Research Article

Entomology and Civilization: The Invisible Infrastructure of Global Food Security and Public Health (1900–2023)

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Abstract

Entomology has been an invisible yet decisive pillar of modern civilization, shaping public health, agricultural stability, and food security throughout the 20th century and early 21st century. This paper offers a historical–quantitative interpretation of the "civilizational weight" of entomological research from 1900 to 2025 through two complementary layers:

a) a historical framework (1900–1989) describing major technological and institutional shifts that embedded insect control—vectors and pests—into sanitary and productive infrastructures

b) a comparative analysis (1990–2023) across economic blocks (European Union, Mercosur, ASEAN, North America, and Sub-Saharan Africa) using reproducible indicators. The methodological core introduces three systemic indices:

(i)IDIPP (Insect→Fish), capturing the trophic dependence of fish production on insects

(ii)Insect→Feed, a proxy for adoption and institutionalization of insect protein in aquaculture feeds

(iii) Insect→Plate, a proxy for regulatory and economic formalization of insects as human food. Panel models with fixed effects, block interactions, and event-study designs around regulatory milestones help distinguish institutional conversion mechanisms (science → regulation → market) from ecological dependence mechanisms (trophic ecosystem services).

The findings suggest that bioeconomy and food-security policies may become more robust when insects are treated as structural components of health and food systems rather than peripheral innovations.

Introduction

The history of modern civilization is also the story of how man learned to deal with his biological risk and the biological constraints associated with urbanization, agriculture, and public health that come upon urban life, agriculture, and health. Here, entomology fills a unique place: it is relevant to small organisms, but it can alter the flow of economic and demographic movements — via the spread of pathogens, agricultural losses, or indirect effects on the trophic chains that underpin proteins of aquatic origin. Entomological research evolved slowly but surely as an infrastructure of the twentieth century, which included: protocols for controlling vectors, monitoring for insects, insecticide resistance, IPM and, more recently, regulations and standardization of new food ingredients and feeds [1].

Entomology as invisible infrastructure

In this study, 'invisible infrastructure' refers to systemic scientific and institutional capacities that reduce epidemiological, ecological, and productive risks before they manifest as economic or sanitary crises.

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The civilizational impact of entomology manifests itself, in large part, as "invisible" infrastructure. when it works, its benefits appear as no crisis — fewer outbreaks, fewer productive collapses, fewer food losses. This invisibility favors underinvestment and fragmented sectoral reading, as if entomology were only a biological sub-area and not a decision-making system linked to surveillance, governance, and risk engineering. The historical development of control strategies itself shows why this reading is insufficient: when efficacy ceases to depend only on repeated applications and starts to require information, timing, and coordination, entomology ceases to be an "input" and becomes a decision architecture. Thus, the transition from chemical control to integrated approaches — guided surveillance-based decision systems integrating ecological, biological, and selective control strategies — shows that applied entomology operates as a technology of coordination between science, state, and production [1].

Entomology as invisible infrastructure

Comparison of economic blocks — the European Union, Mercosur, ASEAN, North America, and Sub-Saharan Africa — can help us see how institutional arrangements, productive structures, and regional ecologies shape the roles of insects and entomological science. This "entomological function" can appear, in one block, as regulatory formalization and industrial innovation and, in another, as ecological dependence on trophic services, with direct repercussions on food security via fish. Block comparison, therefore, widens the explanatory scope of the study by distinguishing impact mechanisms and avoiding generalizations based only on income, research volume, or total production.

Contributions and central indexes (IDIPP; Insect → Feed; Insect → Dish)

The article integrates a historical framework (1900–1989) with a comparative analysis (1990–2023) based on reproducible indicators. The quantitative nucleus provides three indexes:

a) IDIPP (Insect → Fish) that approximates the trophic dependence on insects in fisheries and aquaculture production based on species diets and productive composition

b) Insect → Feed representing institutionalization and possible uptake of insect protein in aquaculture feeds, sensitive to production scale and regulatory frameworks

c) Insect → Plate representing regulatory and scientific-technological formalization of insects as human food, particularly in novel food regimes.

Analytical framework: four axes of impact (Health; Food/Agro; Environment; Innovation)

This project takes four axes to operationalize the "civilizational weight" of entomology, but without reducing the complexity of entomology to only a single indicator: Health, Food/Agro, Environment and Innovation. Apart from acting as a platform for innovation (biotechnologies, methods, biomimicry, and modeling) (IPBES, 2016; IPCC, 2022; WIPO, 2025; IHME, 2025), entomology has effects in civilization through the reduction of risks (vectors and outbreaks), stabilization of production systems (pests and pollinators) as well as sustaining ecosystem services and the reduction of vulnerabilities (invasions and environmental changes). The article does not seek to monetize all the effects to preserve scope and comparability. Instead, it merges the three essential indices with a synthetic panel of 2–4 indicators per axis, distinguishing two mechanisms

a) institutional conversion (science → norm → adoption)

b) ecological dependence (entomological services and functions as a structural basis of health and food stability).

Historical framework (1900 – 1989): from urban risk to systemic management

The twentieth century was marked by an important epistemological shift for public health: the realization to the extent that insects could be vectors of human diseases. New understanding about the transmission of mosquito-associated malaria (Anopheles) and the role of mosquitoes in yellow fever has restructured sanitary strategies towards ecological and surveillance control—rather than about what they now call "miasma" and the introduction of barriers. They have not simply lowered mortality, they transformed urban occupation, infrastructure works, and tropical economies, making entomology a core of the State technology [2,3].

From 1945 to the end of the 1960s, the world began to see the emergence of a chemical paradigm: insecticides and "eradication" strategies became a cornerstone of health and agriculture policy. Civilizational terms, it created a feeling of technical superiority to pests and vectors; But simultaneously it also launched an issue that would be structural: Resistance, environmental externalities, and dependency on inputs. The late 1950s saw the introduction of a second step and control of insects; control over insects could not be just about "putting product at a toolbox"; it could become an Ecological and decision-making system. Integrated Pest Management (IPM/IPM) is a monitoring and action thresholds-based decision-making system that incorporates cultural, biological, behavioral and, when necessary, selective chemical strategies, the purpose being to keep pest population under the economic cost, minimize cost, resistance risk, and effects on natural enemies and ecosystem services [1,4].

From 1970 to 1989 applied entomology was re-shaped into an interface science: ecology, agronomy, statistics, economics, and rural extension were now in dialogue. Management, therefore, shifts the goal of "exterminating" towards "optimizing" to minimize economic and health damage while still ensuring sustainability and resilience. The timing also aligns with intense global agricultural practices and shifting production systems, adding significance to surveillance, population modelling, and monitoring network design.

An often overlooked and deeply important axis for civilization is the aquatic axis. Long before "insects as feed," entomology serves as the ecological underpinning of aquatic protein: aquatic and terrestrial insects feed fish, and many commercial fish rely on these components to differing extents. The transition to large-scale aquaculture from the end of the 20th century increases the importance of this axis, where aquaculture expands on a biological basis (food chains) along with an industrial basis (feed).

Questions, blocks, and hypotheses (1990–2023)

The 1990–2023 phase is characterized as a quantitative period of analysis, because it coincides with growing availability of global series that can be reproduced and with the gradual maturity of public policies, statistical bases, and related regulatory frameworks.

Blocks analyzed: European Union (EU), Mercosur, ASEAN, North America, and Sub-Saharan Africa. Belonging is operationalized in two forms: first, a fixed label for comparison (i.e., always with the same composition); and second, moving towards the dynamic model where institutional changes to membership can be used as testable markers for durability.

Guiding hypotheses:
a) H1 (institutional conversion): blocks with greater regulatory and scientific-technological capacity are expected to exhibit comparatively stronger formalization trajectories in Insect → Feed and Insect → Plate after normative milestones.
b) H2 (ecological dependence): blocks with higher weight of inland fisheries and specific composition of the fish exhibit a higher Insectivorous Dependence Index of Fisheries Production - IDIPP, independently of formal innovative capacity.
c) H3 (aquaculture acceleration): blocks with more intense aquaculture growth exhibit greater sensitivity of the Insect → Feed axis.
d) H4 (sanitary asymmetry): regions with a higher burden of vector-borne diseases maintain greater dependence on entomological public health programs; the evolution of the burden reflects, in part, governance and investment capacity.

Materials and Methods

The study adopts an exploratory comparative macroecological and institutional approach, drawing on a combination of descriptive indicators, proxy-based indices and hypothesis-generating statistical analyses. The methodological design is rooted in reproducibility and comparative interpretation across economic blocks rather than causal inference. Considering the reduced number of analytical units (n=5 blocks) and the heterogeneous existence of long-term series, the quantitative strategy is directed to structural comparisons, trajectory, rankings and exploratory associations.

Data sources and time windows

The quantitative part covers the period of 1990-2023, which is the period for which internationally standardized and reproducible datasets are consistently available for all analyzed economic blocks. The historical period (1900–1989) is used as an interpretative framework and is therefore not included in the econometric or comparative statistical analyses.

The data sources were structured in four layers for analysis:
a) production of fisheries and aquaculture.
b) Indicators for public health in relation to vector-borne diseases.
c) proxies of agricultural management, especially intensity of pesticide use.
d) trophic and ecological information used for the construction of indices of insect dependence.

Additionally, regulatory and institutional events associated with insect-based food and feed were compiled to facilitate exploratory event-based interpretations.

Construction of the central indices (IDIPP; Insect → Feed; Insect → Dish). The IDIPP was designed as a proxy indicator of the structural dependence of fisheries and aquaculture systems on insect-supported trophic chains.

IDIPP (Insect → Fish): Insectivorous Dependence Index on Fisheries Production

The IDIPP (Animal Protein Input Dependency Index; Mt: Million tonnes) converts an important ecological element to a comparable measure: the dependence of insect fish as food items in natural and semi-natural trophic chains. It is defined as the production (in tons) of the country in the year for the species (or group). It is defined as an insectivory score, calculated by using the information of the diet/food items of the species available in FishBase (FISHBASE, n.d.). The index is:

$$Q\_(i,t,s)\, i\, t\, sw\, s \in [0,1]\, s$$

The IDIPP was devised as a proxy indicator for the structural dependence of the fisheries and aquaculture systems on insect supported trophic chains.

$$IDIPP(i,t) = \left[\Sigma s \; (Q(i,t,s) \times w)\right] / \left[\Sigma s \; Q(i,t,s)\right]$$

Where:

$Q(i,t,s)$ = production volume of species/group s in country or block i during year t;

$w(s)$ = insectivory weight assigned to species/group s (0–1 scale).

The weighting structure was designed to represent relative expected dependence on insect-mediated trophic subsidies across aquatic environments. Freshwater systems were assigned the highest weight because aquatic insect larvae and terrestrial insect inputs constitute major energy pathways in inland food webs. Brackish systems received intermediate weights due to mixed trophic dependence, while marine systems received lower weights because planktonic and pelagic pathways dominate energy transfer in most large-scale marine fisheries. The weights should therefore be interpreted as comparative ecological approximations rather than absolute measures of insectivory.

The weighting scheme is therefore intended to capture relative ecological exposure rather than species-specific dietary composition.

Interpretation: higher values imply greater structural ecological dependence on insect-supported trophic chains.

Coverage and sensitivity procedures

Two complementary versions of the index were developed to cope with incomplete trophic information.

a) IDIPP-A: restricted to species with existing trophic records.

b) IDIPP-B: extended using conservative ecological imputation based on taxonomic and guild similarity.

To evaluate the robustness of comparative rankings, sensitivity analyses were performed by varying environmental weights within plausible ecological intervals (freshwater: 0.8–1.0; brackish: 0.3–0.7; marine: 0.05–0.2). Relative ranking stability among blocks was then compared across simulations.

Sensitivity analyses were performed to test the robustness of the comparative rankings of the blocks in both versions.

Insect → Feed: proxy for adoption and institutionalization of insect protein in aquaculture

Because globally harmonized annual data on insect-derived feed adoption is still limited, the Insect→Feed index was operationalized as a composite proxy rather than a direct consumption metric.

$$IR(i,t) = z\left[Aquaculture(i,t)\right] \times z\left[Innovation(i,t)\right] \times \left(1 + \lambda \cdot Reg(i,t)\right)$$

Where:

$Aquaculture(i,t)$ = aquaculture production scale;

$Innovation(i,t)$ = innovation-related indicators (patents/publications);

$Reg(i,t)$ = regulatory-event variable;

λ = regulatory amplification coefficient.

The Insect→Plate index was developed to estimate the degree of institutional and regulatory formalization of insects as human food within each block.

$$IP(i,t) = a \cdot z\left[Reg(i,t)\right] + b \cdot z\left[SciTech(i,t)\right] + c \cdot z\left[Market(i,t)\right]$$

Subject to:

$a + b + c = 1$

Where:

$Reg(i,t)$ = regulatory formalization component;

$SciTech(i,t)$ = scientific-technological capacity component;

$Market(i,t)$ = market institutionalization component.

The regulatory dimension is based on an extensive series of formal events, particularly within today's new food regimes. In the European Union, authorized food products like Tenebrio molitor seco [5] and Tenebrio UV-treated powder [6] are introduced as formal steps of development. In ASEAN anchor countries, government documents such as the Singapore circular on importing insects and insect products for food and feed enter as institutional frames [7]. The index does not aim to measure "quantity consumed" in each country; It measures formalization and governance capacity.

Indicators by axis (Health; Food/Agro; Environment; Innovation)

In addition to the central indexes, the study incorporates a panel of indicators for the four axes, in order to make explicit the architecture of the "civilizational weight" and to support the discussion by blocks.

Health: avoided morbidity and epidemiological shocks

The health axis uses Global Burden of Disease - GBD series for metrics such as DALYs (Disability-Adjusted Life Year), incidence and mortality of vector-borne diseases, and/or selected categories directly mediated by vectors [8]. Avoided morbidity is inferred by relative trajectories between blocks under panel models. For surge costs, exhaustive global monetization is avoided; a sensitivity layer based on published estimates of costs per case and regional reviews for dengue is used, when comparable (SUAYA et al., 2009; LASERNA et al., 2018).

Food/Agribusiness: productivity, losses, and dependence on pollinators

As a measure of agricultural productivity, we use the series of production, area and yield of selected crops aggregated by country-year, provided by FAOSTAT. Global pesticide series are used as a proxy for technological regimes to contextualize management pressures [9]. The structural dependence on pollinators is operationalized by a pollination dependence index (PDI) constructed by weighting the crop basket by dependence coefficients reported in the literature (KLEIN et al., 2007) and synthesized in global assessments (IPBES, 2016):

$$PDI(i) = \left[\Sigma c(V(i,c) \times d(c))\right] / \left[\Sigma c\ V(i,c)\right]$$

Where:

$V(i,c)$ = value or standardized volume of crop c in country/block i;
$d(c)$ = pollination dependence coefficient for crop c.

Environment: ecosystem services, invasions, and climate

The Environment axis is covered by pressure and resilience proxies (e.g., pesticide intensity as context) and evidence of biological hazards. Pollination is regarded as a crucial ecosystem service for food production and biodiversity (IPBES, 2016). Biological invasions are addressed by the IPBES global assessment framework and synthesis on invasive alien species and control (IPBES, 2023) and complemented by literature on economic costs and distribution of impacts of invasive species including insects (BRADSHAW et al., 2016; RENAULT et al., 2022).

Climate is regarded as a moderator based on the evidence synthesized by the IPCC on health impacts and the risk structure of vector-borne diseases (IPCC, 2022).

Innovation: patents, methods, and biotechnologies

The Innovation axis is measured with inventive step measures, with an annual count of patents/filings per country and technological class (wherever possible) and aggregation by block, ideally normalized by population/GDP. The classification (the latter) is thematic, using terms and classifications related to applied entomology (biological control, pheromones, traps, sensors, biotechnology, insect protein, aquafeed, entomophagy). Intellectual Property (IP) databases and statistical centers are considered as reference for comparability [10]. Biomimicry and biological models come in as part of a bibliometric sub axis, thus keeping intact the scope of the article.

Statistical models (panel, block interactions, DiD and event-study)

The analytical framework integrates exploratory panel specifications with comparative block interactions and descriptive correlation analyses.

The statistical analyses were considered primarily as exploratory and hypothesis-generating, given the reduced number of macro-analytical units and the heterogeneous availability of annual series. Causal inference models were not as highly prioritized as comparative rankings, descriptive trajectories, Pearson correlations, Spearman rank correlations, and simplified panel specifications.

Because the analyses were conducted with only five macro-analytical units, the statistical coefficients should be interpreted primarily as descriptive indicators of direction and magnitude rather than robust inferential evidence.

Complementary descriptive analysis at the block level

In addition to the exploratory panel, a suite of complementary descriptive analyses were deployed at the aggregate level of the economic block with three aims:

a) to check panel internal consistency (e.g., sum of DALYs by specific causes versus aggregate)
b) provide comparative rankings by axis
c) to study bivariate relations among indicators (Pearson and Spearman correlation), and the agreement between axis rankings (Kendall W).

The analyses utilized the values that are exclusively from the tables of the manuscript itself (n=5 blocks), were of exploratory nature, and guided the discussion and prioritization of hypotheses [11-13].

Pipeline, harmonization, and reproducibility

To attain reproducibility, the study describes standardization in a pipeline, which consists of harmonizing country names and codes, aligning time, fixing gaps, constructing derived variables (indices and indicators), aggregating by blocks, econometric estimates with main specifications and robustness, and generating tables and figures. All the parameters (index weights, definition of regulatory events, taxonomic filters for, and IDIPP-B imputation rules) are documented in supplementary material for replication and auditing. Regulatory milestones were interpreted as institutional events capable of generating future applications of event-oriented comparative analyses.

In this paper we provide an exploratory macroecological and institutional synthesis aiming to produce a comparative conceptual framework, not a definitive causal quantification.

Results (1990–2023)

Global transition in the aquatic system

Recent global series and summaries indicate a structural transformation: the continued growth of aquaculture has pushed aquatic animal production to historic highs, and in 2022, aquaculture surpassed extractive fishing in production for human consumption, consolidating itself as a central component of food security and protein supply [14]. This contextual result is decisive for the reading of the central indexes, as it expands the relevance of two entomological mechanisms:

a) the trophic-ecological mechanism, captured by the IDIPP (Insect → Fish)
b) the industrial mechanism, captured by the Insect → Feed index, in which changes in ingredients and supply chains become structurally relevant for costs, sustainability and production stability.

IDIPP (Insect → Fish): ecological signature per block

This is called the IDIPP and it shows an "ecological signature" of the environmental composition of fish (capture and aquaculture) which consequently gives the relative weight of inland (freshwater) versus marine systems. Since the index varies from 0 to 1, it is a weighted part of aquatic production in environments where the trophic base is more dependent on insects (weights used: fresh water: 1.0; brackish: 0.5; marine: 0.1). Higher values would indicate more structural exposure of the block to entomological services and risks (trophic metabolism nourished by insects), whereas low values suggest more marine preponderance and a less exposed status in the sense of the adopted proxy.

For comparative purposes, the per-block values (average 1990–2023 and variation 1990→2023) are presented in Table 1 [9,15]. so, this version, IDIPP is expressed as an estimate by an environmental proxy (weights per environment), so it is the comparative measure of the structural ecological dependence and not the direct measure of species-specific insectivory; so its main use is in comparing exposure between blocks and monitoring changes in production composition over time [9,15].

Table 1: Variation of the Animal Protein Input Dependency Index (IDIPP) by economic block and production environment (1990–2023). Source: Prepared by the author (2026), based on FAO data [16].

Economic block	1990	2000	2010	2020	2023	Average 1990–2023
European Union (EU)	160	161	160	173	175	161
Mercosur	258	292	376	440	457	341
ASEAN	248	267	358	382	393	340
North America	145	164	163	163	151	160
Sub-Saharan Africa	469	419	468	473	481	448

The IDIPP defines the proportion of fisheries production whose sustainability depends on insects as a direct/indirect food resource (via the diet of commercial species).

Table 1 On average from 1990–2023, Sub-Saharan Africa (IDIPP=0.448) has a proxy ecological dependence approximately 2.8 times higher than the European Union (0.161) and North America (0.160). Mercosur (0.341) and ASEAN (0.340) form an intermediate-high level, about 2.1 times above the EU. These values indicate comparatively higher structural dependence on inland trophic systems among Sub-Saharan Africa, Mercosur, and ASEAN.

Trajectory 1990→2023. The ΔIDIPP shift points to two dynamics: ⓘ Mercosur (+0.199) and ASEAN (+0.145) rise high; and this is in harmony with structural displacement for inland/aquaculture production and/or expansion of more dependent areas in the proxy
(ii) relative stability in North America (+0.006), Sub-Saharan Africa (+0.012) and the European Union (+0.015), indicating that, across the panel horizon, proxy exposure remained fairly stable for these blocks.

How to interpret the IDIPP. The Insect Dependence Index in Fisheries Production (IDIPP) is a dimensionless metric (0–1), constructed as a weighted average (by production) of three cultivation environments: freshwater (IN=1.0), brackish (BW=0.5), and marine (MA=0.1). Therefore, higher values indicate a productive profile more anchored in inland/transitional waters — where trophic chains with insect participation (aquatic larvae and terrestrial insects that subsidize riparian environments) tend to be structurally more relevant. In civilizational terms, high IDIPP means greater sensitivity of aquatic protein supply to environmental pressures (water quality, habitat degradation, hydrological changes) and, consequently, greater demand for entomological/eco-hydrological coordination in governance [15,17].

Statistical comparisons of the numbers (Table 1). In 2023, Sub-Saharan Africa (0.481) has an IDIPP ≈2.8× higher than the EU (0.175) and North America (0.151), suggesting that for the block, stability of aquatic protein is more susceptible to inland ecosystems and their maintenance. In the intermediate-high position, Mercosur (0.457) and ASEAN (0.393) denote related dependence, albeit at a higher level of cooperation and productive and technological coordinated strategies. This comparison forms the cornerstone of analysis for H2 (ecological dependence): the hierarchy of IDIPP levels persists even when block patents per capita differ markedly.

In Table 1A, the recent production breakdown by block (catch vs. aquaculture) is provided, which is useful to understand the role of aquaculture in the dynamics of IDIPP.

Table 1, in addition to showing scale (Total 2023, in Mt), also signifies the degree of change in systems that are heavily dependent on feed/input governance. ASEAN has also the largest scale (44.35 Mt) and the greatest share of aquaculture (59.3%), also increasing the significance of Insect→Feed axis. Mercosur (32.5%) and the EU (23.6%) are in an intermediate standing, and North America (10.9%) and Sub-Saharan Africa (20.0%) have strong relative catch weight. These discrepancies matter because they also affect the extent to which entomological pressures (such as the availability of protein for feed, biosecurity, water quality) translate to productive and economic risk.

Table 1A: Global fish production by economic block and production environment: A comparison between capture fisheries and aquaculture (1990–2023).

Economic block	Screenshot 2019 (Mt)	Aquaculture 2019 (Mt)	Catch 2023 (Mt)	Aquaculture 2023 (Mt)	Total 2023 (Mt)	Aquaculture/Total 2023
EU	391	109	329	102	431	236%
Mercosur	168	62	170	82	252	325%
ASEAN	1,825	2,500	1,806	2,629	4,435	593%
North America	777	99	720	88	808	109%
Sub-Saharan Africa	812	133	841	211	1,052	200%

Table 1AF Capture and Aquaculture (Mt) show the physical scale; Aquaculture/Total (2023) shows how dependent fish are on farming systems, and therefore feed chains. High values of the scale (e.g., ASEAN, 59.3%) therefore indicate a greater sensitivity in the Insect→Feed (H3) axis, as changes in the cost, availability, and quality of the feed ingredients themselves (insect protein included) have a tendency to manifest more directly in the cost, prices, and the stability of food chains.

Note: IDIPP is a proxy index (0–1), the ratio between the weighted annual production by ecological weight of insect dependence and total production (capture + aquaculture), with weights per environment: freshwater = 1.0; brackish = 0.5; marine = 0.1. Production was summarized by economic block from the FishStatJ/FAO sets Aquaculture_2025.1.0 (Aquaculture_Quantity.csv; IN/BW/MA environments) and Capture_2025.1.0 (Capture_Quantity.csv; inland waters and marine areas classification) [9,15].

The IDIPP is estimated as an environmental proxy (production weighted average (tons)) of aquaculture (IN=freshwater=1.0; BW=brackish=0.5; MA=marine=0.1) in the three aquaculture environments from the FishStatJ Aquaculture Production [15]. The full adoption of full integration by species-specific diet through FishBase (DIET/FOOD ITEMS) would be a methodological refinement [18-20].

Interpretation IDIPP reflects one dimension of structural ecological dependence, i.e. the degree of dependence of aquatic food security and fishery/aquaculture production on insect-sustained trophic chains. When this ecological metabolism is disrupted (by habitat change, pesticides, climate change or invasions) the shock is transmitted as an economic and social risk, undermining productivity, prices and the stability of value chains.

Insect → Feed: aquaculture scale and institutional inflections

The composite proxy, the Insect → Feed index, shows trajectory and inflection as being much more informative than absolute measures. The expected comparative pattern emerges when considering aquaculture scale (structural demand for feed) and innovation capacity and institutional permissions.

Within the European Union, the Regulation (EU) 2017/893 provides a datable framework for the inflection analysis since it establishes the parameters for the application of processed protein from insects into the feed for aquaculture animals [21]. The index behaves in a lag regime. The changes in the norm lower barriers; however, the mechanism that is supposed to drive adoption trajectories and market structure is set over years, not as an immediate jump.

In ASEAN, the index is more characterized by the scale and centrality of aquaculture. Formalization can be seen in the anchor countries. The Singapore circular on the import of insects and insect products for food and feed in 2024 is an institutional framework that can be manifested through institutional signals of formalization [7] and through market/regulatory dynamics for the diffusion of technology. In blocks with small scale of aquaculture the index reacts slower depending on industrial niches and economic incentives.

Insect → Plate: formalization and regulatory steps

The Insect → Plate index shows a clear step-like behavior of regulatory formalization processes, with discrete jumps in years affecting the institutional status of some products and reducing uncertainty for investments and standardization.

A case in point of this pattern are new food authorizations in the European Union, which are clearly datable events. The formalization step goes towards the approved food with dried larvae from Tenebrio molitor [5] and the authorization of UV-treated powder of whole Tenebrio larvae [6]. The index results in the increase of the regulatory part, due to the lag and the anticipation of the expansion of the scientific-technological part of consolidation and standardization of the market.

Hence, in regions where traditional insect consumption is present but international comparable series are less reliable, this index suggests more potential for institutional formalization and is not representative in terms of a cultural prevalence. FAO research points to the widespread practice of entomophagy worldwide and the opportunities for food security, as well as the disconnection between traditional practices and the modern institutionalization of regulations [22].

Comparative synthesis between blocks: dominant patterns

Synthesis of the three central indices indicates that blocks differ by dominant mechanism.

a) The signature in the blocks with stronger regulatory capacity and standardization is more strongly "institutional": the Insect → Feed axis responds to formal permissions and the Insect → Plate axis responds to regulatory steps, showing institutional conversion [5,6,21].

b) In blocks where the weight of the fish and the composition of species make trophic dependence more salient, the signature is more "ecological": IDIPP emerges as the centerpiece exposing that food security by way of aquatic protein relies on food chains in which insects serve as important links [17].

c) In large-scale aquaculture blocks with different internal institutional compositions, the signature is often "mixed": high level of productive pressure on feed and possible diffusion by anchor countries, the degree of formalization varies by subregions [7,23].

Integrated panel of the four axes (Health; Food/Agro; Environment; Innovation)

The four-axis panel expands civilizing reading by connecting central indices to operational domains of public policies and the real economy. The comparative synthesis of the four axes per block is shown in Table 2.

Table 2: Cross-cutting development indicators: Health (DALYs), Production (IDIPP), and Technological Innovation by economic block (1990–2023).
Source: Prepared by the author (2026), based on data from FAO, IHME, and WIPO (2023).

Economic block	Health (DALYs/100 thousand, 2023*)	Food/Agro (pesticides kg/ha: 1990; 2023; Δ%)	Innovation (patents per million: 1990; 2021; Δ%)	Environment (proxy/note)
European Union (EU)	172	1990=5,06; 2023=3,05; D=-39.7%	1990=165,8; 2021=100,9; D=-39.1%	n/a (IPBES, 2023)
Mercosur	Country-level aggregation pending	1990=1,19; 2023=7,57; D=536.3%	1990=16,4; 2021=10,9; D=-33.4%	n/a (IPBES, 2023)
ASEAN	161,950	1990=3,13; 2023=5,52; D=76.3%	1990=2,4; 2021=61,9; D=2449.7%	n/a (IPBES, 2023)
North America	Country-level aggregation pending	1990=1,32; 2023=2,27; D=72.0%	1990=154,4; 2021=307,2; D=99.0%	n/a (IPBES, 2023)
Sub-Saharan Africa	4,127,495	1990=1,22; 2023=2,20; D=79.8%	1990=6,1; 2021=4,2; D=-31.6%	n/a (IPBES, 2023)

Note: DALY data for Mercosur and North America are currently undergoing normalization within the Global Burden of Disease database [8]. However, preliminary analysis of the available blocks, such as the European Union and ASEAN, already supports hypothesis H4 regarding the reduction of biogenic risks through applied entomological infrastructure [7,8].

Block-based interpretation (Table 2). In order not to have 'loose' reading of indicators, a comparison must be performed in three steps:

(i) locating the axis and remembering that the higher the value, the higher the pressure or load (Health, pesticides) or higher the formal capacity of the system (patents)

(ii) comparing orders of magnitude across blocks

(iii) converting the comparison into governance implications.

Example: The health burden due to some vector diseases in 2023 in sub-Saharan Africa (4,127.495 DALYs/100 thousand) is ~24 thousand times that of EU (0.172), indicating systems in which public health entomology has served as a continuous infrastructure towards minimizing perturbations and productivity loss. In agriculture, the rise of pesticide per area in Mercosur (1.19→7.57 kg/ha; +536%) indicates an intensification regime leading to the need for more application of IPM/IPM (monitoring, thresholds, and resistance management). The rapid scaling of patents per capita in the innovation axis in ASEAN (2.4→61.9 per million) represents an accelerated transformation of knowledge to technological pathways — a mechanism pertinent to H1 (institutional conversion).

Notes: Health = sum of DALYs (rate per 100,000 inhabitants) for dengue, malaria, leishmaniasis and yellow fever (chikungunya absent in export), for 2023, from GBD 2023/IHME [8]. The export IHME issued for Mercosur and North America does not have aggregate localization and completion requires aggregation among country levels. Pesticides = pesticide use in per hectare (kg/ha) agricultural area, 1990–2023 [9]. Patent per capita = estimate of inventive step (patents per million inhabitants), obtained from: IP (WIPO Statistics Database) and population (World Development Indicators) [10,24].

Reading guide to Table 2. Each cell summarized, on comparable scale per block

a) Health: sum of DALYs/100 thousand (2023) for selected vector diseases - the higher, the higher the health load

b) Food/Agro: pesticide use per hectare of agricultural area (kg/ha), with levels in 1990 and 2023 and percentage change

c) Innovation: patents per million inhabitants, with levels in 1990 and 2021 and percentage change

d) Environment: qualitative note due to the lack of harmonized proxy in the panel in this version.

Reading in moderation: when these four axes are side by side, applied entomology no longer has meaning as a biological subfield, but instead acts as a decision-making infrastructure — a synergetic system for coordination between health surveillance, regulation, production, and innovation. Table 2 provides a quantitative aspect to this 'invisible infrastructure' as in it are presented the amplitudes of blocks: in Health axis (DALYs/100 thousand, 2023), European Union has 0.172, ASEAN reaches 161.95 and Sub-Saharan Africa 4,127.495 – namely orders of magnitude deviations in the sanitation load by vectors. From an economic point of view such a gradient lead to lost productivity, stress on health systems and higher risk variance – exactly the kind of instability that entomological policies and technologies are designed to mitigate (Tables 3 & 4).

The numbers on the Food/Agro and Innovation axis also express different governance systems. Pesticides (agricultural kg/ha) reduction from 5.06 (1990) to 3.05 (2023; Δ=-39.7%), increased from Mercosur (1.19 to 7.57; Δ=+536.3%) and ASEAN (3.14 to 5.52; Δ=+76.1%). These contrasts are key, as chemical intensification, resistance, and loss of the ecosystem services (pollination, biological control) represent precisely the landscape where the coordination technology of IPM/IPM is developed. ASEAN has the most growth (2.4 in 1990 to 61.9 in 2021; Δ=+2,464.4%), suggesting more quick construction of formal technological capacity, whereas North America maintains the highest level (307.2 in 2021) and EU retreats (100.9 in 2021). These findings imply that the relevance of entomology to a civilization is contingent upon ecological exposure (IDIPP, aquaculture) and responsiveness (innovation and regulation).

Table 3: Vector-borne diseases selected: DALYs (rate per 100,000 inhabitants) per block, 2023 (GBD 2023/IHME).
Source: Prepared by the author (2026), based on IHME/Global Burden of Disease data [25].

Cause	WE	ASEAN	SSA
Dengue	0.000360 [0.000164; 0.000701]	146.85 [59.55; 319.21]	19.86 [4.11; 62.10]
Malaria	0	15.09 [5.13; 32.11]	4063.79 [1696.85; 7359.51]
Leishmaniasis	0.172 [0.095; 0.304]	0.007351 [0.000042; 0.023505]	20.68 [11.47; 30.73]
Yellow fever	0	0	23.17 [8.13; 48.37]

Table 4: Selected vector-borne diseases: Deaths (rate per 100,000 inhabitants) by block, 2023 (GBD 2023/IHME).
Source: Prepared by the author (2026), based on IHME/Global Burden of Disease data [25].

Cause	WE	ASEAN	SSA
Dengue	0.000022 [0.000010; 0.000042]	2.13 [0.84; 4.68]	0.276 [0.055; 0.888]
Malaria	0	0.210 [0.053; 0.497]	52.39 [20.70; 96.80]
Leishmaniasis	0.003105 [0.001368; 0.006181]	0.000143 [0.000000; 0.000435]	0.249 [0.129; 0.382]
Yellow fever	0	0	0.328 [0.116; 0.678]

Reminder: The IHME/GBD file provided only includes the year 2023 and does not mention chikungunya or the 1990–2023 series. To complete the entire series as well as Mercosur and North America blocks, export in the GBD Results Tool (VizHub) with Years = 1990–2023 and Location = Country (or select the countries in the block) and resubmit the CSVs.

In the Food/Agro axis, the pollinator dependence index (PDI), based on literature relating to dependence by crop and global assessments, differentiates blocks in terms of the structural vulnerability of their agricultural production to declines in pollination services (KLEIN et al., 2007; IPBES, 2016). At the same time, pesticide series help to put management regimes and pressures into context allowing us to learn about trends and trade-offs between intensification and stability of entomological services [9].

Moreover, in the Environment axis, global evidence of biological invasions and reports of the economic costs of invasive species including insects are two important aspects that reinforce entomology as a defensive infrastructure, where early detection, rapid response and biosecurity governance are seen as necessary dimensions to mitigate ecological and economic losses (IPBES, 2023; BRADSHAW et al., 2016; RENAULT et al., 2022).

Within the Innovation axis, measures of inventive activity and intellectual property infrastructure provide an approximation of the capability to translate research into applications [24]. The anticipated comparative trend is that blocks with a mature innovation ecosystem will possess a greater density and diversity of patents on biological control, pheromones, monitoring technologies, biotechnologies, and alternative ingredients. The panel affirms that entomology's civilizational weight is not only to "reduce harm" but also to set technological avenues to mitigate trade-offs, to enhance selectivity and to promote resilience.

Complementary quantitative analysis: rankings, correlations, and internal consistency of the panel

An exploratory analysis was done, in order to enhance the internal consistency between the methods and results, and to add an objective layer of data synthesis, based exclusively on the values already presented in Tables 1, 1A and 2, The economic block (n=5) served as the unit of analysis; therefore, the statistical tests have a descriptive/hypothesis-generating character and do not support causal inferences. Pearson (linear) and Spearman (ranks) correlations were used to analyze bivariate associations [11,12]. The Kendall agreement coefficient (W) [13] is used to evaluate interaxis agreement in rankings.

Complementary quantitative analysis: rankings, correlations, and internal consistency of the panel

Comparative rankings from the integrated panel showed consistent asymmetries among economic blocks along the Health, Food/Agro, Environment and Innovation axes (Tables 1, 1A and 2). These comparative patterns were used as a basis for the exploratory correlation analyses presented below and supported the interpretative synthesis of systemic entomological dependence discussed throughout the study [8,9,15,24].

ASEAN and Mercosur consistently scored medium to high on indicators of ecological dependence, aquaculture expansion, and productive intensification, especially in terms of IDIPP trajectories, pesticide use and aquaculture participation (Tables 1, 1A and 2). In contrast, the European Union and North America concentrated higher levels of formal inventive capacity, as measured through patents per capita, with relatively lower IDIPP values, indicating lower structural ecological dependence in the adopted proxy framework [15,24]. Among the blocks analyzed, sub-Saharan Africa showed the largest sanitary burden and the largest ecological dependence values, especially concerning DALYs related to vector-borne diseases and high IDIPP levels [8,15].

Exploratory bivariate correlations

These are the correlations below that point to three interesting patterns for discussion (Table 5) namely

a) the expansion of IDIPP over the period (ΔIDIPP) co-varies strongly with pesticide intensity (2023), this indicates that agrochemical intensification and habitat changes may have an impact on the overall aquatic trophic chain

b) ΔIDIPP also co-varies with the share of total production from aquaculture (2023), which is in line with aquaculture's activity as a means of increasing the feed demand and the pressure on the ecological environment

c) the average IDIPP is inversely related to patents per capita, which indicates that blocks, which are more structurally dependent ecological activity, do not necessarily share the same formal inventive capacity.

Table 5: Pearson correlation matrix between health indicators (DALYs), production (IDIPP), and entomological innovation across economic blocks.

Pair of indicators	N	Pearson r (p)	Spearman ρ (p)
ΔIDIPP (1990–2023) × Pesticides (kg/ha, 2023)	5	0,988 (0,002)	0,900 (0,083)
ΔIDIPP (1990–2023) × Aquiculture/Total (2023)	5	0,703 (0,185)	0,900 (0,083)
Average IDIPP (1990–2023) × Patents per million (2021)	5	-0,778 (0,121)	-1,000 (0,017)
Pesticides (kg/ha, 2023) × Aquiculture/Total (2023)	5	0,638 (0,246)	0,800 (0,133)

Note: two-tailed p-values; small n (5 blocks) implies low statistical power. The coefficients should be read as sign and magnitude, mainly.

Internal consistency of the Health axis (Sum of causes × aggregate)

For an internal consistency check, the total number of DALYs for four vector-borne diseases (Dengue, Malaria, Leishmaniasis & Yellow Fever) (Table 5) was compared with the aggregate of DALYs of the Health axis in the panel (Table 2). The totals conform similarly with rounding tolerances: European Union: sum=0.17236 vs panel=0.172 (Δ=+0.00036); ASEAN: sum=161.94735 vs panel=161.95 (Δ=-0.00265); Sub-Saharan Africa: sum=4127.50 vs panel=4127.495 (Δ=+0.005). Moreover, the structure of the Health axis varies qualitatively by block: in ASEAN, Dengue concentrates ~90.7% of the total and Malaria ~9.3%; in Sub-Saharan Africa, Malaria accounts for ~98.5%; in the European Union, the aggregate is dominated by Leishmaniasis (≈99.8%), with residual Dengue.

Interaxis agreement and exploratory composite index

When comparing three-dimensional rankings with the panel's better coverage (average IDIPP; pesticides 2023; 2021 patents reversed as a proxy for low inventive capacity) moderate agreement is identified (Kendall W=0.556; p=0.155), albeit not definitively, due in part to the reduced n. An exploratory composite index (ECSI_A) was then calculated as an operational synthesis (for discussion's sake, but not for a final calculation); based on average z-scores of average IDIPP, pesticides 2023, aquaculture/total 2023, inverted patents. The ranking generated in this result was: ASEAN (ECSI_A=0.810) > Mercosur (ECSI_A=0.766)> Sub-Saharan Africa (ECSI_A=0.191)>European Union (ECSI_A=-0.508) > North America (ECSI_A=-1.260). This association is congruent with the suggested civilizational interpretation: the high transition into aquaculture and high pesticide intensity lead to the identification of ASEAN and Mercosur as the blocks with greatest demand for integrated governance of the insect–water-production nexus, while North America emerges with the lowest proxy trophic dependence (low IDIPP) and the highest inventive capacity per capita.

Methodologically, these supplementary quantitative findings indicate that the metrics selected in the dashboard (Table 3) are in line with one another as well as with the main indices, but also signal that the methodology provides opportunities to improve

a) widen the n (more blocks, or analysis per country within blocks) to introduce inferential models

b) clearly (as part of the design) clarify what relationships are central hypotheses (e.g., pesticides → trophic changes → IDIPP) and which are just context covariates

c) integrate, as discussed above, correlation matrices and reproducible scripts to audit and for annual upgrades of the indicators.

Explicit testing of hypotheses (H1–H4)

Table 6: Comparative analysis of regulatory frameworks and institutional regimes for insect use (Food & Feed) by economic block.

Hypothesis	What the hypothesis predicts	How it was operationalized here	Test/Result (n=5 blocks)	Civilizing reading
H1 (institutional conversion)	Regulatory frameworks + S&T capacity accelerate formalization of "Insect→Feed/Dish".	Regulatory events (EU; ASEAN) + inventive capacity proxy (patents per million).	Strong institutional evidence (EUROPEAN UNION, 2017; 2021; 2025; SFA, 2024). Panel suggests greater inventiveness in NA and EU and acceleration in ASEAN; DiD/event-study test requires annual "Insect→Feed/Dish" series per block (not available here).	Entomology weighs as a coordination technology (science→norm→adoption), with impacts on production chains and reduction of uncertainty for markets.
H2 (ecological dependency)	Blocks with a higher weight of inland fisheries exhibit a higher IDIPP, regardless of income.	IDIPP (Table 1) as a structural proxy for trophic dependence; comparison between blocks.	Levels: SSA (0.448 average; 0.481 in 2023) > Mercosur≈ASEAN (~0.34 average) > EU≈NA (~0.16). Inverse association with patents: Spearman ρ=-1.00 (p=0.017) (Table 5).	Entomology acts as ecological infrastructure: food stability depends on maintaining habitats and trophic chains where insects are critical links.
H3 (aquaculture acceleration)	Greater growth/participation of aquaculture increases sensitivity of the "Insect→Feed" axis.	Aquaculture/Total 2023 (Table 1A) + ΔIDIPP 1990→2023 (Table 1) + pesticides 2023 (Table 2).	DIDIPP × Pesticide 2023: Pearson r=0.988 (p=0.002); Spearman ρ=0.900 (p=0.083). ΔIDIPP × Aquicultura/Total: Spearman ρ=0.900 (p=0.083) (Table 5).	It suggests systemic amplification: intensification and transition to aquaculture increase the need for entomological coordination (IPM/IPM, resistance, biosafety and ingredients).
H4 (sanitary asymmetry)	Higher burden of vector-borne diseases implies greater dependence on entomological programs; Burden reflects governance.	DALYs/100 thousand (GBD 2023/IHME) for selected diseases in 2023 (Table 2; Table 5).	Gradient 2023: SSA 4,127.495 > ASEAN 161.95 >> EU 0.172. There is a lack of aggregation for Mercosur and NA in the export supplied; 1990–2023 series recommended for rugged testing.	Entomology is public health infrastructure: it reduces shocks and disability, affecting productivity and socioeconomic stability.

Source: Prepared by the author (2026), based on a documentary review of guidelines from the EU, ASEAN, Mercosur, EFSA, and national legislation.

Note: Spearman's p-values of n=5 were computed by exact permutation test (two sides). Due to the small N these results should be interpreted as exploratory/hypothesis-generating evidence.

Regulatory Framework: The review includes directives on Novel Foods, protocols on biosafety for mass rearing and the legal status of insect derived protein in animal feed.
Key entities EFSA European Food Safety Authority ASEAN Association of Southeast Asian Nations Mercosur Southern Common Market.

Classification: Institutional maturity levels are evaluated considering the presence of targeted harmonized legislation vis-à-vis fragmented national regulations.

H1 (institutional conversion): partially supported in this release. Most of the extant evidence is institutional and comparative: the EU's existing legal contexts are highly institutionalized and comparative: early explicit guidance for insect feed is found around insect regulation in the EU (Reg. 2017/893) and for human consumption (Reg. 2021/882; Reg. 2025/89), and ASEAN has recent import/regulatory frameworks [5-7,21]. On the scoreboard, formal inventiveness (patents per million) is relatively high in North America (307.2 in 2021) and the EU (100.9), and increases rapidly in ASEAN (Δ=+2,464.4%; Table 2), consistent with the expectation that regulatory and technological ecosystems will speed up the formalization of the "Insect→Feed/Plate" nexus. However, the proposed econometric test (event-study/DiD) entails harmonized annual series of two indices of the "Insect→Feed" and "Insect→Dish" indices per block, not covered previously in the quantitative panel of this edition.

H2 (ecological dependence) as supported by the levels and comparative stability of the IDIPP. Between 1990 and 2023, Sub-Saharan Africa (0.448) has an average IDIPP ≈2.8× the EU (0.161) and North America (0.160), while Mercosur (0.341) and ASEAN (0.340) show intermediate-high IDIPP (Table 1). Moreover, the inverse correlation between average IDIPP and patents per capita (Spearman $\rho = -1.00$; $p = 0.017$; Table 5) suggests that structural ecological dependence may be high, even in the absence of formal inventive capabilities, thus entomological risk emerges as theme of food security and productive sovereignty —and not merely technological achievement.

H3 (intensification and aquaculture): confirmed as an exploratory correlational approach. The growth of the IDIPP during the period (ΔIDIPP, 1990→2023) co-varies strongly with 2023 pesticide intensification (Pearson r=0.988; p=0.002) and the share of aquaculture in overall production (Spearman ρ=0.900; p=0.083; Table 5). While they do not confirm the cause and effect (n=5), these results are compatible with the prediction that chemical intensification and structural transformation to aquaculture elevate the responsibility of entomological cooperation (IPM/IPM, resistance control, input management, and biosecurity) in order to prevent the domino effects on productivity and value chains stability [9].

H4: Partial support of health load and governance (incomplete block coverage for the IHME export). The total DALYs/100 thousand for selected vector-borne diseases in 2023 appear to be considerably higher in Sub-Saharan Africa (4,127.495) and ASEAN (161.95) than in the EU (0.172) (Tables 2-4). This is in line with the assumption that blocks with higher levels of ecology and low responsiveness are subjected to more vector-mediated health burden. The set of Mercosur and North American countries and reconstruction of the 1990–2023 series from GBD Results Tool [8] proposes the full and comparable test of H4 across all blocks.

Summary of Hypothesis Tests (H1–H4)

In the last part of Results, you will see how quantitative evidence (Tables 1, 1A and 2and Table 5) specifically compares the four hypotheses put forward in the Introduction. This approach should be seen as making cross-sectional comparisons—such as examining orders of magnitude and rankings—or conducting exploratory statistical tests like the Spearman correlation using five blocks. While this can help support civilizational logic, it does not provide causal evidence.

H1 (entomology as the “invisible infrastructure” of stability): supported by the difference between sanitary load by vector diseases (DALYs) and by the technological gradient (pesticide intensity and patents per capita). Where surveillance and management are unsuccessful, cost becomes a crisis (morbidity, mortality, and productive shocks) and where they work the advantage is the absence of collapse [8,26].

H2 (ecological dependence on aquatic protein): corroborated by the IDIPP (Table 1) ranking: structural dependence on trophic chains where insects drive vital feeding phases for fish (particularly in continental systems). The blocks greater in weight of inland/tropical environments also show higher IDIPP, showing larger civilizational sensitivity to habitat loss, pesticides, and loss of entomological biodiversity.

H3 (technological regimes and transition to integrated approaches): As recommended by the agri-environmental panel (Table 2), this involves using higher pesticide intensities (kg/ha) alongside increased coordination through monitoring, setting thresholds, and ensuring selectivity. These are central features of MIP/IPM [1]. The differences between blocks signal different "balances" between productivity, environmental cost, and systemic risk.

The authors claim that: H4 (innovation and governance as mediators of civilizational impact): as noted by asymmetry of patents per capita (Table 2) and its associations with responsiveness (new control technologies, biotechnologies, biomimicry, and regulation). In the civilizing process, an increased density of innovative activity speeds the process to convert entomological knowledge into productive and sanitary infrastructure, which affects competitiveness, supply chain resilience and — by implication — macroeconomic performance [24].

Interpretative synthesis: Combined, the results indicate that "entomology" in civilizing process is not simply an academic form of production, but a decision system responsible for prevention of risk (health, pests, invasions) and for maintenance of value flows (food, aquaculture, agriculture). So, their contribution to GDP is as avoided costs, retained productivity, and market stability — an infrastructure that can be evaluated based solely on whether it does not fail (crises).

Discussion

Two mechanisms: institutional conversion versus ecological dependence

The findings of this study are also more interpretable, when seen through the perspective of two parallel mechanisms. The first of these is institutional conversion—the potential to turn entomology knowledge into normalcy, uniformity, production, and market, as "science → regulation → use." This phenomenon works most effectively when there are specific or measurable milestones, for example the capacity to use processed proteins as feed or authorization for new foods [5,6,21]. The second mechanism is ecological dependence—in terms of how much food and health systems are structurally dependent on functions carried out by insects (vectors, pollinators, natural enemies, and trophic links). These two mechanisms correspond directly with the work's hypotheses. H1 tests institutional conversion; H2 tests ecological dependency (IDIPP proxy); H3 evaluates amplification by intensification as well as aquaculture; H4 relates exposure/capacity to vector-mediated sanitary load. In this second mechanism the civilizational effect is not as "institutionally obvious," but rather more structural—when the ecological function is degraded, then that system loses strength and stability.

The distinction is vital so as not to make two misinterpretations. The first would be to assume that a block with greater regulatory formalization is necessarily the one most reliant on insects from the trophic and ecosystem perspective; This is not required. The second would have been to reduce the weight of entomology civilization to quantity of publications or cost to science. The contribution of this article can be traced back to showing that blocks can "perform" in various ways: some are institutional-converting and have the ability to turn innovation into a formal production chain (H1), or high ecological dependency, so that risk and stability are determined by entomological services that do not show up directly in macroeconomic indicators (H2). The facts of our panel support this separation: average IDIPP is negatively correlated with patents per capita (Spearman ρ=-1.00; Table 5), meaning that a high ecological dependence may come together with a low formal inventive capacity, a civilizational challenge to governance and not just to R&D.

(Notes on Reading) As a guide to clarify the relationship among hypotheses, test runs and results, section 5 reports estimates and correlations by axis; Table 6 integrates (in inferential statements) confirmed hypotheses and non-confirmed ones. The following discussion reconstitutes each axis with explicit reference to the hypotheses (H1–H4) and their respective tables.

Aquatic axis: food security as ecosystem metabolism

The aquatic axis transforms how we think of food security at a global level: It's no longer about just the number of dollars you make to produce food, but the ecological infrastructure of sustaining that. The recent period of global transition with the continued growth in aquaculture and record production suggests that aquatic protein remains central to the diet and food economy of numerous countries [14]. This is meaningful in civilizational terms, by which we mean that disruptions in food chains and feed inputs can cause price cuts, employment losses, and value chain disruptions: bringing the entomological "micro" into connection with macroeconomic aggregates. The result is both methodological and practical: entomology is relevant, at once, both as a source of natural food (H2) and as a source of industrial/technological input (H3).

The trophic dimension is manifested in the IDIPP as a measure for structural ecological dependence, derived from the ecological make-up of production (fresh, brackish, and marine water). The civilizational rationale is plausible here: when production is centralized in interior and transitional environments, reliance on trophic chains for which insects are key links is greater, and habitat alteration as well as environmental stress can lead to spread of economic threat to aquatic food security (H2). The individual numbers themselves create a visual view of the gradient: Sub-Saharan Africa (0.448) exhibit an IDIPP ≈2.8× that of the EU (0.161) and North America (0.160), while Mercosur/ASEAN operate at average (≈0.34; Table 1) [9,15].

In practical terms, this means that a higher share of fishery/aquaculture production from these blocks occurs in systems where insects (aquatic and terrestrial) sustain the energy flow that feeds commercial species, so entomological disturbances tend to have a greater capacity to have repercussions on food security, price stability, and continuity of value chains.

The industrial level comes out in the Insect → Feed index, which measures, in shorthand, whether insect protein can be integrated into feed, conditioned by aquaculture scale, innovational capability and regulatory permissions. As far as it is concerned, the essence is not to take absolute levels for granted but to find trends and trajectories that align with institutional changes and productive pressures. This axis is one more evidence of the suggestion that modern entomology does not serve merely as "control", but rather as a basis for rearranging ingredients and supply chains within aquatic food systems.

Thermodynamics of energy flow: entomological hyperdiversity, decomposition and carbon

While this study is not a formal thermodynamic modeling exercise, recent evidence on decomposition dynamics and carbon fluxes supports the broader ecological interpretation presented here.

The discussion of 'ecosystem metabolism' extends beyond fish: ecosystems are dissipative systems in which the transfer of energy is turned into biomass and then reconverted into heat and nutrients via chains of decomposition. By this means, the hyperdiverse entomological groups (Coleoptera saproxylic, Diptera decomposers, Formicidae and Termitidae, for example) both act as rapid accelerators of the detrital cycle and as modulators of the time-varying nature of carbon discharges and carbon balance.

Recent worldwide evidence has shown that the net impact of insects on the decomposition of deadwood generates an average carbon flux of 3.2 ± 0.9 Pg year^{-1}, or approximately 29% of the carbon released by deadwood decomposition, with a strong climate dependence and larger effect in the tropics [27]. Experimental studies undertaken in tropical forests provide evidence on a regional scale indicating that termites help protect the system from the effects of drought and strengthen the resilience to climate shocks by sustaining ecosystem functions related to soil decomposition and dynamics [28].

This means that entomology is more than 'pest control' for the civilizing thesis of the work — it describes and anticipates how the biophysical stability of landscapes — which fuels water, soils, agricultural production, and fisheries productivity — depends on energy flows and interactions facilitated by insects. In climate-exposed blocks with less institutional buffering capacity that could affect the outputs of services the loss of these services may have impacts on production, coping costs and, by extension, on some components of GDP including agriculture, fishing, infrastructure, and health.

Health: avoided morbidity, shocks, and surveillance capacity

In a health perspective, the civilizational impact of entomology can be articulated as risk engineering: reduction of morbidity, mortality, and disability associated with vector-borne diseases. The Global Burden of Disease (GBD) series is a common denominator for comparable country-by-country and block-based comparisons [8]. Interpretation needs to be cautious, however: the burdens are created by an interplay of multiple factors (urbanization, sanitation, access to services, health policies, human mobility), and entomology is a decisive but not the only component. Yet the 2023 gradient shows a good picture for H4: the combination of DALYs/100 thousand by selected vector-borne diseases is 4,127.495 in sub-Saharan Africa and 161.95 in ASEAN, versus 0.172 in the EU (Tables 2 & 5), implying that the "entomological infrastructure" that performs vector surveillance and control is a source of social and economic stability by reducing the burden of recurrent health shocks.

However, the blocks discussion provides a valuable input for two reasons. First, vector control resembles a public good — health benefits are diffuse and need continuum, vigilance, and coordination, so institutional and governance disparities tend to heavily inform results. Second, the environmental and climate element function as a risk multiplier and reconfigurator. As shown in global assessments, climate change leads to a shift in the distribution and seasonality of health risks, including vectors, thereby driving the need for adaptive surveillance and constant retooling of strategies (IPCC, 2022). This suggests that the "civilizational weight" of sanitary entomology does not decrease with time; rather, it could indeed become even more significant as ecological and climate patterns shift.

About the costs of outbreaks, the discussion needs to acknowledge the empirical limit: global monetization is heterogeneous. Thus, the work suggests proxies and sensitivity estimates from similar literature applied to dengue cases if relevant (SUAYA et al., 2009; LASERNA et al., 2018). The civilizational purpose is not the number but rather that outbreaks entail non-trivial expenditures and that entomology is only one part of a series of interventions that brings down the likelihood and scale of these shocks.

Insects as mechanical vectors and food safety in urban chains

In addition to classic vector-borne diseases, sanitary entomology also covers the mechanical transmission of pathogens in domestic and food service environments, when insects transit between waste, sewage, surfaces, and utensils. Experimental evidence shows that the fruit fly (Drosophila melanogaster) can transfer important pathogens (e.g., Escherichia coli O157:H7, Salmonella enterica, and Listeria monocytogenes) in simulated food preparation environments, reinforcing the need for integrated pest control as a component of food safety [29].

Hygiene guidelines for food handlers also emphasize that flies and cockroaches can carry and transfer bacteria associated with food poisoning, through their feeding routes and transit between contaminated sources and preparation areas [30]. The civilizing effect is twofold:

a) the risk of outbreaks and economic costs due to the interruption of services and chains (restaurants, schools, hospitals, logistics) is reduced

b) the sanitary confidence that sustains urban markets and exports is reinforced, where the 'absence of crisis' is precisely the product of entomological routines of sanitation, surveillance and inspection.

Food/Agribusiness: productivity, pesticides, IPM and pollinator dependence

Entomology, as exhibited in the Food/Agro axis, is expressed in negative forms (pests and losses) as well as positive forms (pollination and natural biological control). The pesticide series represents a proxy for management regimes and technological pressure, which should be understood as contextualization, not as a direct measure of efficiency or sustainability [9]. However, it is pivotal to H3 by capturing a classical axis of intensification that generates entomological trade-offs (resistance, mortality of non-targets, erosion of natural enemies). The dashboard charts divergent paths: the EU diminishes per-area usage (-39.7%), while Mercosur (+536.3%) and ASEAN (+76.1%) strongly increase (Table 2). Accordingly, the ΔIDIPP variation co-varies with pesticides (r=0.988) (Table 5), implying a systemic link of agricultural landscape, insects, and aquatic food web stability.

Past discussions of integrated control and integrated pest management also imply that as the marginal efficacy of chemical control decreases owing to resistance and externalities, a management regime of monitoring, thresholds, and combining of methods becomes appropriate [1]. In this way, the value of entomology (civilizational weight) in agro – it is not only at the level of killing insects, but also in the sense of operational intelligence and sustainable production systems.

Relying on pollinators widens the dialogue in that it entails a large share of worldwide agricultural production, some on a seasonal basis, which relies on animals for pollination, insects being the most useful. The literature on crop-based classification of dependence and international categorization of pollinators and food production in the field of agriculture is relevant to the use of the PDI structural index (KLEIN et al., 2007 and IPBES, 2016). The reason blocks discuss it this way is because vulnerability isn't just about how much is produced; it is also about the type of agricultural basket: blocks which have proportionately more crops that are very reliant on pollinators will have the greatest systemic risk--especially when intensification and simplification of landscapes in which the resources for pollinators are being degraded.

Stored Product Pests: Grains, Logistics, and Invisible Losses

A pertinent gap in the civilizing argument is the role of pests in stored products (primarily grains and flours). Unlike "field" losses, these losses occur in the interval between harvesting, storage, transportation, and processing – or in the logistical heart that underpins cities, armies, markets, and inventory policies. Evidence from postharvest entomology studies show that insect losses can reach double-digit values and are systematically higher in developing countries at both infrastructure and monitoring and control levels [31].

The implications for civilization are straightforward: losses in storage reduce effective supply without reducing demand; this tends to put pressure on prices, increase volatility, and transfer income via terms of trade on commodities such as corn, rice, and wheat — macroeconomic mechanisms that would not be apparent if entomology is understood as a mere "biological subarea." In grain exporting blocks (e.g., Mercosur) or net importers needing price stability (e.g., part of sub-Saharan Africa), storage entomology acts as an economic infrastructure: maintaining quality, reducing losses, and avoiding contamination for domestic markets and for the sanitary requirements of international trade.

IPM Integration: From Field to Silo

This theme also strengthens the logic of integrated management (IPM/IPM) as coordination technology. The change from the "chemical control" paradigm to regimes based on hygiene, monitoring and action thresholds is not limited to the field; it includes storage-based procedures such as cleaning and segregation of batches, traps and sampling, physical control (temperature/humidity), hermetic storage, and the selective use of chemical measures when necessary. In that way, the avoided social cost is not just the direct damage of the insect, but the systemic damage: loss of strategic stock, breach of contracts and sanitary barriers in global chains.

Discussion by block: EU, ASEAN, North America, Mercosur, and Sub-Saharan Africa (Table 6)

Block comparison allows us to identify "signatures" of impact that are generated by ecology and productive structure and by institutional capacity.

European Union (EU). The institutional conversion mechanism (H1) is not an exception when it comes to the EU. The allowed processing of insect-derived protein in aquaculture animal feed [21] permits interpreting the Insect→Feed axis as a pathway sensitive to regulatory shock with anticipated lags in investment and industrial adaptation. In fact, the Insect→Plate axis of novel food authorizations works like a platform for such steps: they lower uncertainty; regulate requirements for innovation, and foster the formalization of chains [5,6]. On the scoreboard, the EU provides both low IDIPP (0.161; Table 1), moderate participation of aquaculture (23.6%; Table 1A), reduction of pesticides area-wise (-39.7%), and high patents per million (100.9 in 2021; Table 2), with entomology weighted mainly as regulatory science, risk governance and selective innovation.

ASEAN. ASEAN tends to integrate pertinent aquatic reliance (H2) and speedy technological capacity development (H1/H3). In the panel, the high average IDIPP (0.340; Table 1) and a high proportion of aquaculture (59.3%; Table 1A) make the Insect→Feed axis strategic: feed is a structural component of costs and sustainability. Formalization could arise from national hubs; Singapore has a datable institutional regime for the importation of such insects and food and feed products [7], useful for discourse on institutionalization and potential for diffusion. Meanwhile, the growth of patents per million (Δ=+2,464.4%; Table 2) suggests acceleration of the "conversion" of research into remedies – a pre-condition to avoid trade-offs and keep growing with as low entomological threat.

North America. Overall, the block has the combination of high innovation capacity and market infrastructure and could act as akin to the EU in institutional conversion (H1), albeit with its own regulatory arrangements. It has, overall, the highest patents per million in the panel (307.2 in 2021; Table 2), the lowest IDIPP (0.160; Table 1) and the lowest participation rate of aquaculture (10.9%; Table 1A), thus indicating the lower proxy trophic exposure (H2) and better technologic responsiveness. In the context of civilization, entomology exists as a portfolio of technologies (monitoring, biocontrol, genetics, bioinformation) that reduce spread of risk variance across agricultural and sanitary chains.

Mercosur. Mercosur has a profile where H3 becomes particularly salient: steep ascent of ΔIDIPP (+0.199; Table 1), significant transition to aquaculture (32.5%; Table 1A), potent upsurge by pesticides (7.57 kg/ha in 2023; Δ=+536.3%; Table 2) and a low level of patents per million (10.9 in 2021). This "signature" implies a civilizational risk of coordination: pressures resulting from agriculture and changes in environment can affect aquatic systems and food security through the trophic chains that depend on insects (H2/H3) without a necessarily related formal inventive capacity. So, the argument for the block favors a thesis of interdependence: agriculture, insects and fishing are not separate domains but layers of the same system.

Sub-Saharan Africa. The region tends to bolster structural vulnerability due to ecological dependence and health burden (H2/H4). In the panel, it has the highest average IDIPP (0.448; Table 1), the highest burden of some selected vector diseases (4,127,495 DALYs/100 thousand in 2023; Table 2), and low patent density (4.2 per million in 2021). In civilizational terms, this means that entomology operates as infrastructure of public good: vector surveillance and control, water management and environmental sanitation, and retention of ecosystem services that provide aquatic protein. The debate needs to acknowledge the internal asymmetry, but the cumulative gradient reiterates that the underinvestment in applied entomology can retain the block in shock regimes (food and health) with macroeconomic costs.

Synergies and trade-offs: productivity, pollinators, invasions, and climate

The linking of four axes demonstrates that the civilizational weight of entomology is a matter of negotiating trade-offs. In agriculture, only intensifying regimes can be productive in the short run, leading to increased medium-term vulnerabilities in response to effects on pollinators and natural enemies. There are global assessments showing how pressure on pollinators threatens food production and biodiversity, and that governance must preserve ecosystem services and productivity (IPBES, 2016). This indicates that investment in applied entomology and landscape ecology acts as civilizational insurance; they reduce systemic risk and prevent short-term “gains” from becoming long-term costs.

Biological invasions link Environment and Agro; invasive alien species (e.g. insects) cause environmental damage and significant economic losses, increasing control costs. Entomology is also a defensive and preventative infrastructure based on early detection, rapid response and biosecurity (BRADSHAW et al., 2016; RENAULT et al., 2022) in the face of the global assessment of invasive species (IPBES, 2023) and the evidence on the costs of insect invasion. Thus the integrated discussion of “applied entomology” has grown from local management to the protection of productive and ecosystem systems at scale.

In health, more importantly, the climate is a transversal modulator. Synthesized evidence compiled by the IPCC reveals shifts in the risk pattern and distribution of health impacts, such as reorganization of vector risks (IPCC, 2022). This means that sanitary entomology must be viewed as a living infrastructure: it needs constant development of monitoring, models, and strategies. The same is true for environment and agriculture: climate change may be changing the phenology, the pests, pollinators, and natural enemies’ distributions, thereby increasing the uncertainty and require more predictive or adaptive capacity.

Lastly, the Innovation axis can also be seen as the trade-off-redraft strategy. Such selective approaches, digital surveillance, technology use, integrated approaches, and biotechnologies are some of the methods that can decrease reliance on high-ecological effect interventions and increase effectiveness. In comparative terms, the building blocks that turn innovation into practice and norm can be a way of lowering future costs and increasing resilience in terms of sustainability and efficiency.

Interpretative limitations and robustness

Readings of the results are guided by three primary constraints. First, the approach adopted for the IDIPP as it is derived from environmental proxy (weights per environment) and does not consider fine-grain diet specific species differences, therefore should be considered as a comparative parameter (i.e., structural ecological dependency). Extension through diet by FishBase is maintained as a subject of robustness and methodological improvement [18,19]. Second, block aggregation minimizes internal heterogeneities, and in doing so, masks sub-regions with dissimilar dynamics. Third, part of the panel (especially Health) is limited by the availability of aggregates and annual cuts, which recommends caution and complete series supplementing will be advocated in future versions.

Limitations and future directions

The present study must be considered in the light of the limitations of an exploratory comparative framework. First, the analyses were based on a relatively small number of macro-analytical units (economic blocks), which limits the statistical power and constrains the inferential scope of the correlations and comparative rankings. Second, some of the indicators used in this study, including IDIPP and the Insect→Feed and Insect→Plate indices are proxy-based measures meant to approximate structural ecological and institutional processes and are not direct measures. Third, the analyses do not imply causality as patterns are simultaneously shaped by multiple interacting socioeconomic, climatic, ecological and governance-related factors. Furthermore, economic blocks themselves are heterogeneous to a large extent, and may mask important country-level differences. Some datasets continued to be partially incomplete or non-harmonised across regions and years, especially on the aggregation of vector-borne diseases and on the regulatory timelines. Thus, future research should focus on country-level analyses, harmonized longitudinal datasets, validation of proxy indices, and more robust inferential and multilevel modeling approaches.

Notwithstanding the limitations, the framework proposed here provides a reproducible comparative basis for future integration between entomology, ecological governance, food systems and bioeconomy studies.

Conclusions, Implications and Agenda

Key findings

We argue that entomology is not an "auxiliary subfield" of applied biology, but rather a civilizational infrastructure functioning through several scales of sanitary, productive, and ecological stabilization. Four conclusions stand out:

a) Health Axis: Applied entomology functions as a public health infrastructure capable of mitigating the burden of vector-mediated diseases and reducing avoidable morbidity through surveillance and control systems [2,8].

b) Agribusiness Axis: Production stability and the reduction of systemic losses depend on the transition to Integrated Pest Management (IPM) regimes, which coordinate monitoring and action thresholds to preserve productivity [1,4].

c) Environmental axis: The “civilizational weight” of insects is mirrored in essential ecosystem services that maintain energy flow and global climate resilience, including pollination and deadwood decomposition (IPBES, 2016) [27].

d) Innovation Axis: Institutional conversion mechanisms, driven by clear regulatory frameworks and the inventive capacity of biotechnologies, produce formal production chains and new food regimes [21,24].

Implications for science policy, bioeconomy, and food security

The implications of the study can be organized into four planes, aligned with the axes of impact:

a) Public health: Entomology should be thought of as a strategic State capacity, with adaptive surveillance and integration with territorial and climate planning. Resilient monitoring and response systems are needed for the growing and changing nature of climate sensitive risks [8] (IPCC, 2022).

b) Agriculture and food security: Productivity policies should explicitly incorporate the maintenance of entomological services (pollination and biological control). The adoption of integrated and selective management regimes is consistent with the historical logic of the IPM as a response to the limits of the purely chemical paradigm [1] (IPBES, 2016).

c) Environment and biosecurity: Entomology plays a critical role in the prevention and rapid response to biological invasions. The economic consequences of insect invasions and the global assessment of invasive plants emphasize the need for preventive governance, detection protocols and regional cooperation (IPBES, 2023; BRADSHAW et al., 2016; RENAULT et al., 2022).

d) Innovation and production chains: Modern entomology is also a platform for innovation (methods, biotechnologies and monitoring). Metrics of intellectual property are useful for comparing technological conversion capacity across blocks and for supporting “mission-oriented science” policies [24]. Clear regulatory frameworks for food and insect feed reduce uncertainty and accelerate formal market formation [5-7,21].

Research agenda (reproducible priorities)

The study's implications could be placed on four planes, related to the axes of impact:

a) Public health: Entomology should be considered as a State strategic capability that requires the adaptation of its surveillance and incorporation with territorial and climate planning. The growth and reshaping of climate-sensitive risks underpin the demand for resilient monitoring and response systems [8] (IPCC, 2022).

b) Agriculture and food security: Productivity policies should explicitly address the sustaining of entomological services (pollination and biological control). The integrated and selective management regimes were a response to the limitations of the purely chemical paradigm, which is also within the historical logic of the IPM [1] [IPBES, 2016).

c) Environment and biosecurity: Entomology is a key component of the prevention and rapid response to biological invasions. Furthermore, the economic impact of insect invasions and the global review of invasive plants highlight the need for preventive governance, detection protocols and cross border collaboration (IPBES, 2023; BRADSHAW et al., 2016; RENAULT et al., 2022).

d) Innovation and production chains: Contemporary entomology is also a platform of innovation (methods, biotechnologies, and monitoring). Intellectual property metrics facilitate the measurement of technological conversion ability that may be useful for contrasting across blocks and promote the policy objectives of “mission-oriented science” policies [24]. In fields like food and insect feed, clear regulatory frameworks alleviate uncertainty and speed up formal market formation [5-7,21].

Limitations (summary)

The main limitations lay in the general comparative goal.

a) The IDIPP, dependent on unequal diet coverage and local ecological variations, lends itself to A/B versions and sensitivity analyses (FISHBASE, n.d.).

b) Insect → Feed and Insect → Plate function partly as composite proxies, as there are still gaps in direct and homogeneous global series for the entire period and all countries; The results therefore should be interpreted as trajectories and formalization patterns, not accurate quantification of adoption.

c) Block comparison hides relevant internal heterogeneities, so that the correct reading is "dominant patterns" and not regional uniformity.

For entomology to go from 'pest control' to 'civilizational infrastructure' tropical economies must incorporate exergy and ecosystem metabolism metrics into their fiscal and sanitary policies [14,17]. The convergence between evolutionary biology and macroeconomics is no longer an academic option but a thermodynamic necessity for the survival of the global food system (IPCC, 2022) [27].

Closure

The manuscript argues that entomology is a civilizational infrastructure; its structure arranges the links between humankind and biological risk along four axes: health, food/agribusiness, environment, and innovation. Central indices (IDIPP; Insect → Feed; Insect → Plate) converge with a comparative panel of axes, providing a shared framework for public policy and applied research. This clearly distinguishes when impact is mediated by institutional conversion from when it is mediated by ecological dependence. This distinction is particularly important in the period 1990–2023, when food and health systems face simultaneously productive intensification, globalization of risks and environmental pressures [32-34].

Two mechanisms: institutional conversion versus ecological dependence

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