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From Components to Complexity via data standardisation: A Call for 'Systems Entomology'

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Abstract

Entomology encompasses a broad spectrum of disciplines, from taxonomy and ecology to molecular biology and applied environmental studies. Yet, despite its diversity, entomological research often remains fragmented, constrained by discipline-specific methods and separate datasets. This paper introduces Systems Entomology, a conceptual and methodological framework grounded in systems thinking and data integration. Systems Entomology seeks to understand insect-related phenomena through the web of interactions that link species, environments and processes, rather than by focusing on fragmented isolated components. Two main challenges were identified for developing this field: the data challenge, concerning the collection, standardisation and interoperability of entomological data; and the systems thinking challenge, concerning the analysis of interactions and emergent properties in complex ecological systems. A worked example, based on the trophic network of *Nebria germari*, demonstrates how standardised data, analysed through network theory, can reveal emergent patterns that contribute to understanding ecological and evolutionary processes. It is expected that Systems Entomology will enhance interdisciplinary collaboration, improve data-driven discovery and foster new ways of interpreting insect diversity in the context of global change.

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Keywords

biogeography, Darwin Core (DwC), emergent properties, entomology, FAIR Data, network analysis, Systems Thinking

Entomology in the era of data integration

Entomology is a scientific discipline structured into various research fields which represents one of the core disciplines within zoology. Traditionally, taxonomists address the adaptive pressures induced by environmental changes in space and time to highlight the presence of peculiar species tied to a particular region (endemic species) or ecosystem (characteristic species), by means of morphological descriptions or molecular data.

The ability of unambiguous identification of species has laid the groundwork for applied branches where entomology plays a key role. For instance, agricultural entomology investigates pest control strategies through the introduction of beneficial insects (Cock et al. 2016, Salas-Araiza et al. 2023) or analyses predator-prey relationships via gut-content studies to assess the role of natural enemies in ecosystem services (Lundgren et al. 2013). Similarly, insects have proven to be sensitive indicators for monitoring climate change, given their rapid responses at both local and global scales (Garnas 2018, Yang et al. 2021).

The above examples and many others actually deal with multiple dimensions of biological interaction. For example, entomology applied to agriculture studies prey-predator interactions or the interaction between food and gut microbiota, while research on global change focuses on the interaction between temperature and insects or between precipitations and insects, yet leaving more complex webs of interactions underexplored.

An example to illustrate this complexity is the ground beetle *Carterus calydonius* (P.Rossi, 1790) (Coleoptera, Carabidae), which preys on *Daucus carota* L. (wild carrot) seeds (Brandmayr and Talarico 2021), not for consumption, but to feed its larvae (i.e., parental care is the aim), while those seeds exist thanks to pollination by wild bees (Morrison et al. 2021). This reveals a non-obvious interaction between *Carterus* and wild bees, mediated by *Daucus*. Understanding such indirect links demands a broader analytical framework, one that treats insects and their interactors as components of interconnected systems. For example, questions may arise on how many pollinators contribute to *Carterus*' reproductive success? Do seeds not eaten by the larvae contribute to *Daucus* dispersal? Do they decompose and contribute to soil micro-fertilisation?

Carterus, *Daucus* and wild bees are the actors participating in a network of interactions, whose properties are not given by the sum of the individual properties of the associated species. They are part of a system that is actually made of further interactions, such as temperature affecting seed ripening or rain flooding *Carterus* nests.

Similar patterns emerge, even in the case where few limiting factors constrain adaptation and survival, as in high elevation ecosystems. The alpine carabid beetle *Nebria germari* Heer 1837, for example, is influenced not only directly by snow persistence and low temperature, but likely also by the cascading effects of climate change on its prey, Collembola (springtails) (Raso et al. 2014). Here again, the system's behaviour cannot be reduced to a single direct prey-predator interaction.

To uncover such multi-layered relationships, entomologists must adopt a shared data language and integrative frameworks. Standardised, interoperable and reusable data, aligned with the FAIR principles (Findable, Accessible, Interoperable and Reusable; https://www.go-fair.org), are essential for synthesising knowledge across subfields and generating new hypotheses.

A bibliometric analysis of publications (Aria and Cuccurullo 2017) containing the words "insects" and "interaction" (n = 925 titles since 1938) reveals a paradox: while the intellectual structure of the field (co-citation network) is rich and interconnected (Suppl. material 1), the collaboration network amongst researchers remains sparse and fragmented (Suppl. material 2). This discrepancy suggests that a lack of data standardisation and sharing hampers collaboration and synthesis in entomological research.

Organisations, such as Biodiversity Information Standards (TDWG), have developed frameworks like Darwin Core (DwC) to promote consistent data annotation and interoperability. DwC provides a structured vocabulary for describing datasets, enabling researchers to integrate information about taxonomy, occurrence, sampling protocols and interactions. Widespread adoption of such standards is a prerequisite for the emergence of a truly integrative, systems-oriented entomology.

The concept of Systems Entomology

From field and laboratory research, we collect ecological, molecular and biogeographical data that reflect different aspects of insect life. However, these data are rarely analysed in relation to one another. To reach broader syntheses, we must study the links amongst these domains through the lens of systems thinking.

The term "systems" is generally used in science to indicate the application of systems thinking to a particular field of scientific research (consider systems biology or systems ecology). Systems approaches seek to understand the behaviour of complex systems by examining the relationships amongst their components, often revealing emergent properties not apparent from studying each part independently (Bertalanffy 1968, Drack 2009, Tani et al. 2018).

In entomology, a systems approach involves integrating diverse data streams, ranging from insect behaviour and population dynamics to genetic traits and environmental variables, to gain a holistic understanding. Holistic in the sense that, when data interact, they show properties linked to the kind of the active interactions. These properties are the

emerging properties given by the collective behaviour of the system, much like the coordinated motion of a bee swarm (Hasenjager et al. 2022) or a starling flock (*Sturnus vulgaris* L. (Sturnidae); Cavagna et al. (2010)), where many individuals behave as a self-informed system.

Systems Entomology can thus be defined as a research field that studies the complex networks of interactions involving the diverse world of insects. It applies systems thinking to reveal how interconnected relationships amongst actors generate emergent properties and collective behaviour that remain hidden when interactions are studied in isolation.

Challenges for Systems Entomology

The Data Challenge

The application of Systems Entomology depends on the availability of standardised, interoperable data. The data challenge involves compiling baseline data from both unpublished sources and the scientific literature. In the latter case, it is essential to establish a protocol for identifying relevant topics in publications and the level of detail required for annotation.

Data explicitly describing relationships (whether one-to-one or one-to-many) are particularly valuable, as they provide direct evidence of biological interactions. Baseline datasets should be standardised using Darwin Core (DwC) terms, selecting the minimum necessary fields for meaningful annotation. Furthermore, appropriate ontologies and vocabularies must be referenced, especially where DwC allows free-text fields (e.g. dwc:habitat).

The ultimate repository for these standardised datasets should be GBIF (Global Biodiversity Information Facility), which supports open, FAIR-compliant data publication, allowing the data to be integrated with other datasets annotated in the same way by different researchers. Once integrated into GBIF, such datasets can be analysed collectively to identify relationships not explicitly annotated, such as species–habitat co-occurrence (captured by dwc:scientificName and dwc:habitat).

For these analyses, AI-driven methods will be instrumental in detecting latent patterns, inferring missing links and suggesting potential interactions, based on existing data.

The Systems Thinking Challenge

The systems thinking challenge concerns the construction and interpretation of interaction networks that combine explicit and implicit relationships amongst entities. By creating an “interaction of interactions” network, researchers can visualise how various biological processes connect across scales.

Quantifying the strength or importance of these connections requires identifying suitable network metrics (e.g., such as degree centrality and betweenness centrality), which

measure the flow of information and the functional roles of nodes (e.g., hubs and bridges).

Through such analyses, emergent properties, i.e., novel characteristics or types of behaviour that are not present, or not evident, in the individual entities of the system, can be detected. These are not simply the result of increasing the number of entities, but of greater complexity of the system, arising from enhanced number and diversity of interactions amongst its constituent elements.

A worked example: the diet of *Nebria germari*

A simple example of the Systems Entomology approach can be demonstrated using limited data on the diet of *Nebria germari*.

Phase 1: Dataset Construction

- The dataset was derived from two sources:

Nebria AT (Austria) — curated literature data (Raso et al. 2014).

Nebria IT (Italy) — unpublished field data (Panni, Foresta & Pizzolotto 2024).

- These data were standardised according to the Darwin Core Archive (DwC-A) star schema, in which a unique identifier (dwc:eventID) links records across multiple extension tables.

Event table (core): each eventID represents a predator–prey interaction (see Salim et al. (2022)). This is the unique identifier appearing in all the tables of the dataset.

Occurrence tables (extensions): record the abundance of predators and prey per eventID.

Resource relationship table (extension): Links entities A (predator) and B (prey) using the Relation Ontology “preys on” (https://oborel.github.io/).

- The resulting DwC-A dataset was created through the Integrated Publishing Toolkit (IPT) and uploaded to GBIF, thus adhering to FAIR principles and contributing to global biodiversity data on *Nebria germari*.

Phase 2: Building the Interaction Network

- Explicit relationships derived from literature and field data (those in resource relationship table) were used to build part of the network, representing predator–prey interactions combined with inferred ones, such as co-occurrence patterns amongst entities sharing the same eventID.

- Non-explicit relationships were inferred from occurrence and event tables. In particular, the relationship of predator and preys vs. habitat was used to build the rest of the network.

- The final network gave the (simplified) structure of the predator-prey-habitat entomological system (entosystem), where the metrics were based on the number of interactions, rather than on the number of species (dataset available at https://doi.org/10.15468/nzznpk). The entosystem after network analysis revealed key information flows, identified through network centrality measures. In particular, degree centrality was evaluated to show those nodes with the highest number of links to other nodes in the network. This metric gives the quality of node interconnectedness (Landherr et al. 2010) and, in our case, it shows the breadth of the predator trophic niche or mirrors ecosystem species richness within the network. Betweenness centrality was evaluated to show how many times a node bridges two other nodes along their shortest path (Matas et al. 2017). In our case, high betweenness centrality means how much a node mainly affects the interaction between two populations of the predator.

Phase 3: Interpretation

The entosystem (Fig. 1; Table 1) shows *Nebria germari* and the siliceous scree ecosystem (NATURA2000 code: 8110, NAT2k8110) as hubs within the interaction network. Despite being fundamentally different entities (an animal species and a habitat type), both occupy equivalent functional roles, an example of an emergent property arising from system-level interactions. Furthermore, it is worth noting that such property is given by the interaction between two entities whose reality is expressed at different biological scales. *Nebria germari* is an organism within which "biological" interactions take place, while the NAT2k8110 ecosystem is a portion of territory within which interactions between organisms and abiotic factors take place.

Table 1.

Network metrics for the *Nebria germari* system.

name	degree	betweenness
Nebria germari	36	35.1
8110 Siliceous scree	22	1.4
8240 Limestone pavements	14	8.5
Collembola	10	0
Pardosa Koch, 1847	8	0
Mitopus glacialis (Heer, 1845)	6	0
Lepidoptera	2	0
Oligochaeta	2	0
Stigmatophora	2	0
Opiliones	2	0
Araneae	2	0
Oribatidae	2	0

When populations from Austria and Italy are analysed separately, geography becomes an additional variable influencing network structure (Fig. 2; Table 2). The hub role of ecosystems remains stable, while Collembola emerge as bridges, connecting geographically distinct subsystems.

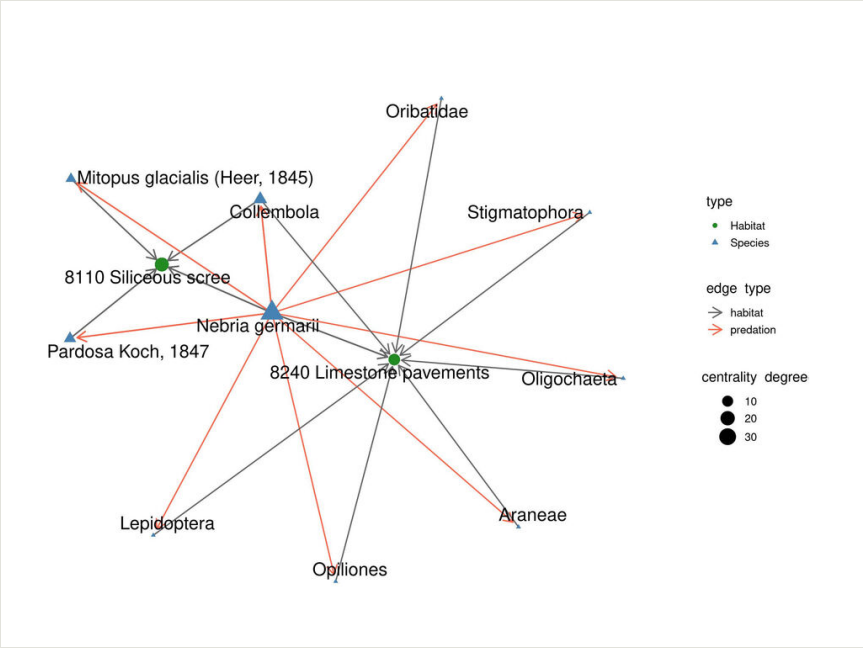

Figure 1.

Species-habitat and predator-prey system. Node diameter is proportional to centrality degree, while in this model no value was linked to arrow length and thickness.

This allows us to hypothesise that, as a general rule, the information flow characterising the structure of the entosystem is influenced by the diversity of prey captured by the predator (breadth of the trophic niche) and by the diversity of ecological factors to which the predator and prey have adapted (breadth of the ecological niche).

The new emergent property (the bridging role of Collembola) provides insight into the post-glacial recolonisation of alpine environments. *Nebria germari* belongs to the group of long-distance re-immigrants (Holdhaus 1954), species that recolonised the European Alps from peripheral glacial refugia (Holderegger and Thiel-Egenter 2009). Since alpine Collembola are strongly linked to the periglacial melt zone (Eisenbeis and Meyer 1999, Valle et al. 2025), their bridging role suggests that *Nebria germari*'s range expansion was both pushed by its dispersal ability and pulled by the retreat of its preferred prey.

Identifying such emergent properties highlights how Systems Entomology can reveal not only ecological relationships (prey and habitat preferences), but also evolutionary and biogeographical processes underlying species distributions.

Table 2.

Network metrics for the *Nebria germari* system with geographic partitioning.

name	degree	betweenness
Nebria germari AT	22	9.5
8110 Siliceous scree	22	9.5
Nebria germari IT	14	22.5
8240 Limestone pavements	14	22.5
Collembola	10	32
Pardosa Koch, 1847	8	0
Mitopus glacialis (Heer, 1845)	6	0
Lepidoptera	2	0
Oligochaeta	2	0
Stigmatophora	2	0
Opiliones	2	0
Araneae	2	0
Oribatidae	2	0

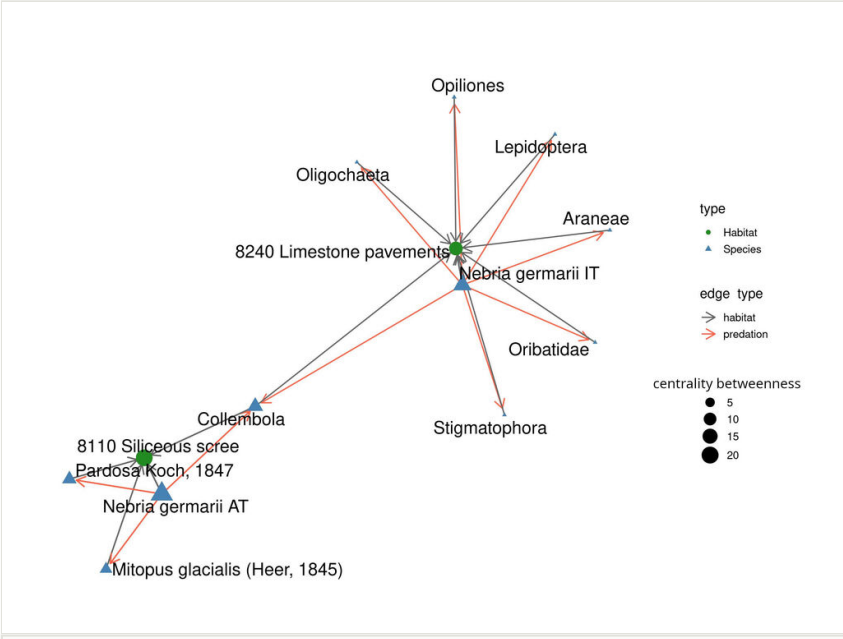

Figure 2.

Regional distinction of species-habitat and predator-prey system. Species-habitat and predator-prey system. Node diameter is proportional to centrality betweenness, while, in this model, no value was linked to arrow length and thickness.

Perspectives and Future Directions

The Systems Entomology framework provides a roadmap for integrating disparate entomological data into coherent, analysable systems. Its aim is the "coherent whole" of insects, where the unity (the wholeness) of the entomological system lies in the fact that insects possess a unique morphophysiological organisation; for example, respiration via tracheae, the haemolymph, hexapody and the exoskeleton. The morphophysiology of insects has allowed them to evolve a unique set of interactions with other organisms and abiotic factors, so that even if the entomological system is a system connected to other systems, yet it is a system with its own internal/intrinsic stability.

To include the entosystem into a super or meta-system (e.g. biology system) could indeed be practised, at least at the conceptual level, but at the expense of entomology understood as a system. This means that we would have to adopt a theoretical (epistemological) approach that simply considers the "whole" as a system; however, this was our starting point: to analyse the "whole" and see if there are components that confer a structure upon it. Such a structure does exist and its components are endowed with their own "wholeness," where the components are the entomological, ecological and biological systems, amongst others.

The first prerequisite for achieving this goal is data "FAIRification", ensuring a real open format and a true findability of data, as the extraction from research articles is not always possible or very laborious in terms of human and economic resources demand. If, on one side, it is understandable that many researchers follow a protective behaviour on the data they collected, on the other side, they run the risk of waiting that someone is asking for their data, while getting no request at all.

FAIR entomological data, structured according to a consistent, interoperable format that minimises ambiguity, is the second requisite to share data and to benefit from AI applications.

The primary need is to have data standardised under a single scheme that avoids the use of free-text fields, so as to reduce interpretive uncertainty and facilitating automatic data aggregation. The Darwin Core (DwC) standard is fundamental for encoding entomological data; however, it is essential to define which DwC terms are most relevant to the Systems Entomology approach, representing the minimal, yet sufficient information to describe system components and their interactions.

In Systems Entomology, the focus on data standardisation is particularly critical because AI-driven interaction mining can aggregate the vast amount of information still waiting to be (re)discovered from grey literature, datasets siloed in private or public organisations, citizen-science projects and unstandardised data, buried in supplementary materials of scientific papers. Standardisation also ensures that information for each component of the system remains separable, allowing researchers to later evaluate whether merging certain data (e.g., grouping species sharing the same prey) introduces circularity or redundancy into the system.

Systems Entomology also entails constructing a wide range of potential (either latent or hidden) interactions within an entosystem, extending beyond trophic relationships (i.e., who eats whom) to include “who or what affects whom or what” (see Ings et al. (2008)). The researcher’s expertise remains crucial at this stage: human oversight is needed to verify the consistency between DwC terms and real data, particularly when annotation is initially generated by AI-assisted tools. As illustrated in the worked example above, researchers can add interpretative depth by contextualising and validating the interactions highlighted through the Systems Entomology framework.

The *Nebria* example above was structured around three variables: predator, prey and ecosystem. One question to be addressed concerns the richness of variables within the entosystem, where a high number of variables implies a high number of nodes, resulting in a multivariate network.

The entosystem is a fuzzy set of interactions organised in the form of a network. The limiting "dimension" of the entosystem is not defined by a sharp boundary, but by a threshold; as one "moves away" from the entosystem, the interactions that characterise it diminish. In this sense, the fuzziness of the entosystem defines the breadth of the threshold that delimits the network of interactions.

From a functional perspective, the richness of nodes reaches a limit when isolated nodes appear, nodes that are merely co-present with others, but exhibit no interactions with the entosystem. Therefore, the multivariate network cannot be infinite; it is delimited by "zones" of lower interaction density.

By adopting standardised formats (DwC), open repositories (GBIF) and advanced analytical approaches (AI and network theory), researchers can uncover hidden relationships and emergent ecological patterns.

Future developments should focus on:

- expanding datasets to include multiple one-to-many species and environmental interactions;
- implementing AI-assisted data mining to infer unrecorded or implicit interactions;
- developing visualisation tools to represent and explore interaction networks;
- promoting interdisciplinary collaboration across molecular, ecological and computational entomology.

Insects are amongst the most diverse and ecologically significant organisms on Earth. Systems Entomology represents a shift in perspective, from studying insects as isolated entities to understanding them as integral parts of dynamic, interacting systems. By bridging data silos and disciplinary divides, this approach opens the way to new discoveries about biodiversity, adaptation and the functioning of ecosystems in a rapidly changing world.

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Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: Co-citation network doi

Authors: Roberto Pizzolotto
Data type: number of papers
Brief description: Bibliometric analysis of publications containing the words “insects” and “interaction” in titles.
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Suppl. material 2: Co-authoring network doi

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Data type: number of publications
Brief description: Bibliometric analysis of publications containing the words “insects” and “interaction” in titles.
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