelä, 2003; Gerlach *et al.*, 2013). The use of beetles as bioindicators also benefits profoundly from their representation across various trophic levels, allowing for a direct assessment of pollutant transfer and biomagnification through food webs (Lövei & Sunderland, 1996).

2.2 Functional Traits as Indicators

Beyond simple presence/absence data, beetle functional traits provide sophisticated insights into environmental conditions. These traits include morphological characteristics (e.g., body size, wing morphology—macropterous vs. brachypterous), physiological tolerances, dietary preferences, and reproductive strategies (Brose, 2003). For example, large-bodied, flightless ground beetle species are often particularly sensitive to habitat fragmentation due to their limited dispersal capabilities, while species with specific moisture or temperature requirements can serve as precise indicators of microclimatic changes (Ulrich *et al.*, 2004).

Research by Qiu *et al.* (2023) demonstrated that less mobile, non-flying carnivorous beetle species are more likely to decline in warmer, drier climates, a finding with significant implications for natural pest control services in agricultural ecosystems. This trait-based approach allows researchers to move beyond taxonomy and predict how beetle communities—and the essential ecosystem functions they provide, such as decomposition and predation—might respond to ongoing environmental changes, including pollution and climate change (Gossner *et al.*, 2016).

Table 1: Key Beetle Families Used as Bioindicators and Their Applications

Beetle Family	Common Name	Primary Habitat	Pollution Applications	References
Carabidae	Ground beetles	Terrestrial, soil-dwelling	Heavy metal accumulation, habitat disturbance, pesticide impacts	(Kotze <i>et al.</i> , 2011)
Staphylinidae	Rove beetles	Various, often in decomposing matter	Indicators of soil health and organic pollution	(Bohac, 1999)
Scarabaeidae	Dung beetles	Terrestrial, coprophagous	Habitat fragmentation, ecosystem functioning, climate change	(Nichols <i>et al.</i> , 2008)
Cerambycidae	Longhorn beetles	Wood-boring	Forest health, climate change indicators	(Hanks, 1999)

Table 2: Metal Accumulation Patterns in Ground Beetles Across Pollution Intensities

Metal Type	Low Pollution Response	Extreme Pollution Response	Biological Significance	Reference
Cadmium (Cd)	Efficient excretion	Significant accumulation	Non-essential metal, high toxicity, long biological half-life	(Tózsér <i>et al.</i> , 2019)
Lead (Pb)	Moderate accumulation	Significant accumulation	Non-essential metal, neurotoxic, affects behaviour (Lagisz &	Laskowski, 2008)
Zinc (Zn)	Homeostatic regulation possible	Moderate accumulation	Essential metal, but toxic at high concentrations	(Maryanski <i>et al.</i> , 2002)
Copper (Cu)	Homeostatic regulation	Variable accumulation	Essential metal for enzymes, toxic at elevated levels	(Buteler <i>et al.</i> , 2015)

3. Beetles in Monitoring Heavy Metal Soil Pollution

Soil pollution by heavy metals represents a significant and persistent environmental challenge due to the toxicity, bioaccumulation potential, and longevity of these contaminants. Beetles, particularly ground beetles (Carabidae), have emerged as valuable indicators for assessing heavy metal contamination in terrestrial ecosystems.

3.1 Pollution Intensity-Dependent Accumulation

A seminal meta-analysis by Tózsér *et al.* (2019) examined the pollution intensity-dependent disposal hypothesis in ground beetles, analyzing data from multiple studies on five pollutants (Cd, Cu, Mn, Pb, and Zn) across a gradient of soil pollution intensity levels (low, moderate, high, and extreme). The research revealed a crucial pattern: decontamination and excretion mechanisms in ground beetles are effective in lowly or moderately polluted habitats, but become physiologically overwhelmed and ineffective under high or extreme pollution conditions. This leads to a significant accumulation of non-essential metals like cadmium (Cd) and lead (Pb) in beetle tissues in extremely polluted environments.

This finding helps explain previously inconsistent results in the literature regarding metal accumulation in invertebrates and underscores the critical importance of considering pollution intensity when interpreting bioindicator data. The study also highlighted the potential for entomoremediation—the use of insects to remove pollutants from ecosystems—under extreme contamination scenarios, although this application requires further investigation (Tózsér *et al.*, 2019).

3.2 Factors Influencing Metal Accumulation

Metal accumulation in beetles is not a uniform process; it varies significantly based on species-specific characteristics, trophic position, and life history traits. Carnivorous ground beetles typically accumulate lower concentrations of certain metals than herbivorous or omnivorous species due to their position higher in the food web and potentially more efficient excretory systems (Buteler *et al.*, 2015). However, this generalization has notable exceptions, emphasizing the need for species-level understanding.

4. BEETLES AS SENTINELS FOR EMERGING CONTAMINANTS

Beyond traditional heavy metal pollution, beetles are increasingly recognized as valuable indicators for emerging contaminants, including microplastics and pesticides, which pose growing and complex threats to ecosystem health.

4.1 Microplastic Contamination

The pervasive problem of **microplastic pollution** has recently been investigated using beetles and other insects. A pilot study by Meacci and Orsini (2022) demonstrated the potential of carabid beetles as indicators of microplastic contamination in soils, highlighting their role in transferring these synthetic contaminants through terrestrial food webs. Although research in this area is still nascent, beetles' widespread distribution, diverse feeding habits, and soil-dwelling life stages make them promising sentinels for microplastic pollution. Perhaps more strikingly, research on hymenopterans has revealed that microplastic contamination can enter insect populations through unexpected and direct

anthropogenic pathways. Buteler *et al.* (2023) documented that microfiber sheets used to control small hive beetles (*Aethina tumida*) in honeybee colonies resulted in significant microfiber contamination of bees and honey, creating a novel route for human exposure. This finding has profound implications for beetle monitoring, suggesting that pest management practices themselves can introduce novel contaminant pathways that bioindication programs must consider.

4.2 Pesticide Impacts

Beetles have long been used to assess the non-target impacts of pesticides in agricultural ecosystems. Changes in species composition, abundance, and functional group diversity within carabid and staphylinid communities provide valuable insights into the broader ecological effects of pesticide applications (Holland & Luff, 2000). For instance, declines in specific functional groups, such as large, carnivorous carabid beetles, can indicate ecosystem-level disruptions with cascading effects on natural pest control services, potentially leading to increased pest outbreaks (Kromp, 1999). The sensitivity of beetles to pesticides varies considerably among species, influenced by factors such as cuticle thickness, detoxification enzyme systems (e.g., cytochrome P450s), and habitat preferences (Desneux *et al.*, 2007). This variability enables researchers to develop sensitive indicator systems based on the ratio of sensitive to tolerant species, providing a more nuanced and ecologically relevant assessment of pesticide impacts beyond simple lethal dose measurements.

5. BEETLES AS INDICATORS OF CLIMATE CHANGE IMPACTS

Climate change represents a form of global environmental alteration with profound implications for species distributions, phenology, and ecosystem interactions. Beetles are increasingly valuable for monitoring and understanding these impacts due to their sensitivity to temperature and humidity changes, along with their well-documented distributions and ecologies.

5.1 Elevational Specialization and Thermal Tolerance

Research in tropical mountains has demonstrated that beetle species with narrow elevational ranges serve as excellent indicators of climate change impacts (da

Silva *et al.*, 2020). In the Atlantic Rainforest of Brazil, scientists identified several beetle species from families including Cerambycidae, Chrysomelidae, and Lampyridae that are particularly suitable for monitoring programs due to their restricted thermal tolerances and high abundance. These species, especially those with the narrowest elevational ranges, can provide early warnings of climate-induced distributional shifts and potential local extinctions. The methodology of systematic sampling across elevational gradients coupled with microclimate monitoring offers a replicable framework for identifying bioindicators in other mountainous regions globally. Since temperature decreases predictably with elevation (approximately 0.5–0.6°C per 100 meters in tropical mountains), these gradients serve as powerful natural laboratories for studying climate change effects and calibrating beetle responses (Colwell *et al.*, 2008).

5.2 Climate-Mediated Ecosystem Disruptions

Beetles also serve as indicators for indirect climate change impacts, such as pest outbreaks mediated by warming temperatures. The unprecedented mountain pine beetle (*Dendroctonus ponderosae*) outbreak in the forests of western North America illustrates this phenomenon perfectly (Raffa *et al.*, 2008). Warmer winter temperatures, particularly the reduction in the frequency of extremely cold days (< -40°C) that normally cause high beetle mortality, have enabled massive, landscape-scale infestations affecting millions of acres of pine forest (Bentz *et al.*, 2010). This climate-mediated outbreak has had cascading effects on essential ecosystem services, including water purification, carbon sequestration, and forest fire regimes, with subsequent implications for human health through increased water turbidity, air pollution from fires, and loss of recreational and economic opportunities (Kurz *et al.*, 2008). Monitoring bark beetle populations and their range expansions thus provides valuable insights into both the direct biological impacts of climate change and the associated, large-scale ecosystem disruptions.

6. CHALLENGES AND LIMITATIONS IN USING BEETLE BIOINDICATORS

Despite their considerable utility, the application of beetle bioindicators faces several challenges that must be addressed to enhance their reliability, standardization, and integration into policy.

6.1 Taxonomic and Methodological Constraints

The immense taxonomic complexity of Coleoptera presents a significant challenge for their use in widespread monitoring programs. While well-studied families like Carabidae have relatively stable taxonomy in temperate regions, many tropical beetle groups, which host the majority of the planet's diversity, remain poorly described, making species-level identification difficult or impossible for non-specialists (Stork, 2018). This limitation underscores the urgent need for increased taxonomic capacity and the development of complementary identification methods, such as DNA barcoding, to facilitate large-scale, beetle-based monitoring (Ji *et al.*, 2013).

Methodologically, many beetle studies rely on pitfall trapping, which measures activity density—a product of abundance and movement—rather than true population abundance. This metric is influenced by a multitude of factors such as vegetation structure, weather conditions, and species-specific behaviour, introducing potential biases that must be accounted for when comparing results across studies or establishing long-term monitoring programs (Woodcock, 2005). The standardization of sampling protocols, including trap design, spacing, and sampling duration, is essential for generating robust and comparable data.

6.2 Ecological Complexity and Interpretation Challenges

The ecological responses of beetles to environmental stressors are often complex and context-dependent, influenced by interacting factors such as habitat quality, landscape connectivity, biotic interactions, and the legacy of past disturbances (Tscharrntke *et al.*, 2012). For example, a study on North American ground beetles revealed that local habitat conditions, such as dense understory vegetation and fallen logs, can create microclimate refugia that mitigate the negative effects of warming, thereby reversing expected climate change impacts at a local scale (Qiu *et al.*, 2023). This complexity necessitates careful, multi-factorial study design and cautious interpretation of results.

Furthermore, the indicator potential of beetles—their ability to reliably reflect conditions for other taxonomic groups, particularly rare or threatened species—requires critical evaluation and validation (Caro, 2010). While beetles may reliably indicate

specific environmental parameters or their own responses, assuming they are perfect surrogates for overall biodiversity can be misleading. Complementing beetle data with information from other indicator groups (e.g., plants, birds, or soil microbes) provides a more comprehensive and resilient assessment of ecosystem health.

7. FUTURE DIRECTIONS AND CONCLUSION

Based on the current state of research, several promising and critical directions emerge for advancing the use of beetles as bioindicators of environmental pollution in the 21st century.

7.1 Integrative Approaches and Technological Innovations

Future environmental monitoring programs should adopt integrative, multi-taxa approaches that combine beetle data with information from other indicator taxa, direct physicochemical measurements, and data from remote sensing platforms (Turner, 2014). This multidimensional assessment provides a more complete picture of ecosystem health, helps validate the responses observed in beetle communities, and allows for the detection of synergistic effects between multiple stressors.

Additionally, emerging technologies offer transformative opportunities to enhance beetle-based monitoring. Environmental DNA (eDNA) metabarcoding of soil samples could allow for the detection of beetle species presence without physical collection, potentially increasing detection sensitivity and reducing sampling effort (Thomsen & Willerslev, 2015). Automated acoustic monitoring could be used to detect soniferous beetles, while remote sensing and LiDAR can provide detailed habitat structure data to better interpret beetle community patterns (Sueur *et al.*, 2008). The development of standardized protocols for beetle collection, preservation, identification, and data analysis represents another critical priority. Such standardization is a prerequisite for large-scale meta-analyses, long-term trend detection, and the integration of citizen science data into formal monitoring frameworks.

7.2 Conclusion

Beetles have firmly established their value as bioindicators for a wide spectrum of environmental

pollutants, from heavy metals and pesticides to microplastics and the pervasive effects of climate change. Their unparalleled diversity, well-studied ecology in many regions, and position across multiple trophic levels make them uniquely useful for assessing both specific contaminant exposures and overall ecosystem health. The pollution intensity-dependent accumulation patterns observed in ground beetles provide a nuanced framework for pollution assessment (Tózsér *et al.*, 2019), while species with narrow elevational and climatic distributions offer sensitive indicators of a warming world (da Silva *et al.*, 2020).

Despite persistent challenges related to taxonomy, methodology, and ecological interpretation, beetles remain powerful, cost-effective tools in the environmental assessor's toolkit. As we face increasingly complex pollution scenarios and accelerating climate change impacts, harnessing the full indicator potential of beetles through innovative, integrated, and standardized approaches will be essential for effective ecosystem monitoring, conservation, and the development of evidence-based environmental policy. Future research must focus on validating indicator relationships across biomes, understanding the mechanisms underlying their responses, and expanding beetle-based monitoring to the most biodiverse yet understudied regions of the planet.

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