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Multidimensional assessment of the potential of insects for sustainable agri-food systems

Karol B. Barragán-Fonseca[1,3], Esteban Ortiz[3], Juan David García[2], David Giron[4]

[1]LE STUDIUM Institute for Advanced Studies, 45000 Orléans, France
[2] Universidad Nacional de Colombia. Sede Bogotá. Faculty of Medicine. Bogotá, Colombia
[3] Universidad Nacional de Colombia. Sede Bogotá. Faculty of Veterinary Medicine and Animal Sciences. Bogotá, Colombia
[4] Institut de recherche sur la biologie de l'insecte (IRBI) UMR7261 Centre National de la Recherche Scientifique / Université de Tours. Tours, France

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Fellow: **Prof. Karol BARRAGÁN-FONSECA**
From Universidad Nacional de Colombia
Host laboratory in region Centre-Val de Loire: Insect Biology Research Institute (IRBI), University of Tours / CNRS
Host scientist: **Dr. David Giron**
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ABSTRACT

This study presents a multidimensional framework to evaluate the socio-ecological roles (SER) of insects in agrifood systems. Insects contribute to all four categories of ecosystem services: provisioning, regulating, supporting, and cultural, while also posing context-specific challenges. Using a transdisciplinary approach, we assessed 120 insect species across four dimensions: Productive Potential, Ecosystem Potential, Use, and Challenges. Unsupervised machine learning identified species clusters that provide useful insights for context-specific management strategies, including conservation, pest/vector control, wild gathering, and farming. While some species consistently perform well across dimensions, others require more localised or tailored approaches. Rather than offering definitive answers, this framework provides a starting point to support more adaptive and inclusive decision-making for sustainable insect use. It contributes to balancing productivity, biodiversity, and cultural relevance, while guiding future research and policy efforts aligned with agri-food system transformation and biodiversity goals.

1- Introduction

Insects play vital ecological roles essential for planetary survival. Their socio-ecological roles (SER), including pollination, nutrient cycling, pest control, and cultural functions, have been widely acknowledged (Barragán-Fonseca et al. 2024; Eilenberg and van Loon, 2018). Yet, despite their recognized importance, there is still a pressing need for researchers and stakeholders to jointly evaluate insect services through diverse management strategies and context-specific methodologies. Determining which insect species should be conserved, collected, or farmed, and which products should be derived from them, requires assessing their ecosystem services (ES) potential, considering ecological conditions, community needs, local regulations, and scales of use.

Insect-based solutions hold promise for societal transformation, particularly where insects have a long history of use (Borrello et al., 2016). However, not all insect species are suitable for all purposes, and their mismanagement can pose risks. A comprehensive, interdisciplinary approach is therefore required to evaluate the social, environmental, and economic sustainability of insect use. Mapping global insect usage and identifying "hotspots" may guide context-sensitive decisions around species selection, production methods, and use scales (Barragán-Fonseca et al. 2024). Such efforts should be grounded in questions like: Where are these insects located? What roles do they play? How are they obtained and used? And how can we best evaluate their potential to support ecosystems and human activities?

In response, we propose a qualitative evaluation method, developed by a transdisciplinary team in animal science, biology, and data science, that integrates three dimensions: Productive Potential (PP), Ecosystem Potential (EP), and Use (U). This framework assesses the insect's capacity for farming, its ecological contributions, and its human use across regions. We applied this approach to a global selection of insect species, enriched by literature review and direct research, and combined it with unsupervised machine learning to identify patterns and challenges.

The urgency of rethinking agrifood systems amid biodiversity loss and environmental pressures requires circular solutions. Insects, due to their diversity and their ability to provide all four categories of ecosystem services (provisioning, regulating, supporting, and cultural; Elizalde et al., 2020), offer a unique opportunity. By transcending anthropocentric ES frameworks and embracing the broader SER of insects, we aim to contribute to sustainable insect management strategies that integrate traditional knowledge and innovation. These strategies are essential for designing resilient agrifood systems aligned with the Sustainable Development Goals (SDGs) and local development needs (Dicke, 2018).

2- Methodological approach

To establish a robust framework for evaluating the SER of insects in agrifood systems, we developed a reflexive, transdisciplinary methodology that combines structured literature analysis, expert-based assessment, and data-driven classification. Our goal was to understand not only the benefits that insects provide through ES, but also the challenges they pose, and how they are managed in diverse geographical, cultural, and ecological contexts.

We conducted a comprehensive review of scientific literature addressing insect contributions to the four ES categories defined by the Millennium Ecosystem Assessment (MEA; MEA, 2005) alongside challenges such as pests, vectors, or invasive behaviour (Eilenberg and van Loon, 2018). The search was performed across Scopus, Web of Science, and Google Scholar using key terms related to "ecosystem services," "socio-ecological roles," and "insect management" within agrifood systems. Insights from wildlife and sustainable management were integrated to broaden the perspective.

We built a qualitative framework that evaluates insect species across four dimensions: Productive Potential (PP), Ecosystem Potential (EP), Use (U), and Challenges (C). We applied this framework to a sample of 120 insect species selected for their geographical distribution, functional diversity, and relevance across use and management contexts. Each species was scored using a structured questionnaire assessing over 100 variables, grouped into categories such as reproduction, nutrition, market potential, cultural roles, and ecological functions. Scores ranged from 0 (unfavourable) to 3 (highly favourable), based on expert consensus and supporting literature.

To explore patterns in species characteristics, we applied unsupervised machine learning techniques. A numerical matrix representing species-variable combinations was generated, and dimensionality was reduced using UMAP (Uniform Manifold Approximation and Projection) to visualise similarities. DBSCAN (Density-Based Spatial Clustering of Applications with Noise) was then used to identify meaningful clusters of species with shared traits across PP, EP, U, and C.

3- Results and discussion

3.1. Socio-ecological roles and strategies for insect management

Insects provide diverse and essential SER in agri-food systems. Their contributions include pollination, nutrient cycling, biological control, soil formation, and food provisioning, among many others. While traditionally framed as ES under the MEA, this study uses the broader concept of SER, which encompasses both benefits (services) and challenges (disservices), reflecting a more holistic view of insects' roles within ecosystems and societies. These SER can be divided into four categories: provisioning, regulating, supporting, and cultural roles.

Insect management strategies are necessary to optimise these roles while minimising ecological and social risks. Four main strategies were identified: (1) conservation management, to protect declining insect biodiversity; (2) pest and vector management, to mitigate negative impacts on crops and health; (3) wild insect gathering, to support traditional food systems and cultural practices; and (4) insect husbandry or farming, aimed at food production, bioconversion, or scientific use. Each strategy addresses different objectives but may overlap in practice and must be integrated contextually. Understanding which species are appropriate for each strategy requires evaluating their productive potential, ecological roles, cultural use, and associated risks.

3.2. Independent clustering analysis by dimension

3.2.1. Ecosystem potential

The analysis of EP revealed four main clusters and one group of species that did not clearly fit into any cluster. These categories reflect different types of ecological contributions and symbolic roles insects play within agri-food systems. One of the most distinct groups consisted exclusively of ants, particularly species like *Eciton burchellii* (army ant) and *Oecophylla smaragdina* (weaver ant). Though rarely highlighted in conventional ecosystem service assessments, these ants are crucial soil engineers and natural regulators (Mundim et al., 2009). Their capacity to structure soil, recycle nutrients, and control pests indicates a strong ecological role that should be better integrated into conservation and regenerative farming efforts.

A second group included species commonly used in insect farming, such as the black soldier fly (*Hermetia illucens*), the house cricket (*Acheta domesticus*), and the yellow mealworm (*Tenebrio molitor*). These insects, while mostly known for waste bioconversion and protein production (Pilco-Romero et al., 2023; Barragán-Fonseca et al., 2017), also contribute significantly to soil health, especially through the application of their frass as organic fertilizer.

Other clusters were formed by ecologically multifunctional and culturally important insects, including pollinators like *Apis mellifera* (honeybee), *Melipona eburnea* (stingless bee), and butterflies such as *Danaus plexippus* (monarch butterfly). These species are central to pollination, education, and cultural identity (Malagodi-Braga and Peixoto, 2004).

Additionally, large beetles like *Dynastes hercules* (Hercules beetle) and *Lucanus cervus* (stag beetle) were grouped for their symbolic presence and ecological functions, especially in nutrient cycling (Asano et al., 2023). A few species, such as the ant *Atta cephalotes* (leafcutter ant), stood apart from all clusters, illustrating both beneficial and harmful impacts in agroecosystems and reinforcing the need for species-specific strategies.

3.2.2. Productive potential

In terms of productive potential, the clustering showed a clear separation between highly farmable species and those more limited to niche or local use. The most promising group included the black soldier fly, house cricket, yellow mealworm, and the honeybee (*A. mellifera*), which are either domesticated or semi-domesticated. These species have traits that make them ideal for farming: rapid reproduction, efficient feed conversion, and established market pathways for products like food, animal feed, honey, or organic fertilizer (Ngonga et al., 2021; Moruzzo et al., 2021).

In contrast, species such as the monarch butterfly (*Danaus plexippus*), stag beetle (*Lucanus cervus*), and the parasitoid wasp *Aphidius colemani* showed lower scalability due to factors like specialized diets, low reproductive rates, or conservation status. Some, like the palm weevil (*Rhynchophorus palmarum*), are traditionally harvested and hold value in local food systems but require careful management to prevent overexploitation (Gerda et al., 2001). The analysis suggests that while some insects are well suited for industrial or commercial production, many others are better integrated into small-scale, locally rooted initiatives focused on education, ecological restoration, or cultural resilience.

3.2.3. Use

The analysis of how insect species are used in human societies produced six functional groups. The first included widely farmed insects such as the black soldier fly, house cricket, and yellow mealworm, all of which play key roles in food production, animal feed, and organic waste management. Their global success depends heavily on local regulations, cultural acceptance, and whether they are native to the production area. Another group included culturally significant species like the leafcutter ant, stingless bee, and palm weevil, which are commonly collected from the wild for food or artisanal uses (Mundim et al., 2009; Gerda et al., 2001). These insects support traditional knowledge and local economies, though their sustainable use depends on community-based management and conservation.

Other clusters included insects used in very specific contexts, such as the parasitoid wasp *A. colemani* for biological pest control or the green bottle fly *Lucilia sericata* in medical treatments. Iconic species like the monarch butterfly and stag beetle were grouped for their symbolic and educational roles, especially in biodiversity conservation. Underutilised regional species such as the long-horned grasshopper *Ruspolia differens* offer potential for nutrition and health but still face legal and social challenges. Lastly, a group composed of pest and vector species, including the mosquito *Aedes aegypti* and kissing bugs (*Triatoma* spp.), highlighted the dual roles insects can play as health threats in some regions and valuable research models in others (Carvalho et al., 2014). This complexity calls for adaptive strategies that consider both ecological and cultural dimensions.

3.2.4. Challenges

When looking at the challenges associated with insect use and management, four groups were identified. One included insects that pose high health risks, particularly disease vectors like the mosquito and kissing bugs, which are associated with diseases such as dengue or Chagas. Their use is restricted to research and control programs under strict biosafety conditions. Another cluster included species like the black soldier fly, yellow mealworm, and honeybee, which are widely used but face moderate risks, including potential allergenicity, invasive behaviour, or lack of clear regulations (Barragán-Fonseca, 2024).

A third group included species like the migratory locust (*Locusta migratoria*), the palm weevil, and grain pests from the genus *Sitophilus*, which are both valuable and problematic. Depending on the region, they may serve as food sources or be considered major agricultural pests. Their use must therefore be carefully managed through local biosecurity and education. Lastly, beetles like *Trypoxylus dichotomus* (Japanese rhinoceros beetle) were grouped for their vulnerability rather than risk. Their conservation status limits their use to non-extractive purposes such as education or ecotourism. These findings highlight the importance of designing management strategies that are both species-specific and context sensitive.

3.3. Implications for sustainable insect management

The multidimensional clustering analysis, framed through SER, offers a flexible tool to support insect management decisions across four strategies: conservation, pest/vector control, wild gathering, and farming. These strategies are not fixed recipes, they must be applied with attention to context, particularly species' native status, ecological function, cultural relevance, and regional priorities. What works in one setting may not in another, and responsible management depends on adapting to local realities.

Species such as the black soldier fly, house cricket, and yellow mealworm consistently performed well across productivity, ecosystem functions, and use, making them strong candidates for insect farming in many systems. Yet, when introduced outside their native range, they require strict biosecurity and regulatory oversight. Others, like the leafcutter ant and the palm weevil, which serve ecological or cultural roles but may also be pests, highlight the importance of context-sensitive wild gathering strategies rooted in local knowledge and supported by ecological monitoring. Likewise, the monarch butterfly and stag beetle align with conservation efforts, while the parasitoid wasp *A. colemani* and the green bottle fly illustrate the potential of regulated scientific use. High-risk species like the mosquito remain central to pest and vector control.

Rather than offering a definitive solution, this framework provides a structured starting point for integrated and interdisciplinary decision-making. By linking insect traits, roles, and risks to appropriate management strategies, it helps address sustainability challenges while opening space for dialogue among scientists, communities, policymakers, and other stakeholders. In doing so, it supports more inclusive, adaptive approaches to the sustainable use of insect biodiversity in agri-food systems.

4- Conclusion

This study demonstrates the value of a multidimensional, data-driven approach to assess insect species across productive, ecological, cultural, and risk dimensions. Using unsupervised machine learning, we identified clusters that inform context-sensitive management strategies, supporting conservation, control, wild gathering, and farming. However, optimizing the socio-ecological roles of insects requires more than classification. It demands integrated, interdisciplinary collaboration that bridges science, policy, and practice.

Our ongoing partnership with IRBI has laid the foundation for such collaboration, and this study offers a concrete platform to deepen and expand this work. By aligning scientific evidence with local knowledge and stakeholder perspectives, we can co-develop strategies that are adaptive, inclusive, and regionally grounded. Insects hold unique potential to contribute to biodiversity conservation, circular economies, and agri-food transformation, provided their use is guided by cooperation, innovation, and shared responsibility.

5- Perspectives of future collaborations with the host laboratory

The collaboration with the host laboratory (IRBI – Insect Biology Research Institute, University of Tours/CNRS) has been highly productive and enriching. It enabled the refinement of the Insectonomy framework and opened strong interdisciplinary dialogues.

Several follow-up initiatives are already in motion. Notably, promising collaborations have emerged with the Laboratoire d'Économie d'Orléans, led by Dr. Thaïs Nuñez, and the École Supérieure d'Art et de Design d'Orléans (ESAD Orléans), through Sylvia Fredriksson. These partnerships expand Insectonomy beyond science, integrating ecology, economics, and creative communication to reach broader audiences.

A key milestone was the successful international workshop "*Insects for Sustainable Agrifood Systems: Ecosystem Services and Management*", held on March 27–28, 2025 in Tours. The event brought together researchers and professionals from across France and beyond, reinforcing the network. As part of the Le Studium experience, the workshop also embraced the intersection of science and art through a collaboration with artist Umberto Diecinove. His installation *Hypersystms*, inspired by the complexity and interdependence of insect ecosystems, offered a powerful, sensory interpretation of the research themes. It fostered new dialogues between artistic expression and scientific exploration.

Future perspectives include student exchanges, co-supervision, joint publications, and comparative studies using the multidimensional framework developed during the project. The *Insectonomy.org* platform will also be improved as an open, collaborative tool to explore insect roles and management strategies.

Together, these efforts aim to build a lasting, transdisciplinary research network between

France and Colombia, advancing shared goals in sustainability, innovation, and inclusive knowledge creation.

6- Articles published in the framework of the fellowship

During the fellowship, we submitted the manuscript "*The role of insects in agri-food sustainability: taking advantage of ecosystem services to achieve integrated insect management*". We are currently working on another article titled "*Evaluating Insect Species for Sustainable Agrifood Systems: An Integrated Clustering Analysis*".

In addition, we published the following abstract: Barragán-Fonseca, K.B., Ortiz, J.E., García-Arteaga, J.D., and D. Giron. (2024). *Evaluating Contributions of Insect Species to Sustainable Agri-Food Systems: A Multidimensional Approach*. Abstract. Proceedings of Insects to Feed the World 2024, Singapore. Journal of Insects as Food and Feed, Volume 10, Issue 13. We also improved and updated the project website: *www.insectonomy.org*.

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