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Viewpoint

Escaping the Reductionistic Trap: A Systems-Based Approach to Environmental Risk Assessment

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Chemical regulation stands at a critical juncture. Decades of reliance on reductionist environmental risk assessment (ERA) frameworks have produced a paradox: increasingly sophisticated models that fail to predict real-world harms. Postmarket bans of neonicotinoids, widespread restrictions on glyphosate, and documented pollinator declines across multiple continents reveal a fundamental methodological failure embedded in how we evaluate chemical safety. This conceptual failure has been recognized in relation to EU pesticides[1] and chemicals.[2,3] Moreover, previous work[4,5] has pointed to the naive assumption in the current ERA paradigm that understanding individual chemical−ecosystem interactions in isolation, using abstract risk ratios and standardized scenarios, can provide adequate protection. On the contrary, by ignoring ecosystem interactions, cumulative stressors, and system-level thresholds, traditional approaches create an illusion of precision while systematically missing the complex cascading impacts that drive environmental harm. We argue that underlying these shortcomings is a fundamental cognitive bias that drives debate and action in the wrong and futile direction, that increased precision can be equated with accuracy. We call this the reductionist trap.

As Tukey famously stated,[6] it is "better to have an approximate answer to the right question than an exact answer to the wrong one."

Previous discussions have primarily advocated for systems thinking without providing operational frameworks for implementation. What remains needed is a tangible architecture that translates systems principles into regulatory practice. Here we suggest defining ecosystem-level stress budgets analogous to carbon budgets, establishing hierarchical assessment workflows that reverse current chemical-by-chemical

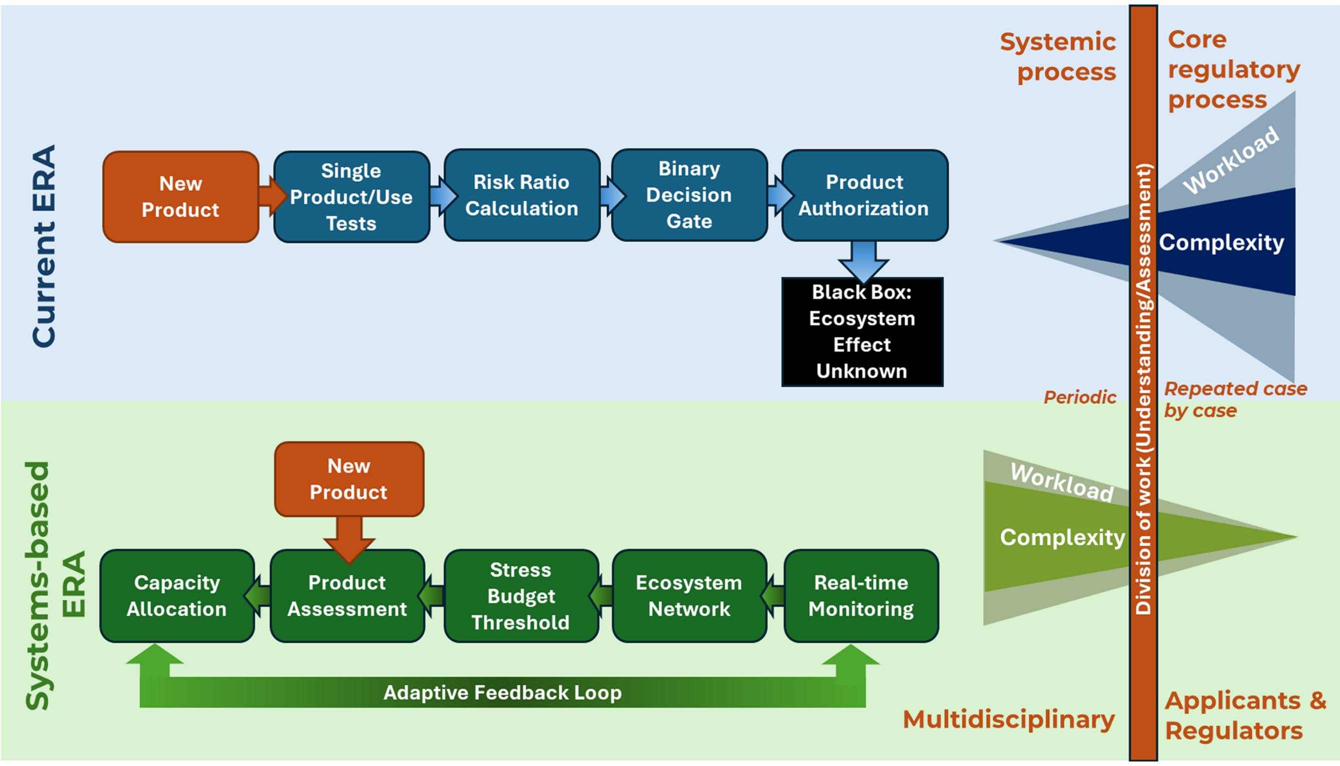

Figure 1. Workflow reversal from reductionist to systems-based environmental risk assessment. Current ERA (top left) proceeds linearly from individual chemicals through isolated testing to binary authorization decisions, with no mechanism to detect cumulative ecosystem impacts. Systems-based ERA (bottom left) reverses this workflow. Ecosystem monitoring and modeling establish stress budget thresholds first, and then individual products are assessed within this context, with continuous monitoring creating adaptive feedback to refine both system understanding and management decisions. The right panel shows how this reversal inverts assessment complexity. High-complexity systems-level work is conducted once as a periodic multidisciplinary process (green triangle), while routine product assessments become simplified with capacity-allocation decisions repeated on a case-by-case basis (blue triangle). In contrast, the current ERA repeats complex assessments, multiplying the workload for every product while never establishing cumulative impact thresholds.

logic, and creating adaptive management mechanisms that respond to real-world cumulative impacts rather than predicted single-chemical effects.

THE REDUCTIONIST FAILURE

Anderson[7] identified that reductionism does not imply constructionism. The pesticide regulatory framework exemplifies the resultant trap. Current ERA conducts detailed risk assessments in isolation. Notably, this applies to not only the classic form of chemical risk assessment, which tests single species under controlled laboratory conditions, but also the so-called tiered approach, which is particularly well developed in the ERA for plant protection products. In this approach, environmental behavior and ecotoxicological effects are often measured in multispecies model ecosystems or even in field tests. Paradoxically, increased precision under specific test conditions creates false confidence while simultaneously reducing representativeness across the diverse conditions that exist in real ecosystems. The current ERA produces sparse, fragmented quantitative estimates of acceptable exposure and declares products “safe” based on the calculated absence of effects above thresholds, yet real ecosystems function as interconnected, multiscale networks where multiple stressors interact in emergent ways that no isolated assessment can capture. When neonicotinoids were authorized in the 1990s, assessments examined effects on honeybees in controlled settings. The framework failed to account for sublethal impacts across multiple bee species, synergistic interactions with other stressors, or landscape-level consequences of widespread deployment.

This methodological failure is not unique to pesticides. Pharmaceutical and industrial chemical ERAs are adopting the identical reductionist structure, systematically replicating these failures across the entire chemical regulatory landscape. Backhaus, Scholze, Brack, Martin, Slunge, Ågerstrand, Kortenkamp, and Escher[2] explicitly recognize that mixture exposures require a more systemic view of chemical risk and propose a mixture allocation factor (MAF) as a laudable and pragmatic fix. However, this solution remains embedded in the current ERA paradigm, which is centered around refinements of single-point RQs, and effectively assumes that mixture risks can be managed through isolated regulatory decisions on individual chemicals, rather than through systems-level management. We are building a regulatory infrastructure that ensures we will miss systemic harm until agroecosystem integrity is already in decline.

The underlying problem stems from what psychologists call overconfidence in detail, i.e., people judge more detailed scenarios as more representative, even though it follows from logical inference that they are not.[8] While false precision feels reassuring to regulators and industry alike, it protects neither ecosystems nor public health.

A SYSTEMS-BASED ALTERNATIVE

A systems-based ERA inverts this logic (Figure 1). Rather than beginning with individual chemical assessments, it reverses the

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workflow to identify ecosystem-level thresholds upstream, effectively establishing a system stress capacity. Only then are product-specific authorizations considered within this broader context.

A systems-based ERA rests on three pillars. First, hierarchical systems theory recognizes ecosystems as interconnected networks where emergent properties arise across multiple scales. Second, computational models built from ecological, toxicological, and environmental monitoring and experimental data capture these dynamics and interactions that reductionist approaches miss. Third, once these models are validated and system behavior is understood, derived assessment tools operationalize this understanding into actionable management strategies. These range from simple rules analogous to speed limits to machine-learning emulators that provide rapid decision support. This sequence prioritizes systems understanding over methodological complexity.

Rather than binary "safe/unsafe" classifications, this framework employs chemical stress budgets that define acceptable cumulative impacts for types of ecosystems. For instance, watersheds have thresholds for nitrogen loading, persistent organic pollutants, and multiple classes of pesticides. New products are authorized taking into account their expected contribution to the overall landscape pesticide carrying capacity, and their actual impacts are continuously monitored. Products that exceed predicted impacts trigger adaptive management interventions.

IMPLEMENTATION PATHWAYS

Practical implementation requires several coordinated steps. Open-source ecosystem models must be developed for major habitat types, integrating available ecological, toxicological, and climate data. Regional implementation can build on existing frameworks such as EU biodiversity monitoring programs, USGS environmental monitoring networks, and similar initiatives worldwide. This requires sustained funding and institutional collaboration across research agencies and regulatory bodies but offers long-term cost savings by reducing reactive bans and environmental damage. Real-time environmental monitoring networks must be integrated into regulatory frameworks, moving beyond retrospective compliance testing to genuine ecosystem surveillance.[5]

This approach inverts assessment complexity in ways that enhance both efficiency and protection. Establishing ecosystem stress budgets requires initial investment in monitoring and modeling, but this work is conducted once per ecosystem type rather than being implicitly repeated in every product assessment. Individual authorizations then become simpler decisions about capacity allocation, analogous to building permits checking zoning limits rather than re-evaluating entire urban plans. Industry gains predictability through transparent stress budgets while regulators avoid duplicative assessments, ensuring both streamlined approvals and enhanced environmental protection.

Establishing environmental thresholds analogous to climate targets, similar to biodiversity targets under international frameworks such as the Kunming-Montreal Global Biodiversity Framework and regional legislation like EU nature conservation law, provides the scientific and policy foundation for this transition. This work should be conducted at the ecosystem scale outside individual product authorization procedures, reducing duplicative compliance costs while increasing decision predictability.

BROADER IMPLICATIONS

This paradigm aligns naturally with One Health principles and supports policy coherence across biodiversity, water, and climate legislation globally, with examples including the EU's Sustainable Use Directive, the US Endangered Species Act consultation processes, and international nature restoration initiatives. Beyond environmental regulation, systems-based approaches offer scalable models for other domains facing similar reductionist traps, from financial risk management to pandemic preparedness.

Successful reform requires overcoming institutional inertia through enhanced agency collaboration and data sharing. Critically, advancing ERA methods alone is insufficient; parallel development of risk mitigation strategies is essential to maintain product authorization pathways and ensure political acceptance of more rigorous assessment standards.

Environmental regulation has an opportunity to learn from systems thinking that has revolutionized biology, chemistry, and complexity science. The evidence is clear that incremental refinements to reductionist frameworks will not solve the fundamental problem. We need a paradigm shift, we need it now, and there is a path available.

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Notes

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Biography

Christopher J. Topping is a full professor and leads the Social-Ecological Systems Simulation (SESS) research group at the Department of Agroecology, Aarhus University, Denmark. He has 16 years of experience working in European Food Safety Authority working groups and served six years as Vice Chair of the EFSA's Plant Protection Products and Residues Panel and as Editor-in-Chief of *Food and Ecological Systems Modelling Journal*. His research focuses on systems-based approaches to ecological risk assessment, developing and applying agent-based models to evaluate agricultural sustainability and pesticide impacts. He coordinates the Horizon Europe project PollinERA and is creator of the ALMaSS (Animal Landscape and Man Simulation System) modeling platform, including the ApisRAM honey bee model. ALMaSS has been applied in five major Horizon projects and has informed pesticide risk assessment policy development in Europe.

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