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EDITED BY
Jaime Cesar Pinero,
University of Massachusetts Amherst,
United States

REVIEWED BY
Emmanuel Oliver Fenibo,
Hensard University, Nigeria
Poornima Nagesh,
Radboud Institute for Biological and
Environmental Sciences, Netherlands

*CORRESPONDENCE
Liz Kreick
eakreic@ncsu.edu

†PRESENT ADDRESS
Madison Love,
Department of Horticulture, University of
Georgia, Griffin, Georgia, United States

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Can we resolve the pesticide quandary with eco-efficiency metrics?

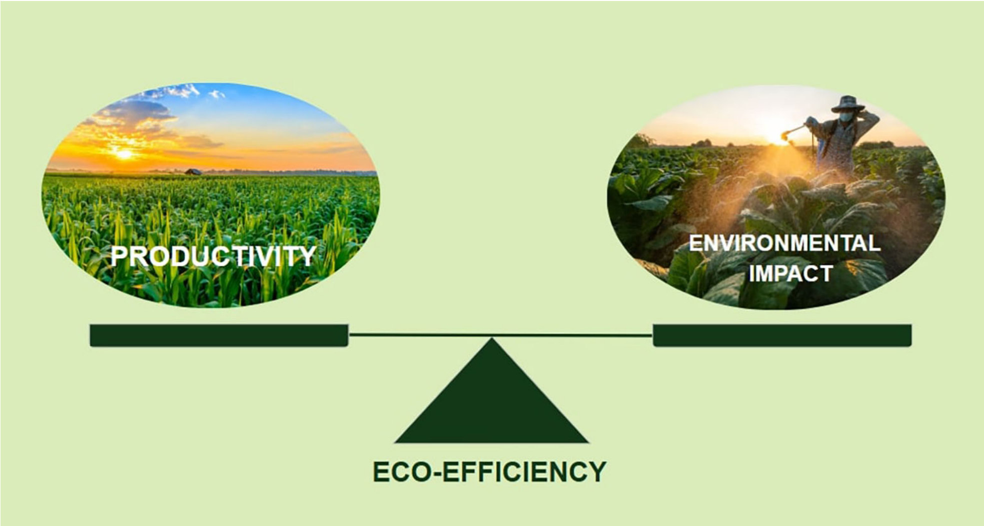
Liz Kreick[1*], Roger D. Magarey[2], Madison Love[1†] and Danesha Seth Carley[2]

[1]Department of Horticultural Science, North Carolina State University, Raleigh, NC, United States,
[2]Center for Integrated Pest Management, North Carolina State University, Raleigh, NC, United States

More than fifty years after the publication of *Silent Spring*, the United States continues to struggle with balancing the benefits of pesticide use against their environmental and public health costs. These costs are also known as pesticide externalities because these are paid by society at large rather than factored into the costs of production. A major contributing factor to this imbalance is the absence of standardized, widely adopted metrics and tools for assessing and reducing pesticide externalities in day-to-day agricultural production and urban pest management. This leaves producers, consumers, and policymakers without clear guidance for decision-making. Researchers are also impacted, left without coordinated direction or incentives to focus their work on the reduction of pesticide externalities. This has contributed to what we call the Pesticide Quandary: a social-ecological trap in which dependence on chemical controls perpetuates feedback loops of increasing pesticide resistance and pesticide externalities. Addressing this systemic challenge requires rethinking how policies, incentives, and research agendas align to break out of this trap. Historically, Integrated Pest Management (IPM) was promoted as a strategy to mitigate the Pesticide Quandary with some notable success stories. However, a lack of clear metrics to measure IPM's impact on pesticide externalities has limited federal support for IPM adoption by producers and also funding for IPM research and Extension. Eco-efficiency offers a potential solution to the Pesticide Quandary by tracking and incentivizing IPM practices that reduce pesticide externalities while sustaining agricultural productivity. Eco-efficiency is a strategy used to improve environmental outcomes in a variety of industries. A simple eco-efficiency score can be calculated from the productivity of a crop divided by the total toxicity of the pesticides applied. An eco-efficiency framework offers a standardized method for quantifying, tracking and incentivizing increased productivity and reductions in environmental and human health externalities from pesticides and improvements in productivity. Key recommendations include the development of standardized eco-efficiency scoring systems, their integration into decision support tools, and regulatory policies that encourage the adoption of sustainable pest management practices. This analysis underscores the need for measurable, incentive-driven frameworks to break the negative feedback cycle of the Pesticide Quandary and promote long-term sustainability in agricultural and urban systems.

KEYWORDS

eco-efficiency, integrated pest management, pesticides, pesticide policy, policy, life cycle analysis (LCA), pesticide externalities, toxicology



GRAPHICAL ABSTRACT

1 Introduction

Humanity faces a profound challenge: the urgent need to produce enough food to sustain a projected global population of over ten billion people by 2080 (UN, 2024) and the continued reliance on pesticides to meet agricultural productivity despite the risks they carry. Government regulators, scientists and producers increasingly recognize the challenge of using pesticides in ways that maximize productivity while minimizing environmental and human health risks (Brunelle et al., 2024; Kvakkestad et al., 2021; Reeves et al., 2019). Various countries have pursued different strategies to address these concerns: banning certain active ingredients outright (Chowdhury et al., 2018; Donley, 2019; Peng et al., 2020), limiting chemical residues in food products (De O. Gomes et al., 2020), promoting lower-risk cultural or biological practices, or penalizing pesticide overuse and misuse (Matyjaszczyk, 2019). In the most extreme example, Sri Lanka banned the use of almost all agrochemicals across the nation's food and floriculture production systems leading to crop failures and food shortages (Nadeeka Kumari and Pushpa Malkanthi, 2024). More than half a century after *Silent Spring* sparked environmental protection in the United States, the nation still struggles to reconcile pesticide use with its environmental and human health consequences. While advances in toxicology, regulation, diagnostics, and decision support tools have mitigated negative impacts, the core dilemma remains: how to maintain agricultural productivity while reducing the negative impacts of pesticide use. This challenge is not simply technical but requires systemic solutions.

Integrated Pest Management (IPM) has potential to resolve this challenge. IPM is a holistic approach that integrates biological, physical, cultural, and chemical controls to manage pests while minimizing risks to human and environmental health (Naranjo and Ellsworth, 2009). A recent model of IPM has evolved to include management considerations, business operations, and sustainability (Dara, 2019). Examples of IPM practices and tools that could reduce pesticide externalities include mitigating pest resistance, crop rotation, cover crops, biopesticides, monitoring, thresholds, pest forecasting, decision support tools, robotics and biological controls

(Dara, 2019; Farrar, 2023; Kogan, 1998). Due to the complexities, costs, and time related to implementing IPM practices, long-term and consistent adoption of these practices has been challenging (Lane et al., 2023). A particularly influential report by the United States Government Accountability Office (GAO) concluded that IPM programs lacked clear metrics and had not consistently delivered measurable reductions in pesticide risk (GAO, 2001). This critical assessment likely contributed to declining federal support for IPM research, Extension and implementation efforts (Jacobsen, 1996) that continue today.

At the heart of the issue is the need for more standardized, accessible tools and metrics to evaluate and reduce pesticide risk, including incentivizing the adoption of IPM. Simply quantifying the mass of pesticides applied is an inadequate metric, since pesticides differ greatly in their toxicity potential. Producers, consumers, and policymakers operate without clear, consistent guidance for identifying lower risk practices or measuring progress. Although concern over pesticide-related exposures continues to grow, there remains a lack of outcome-based funding programs equipped with robust, quantifiable metrics to guide and support targeted research and Extension efforts in pesticide risk mitigation. This fragmentation contributes to what we define as the *Pesticide Quandary* which is a social-ecological trap in which short-term reliance on pesticides reinforces long-term vulnerabilities, including resistance development, biodiversity loss, regulatory gridlock, and public health threats (Magarey et al., 2019).

This policy and practice review explores the roots and manifestations of the Pesticide Quandary in the U.S. context and introduces eco-efficiency as a potential pathway out. Eco-efficiency was developed by the World Business Council on Sustainable Development (WBCSD) at the 1992 Earth Summit, and at its simplest is a ratio between value or production and the environmental impacts of the product or service (Corson, 1994). By quantifying the ratio of agricultural productivity to environmental impact, eco-efficiency offers a standardized, scalable metric for evaluating and incentivizing sustainable IPM. Eco-efficiency is not a replacement for IPM, but a tool to better measure and incentivize IPM adoption and thus reduce pesticide impacts. This strategy is particularly important in the United States, where agricultural subsidies tend to prioritize crop insurance and income support rather than incentivizing sustainability or pesticide risk reduction, leaving producers to manage environmental and health tradeoffs under significant economic pressure (McFadden and Hoppe, 2017; Mishra et al., 2005). Eco-efficiency can incentivize existing IPM strategies, provide direction to researchers, and reshape decision-making across agricultural and urban pest systems. Barriers and solutions to eco-efficiency adoption are examined including: i) Stakeholder acceptance; ii) Data availability; and iii) Specific mechanisms for implementation of eco-efficiency scoring. Finally, we argue that without measurable frameworks capable of capturing systemic productivity and risk, well-intentioned efforts, from research grants to regulatory reforms, will continue to fall short. A shift toward eco-efficiency can help break the feedback loops of the Pesticide Quandary and chart a new course for sustainable pest management.

2 The pesticide quandary and integrated pest management

The Pesticide Quandary is in part inspired by Robert Van Den Bosch's concept of the pesticide treadmill, a negative cycle dominated by pest resistance, pest resurgence, and secondary pest outbreaks, requiring more frequent or more toxic pesticide applications, trapping producers in a cycle of increasing chemical dependence (Flint and Van Den Bosch, 1981). This paper presents an expanded and improved version of the Quandary to more effectively address key challenges and identify potential solutions with a focus on pesticide use in the United States. The pesticide quandary is a social-ecological trap that results in over-reliance on pesticides and unnecessary long-term environmental and human health costs (Magarey et al., 2019). A social-ecological trap occurs when reinforcing feedback loops drive a system towards an undesirable state that is difficult to escape (Stockholm Resilience Centre, 2012; Wang et al., 2023). In the case of the Pesticide Quandary, these feedback loops are driven by pest pressures, economic incentives, demand for agricultural products, pesticide dependency and limited alternatives. This framework and subsequent analysis aim to bridge the space between academic discussions on eco-efficiency and the material practices needed for adoption by producers and acceptance by consumers and community members.

In this paper, the discussion is framed step by step using Figure 1, with the top-half representing the Pesticide Quandary and the bottom-half a potential solution using eco-efficiency tools and metrics. The trap begins with pesticide production and use (Figure 1a). In the United States alone, an average of over one billion pounds of conventional pesticides are used annually (Atwood and Paisley-Jones, 2017). Globally, pesticide expenditures have reached an estimated 40 billion dollars (Sharma et al., 2020). Despite the advancements in alternative pest management solutions, such as biological pesticides, crop rotation, and resistance management practices, the Food and Agriculture Organization (FAO) of the United Nations reports that conventional pesticide use continues to increase (FAO, 2023). Both domestic and global crop yields (Figure 1b) remain heavily dependent on pesticide use, where loss to pest damage can lead to significant or even total yield loss (Ficke et al., 2018; Savary et al., 2012; Willocquet et al., 2018), depending on the crop, region, and production system. Even with widespread pesticide use, the FAO estimates that pests still account for almost 40% of annual global crop losses, equating to approximately $220 billion dollars in economic damage each year (Sarkozi, 2019). Another modern factor of pesticide use is the overreliance on a limited number of pesticide active ingredients, especially ones associated with genetically engineered herbicide-tolerant crops. This is most notably observed in the high-use of the herbicide glyphosate, which initially was less than 3% of total pesticide use on U.S. corn, cotton and soybean crops in 1992 rising to 23-45% by 2018 (Maggi et al., 2019; USGS, 2018). The development of pesticide resistance (Figure 1c) is a new addition to the original quandary framework. As pesticide use increases, efficacy declines due to the

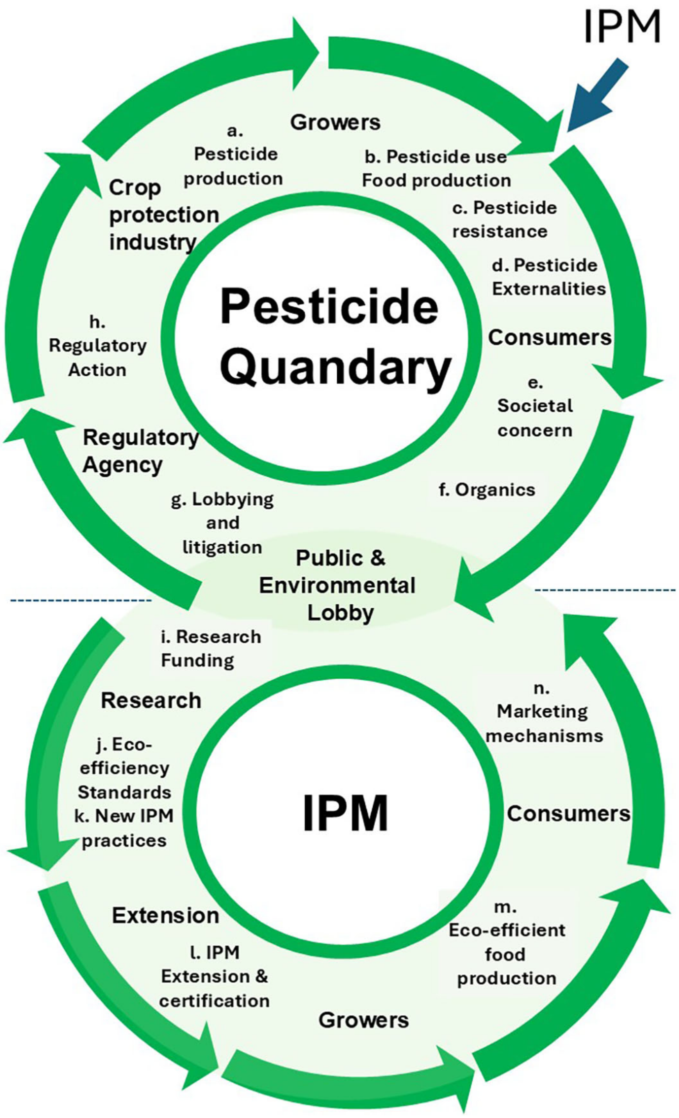


FIGURE 1
The revised pesticide quandary consists of a negative feedback cycle (top) dominated by pesticide dependency and associated externalities and a counter cycle (bottom) consisting of IPM research, Extension and adoption incentivised through eco-efficiency standards. Key elements include: **(a)** Pesticide production, **(b)** Pesticide use in food production, **(c)** Pesticide resistance, **(d)** Pesticide externalities, **(e)** Societal concern, **(f)** Organics research, **(g)** Lobbying and litigation, **(h)** Regulatory action, **(i)** Research funding, **(j)** Eco-efficiency standards, **(k)** New integrated pest management (IPM) practices, **(l)** IPM extension and certification, **(m)** Eco-efficient food production, and **(n)** Marketing mechanisms. The diagram highlights interactions among key stakeholders (e.g., growers, regulatory agencies, consumers, and the crop protection industry) and pathways to address pesticide challenges through regulatory action, societal engagement, eco-efficiency, and IPM practices.

emergence of resistance, which in turn drives even greater pesticide use or reversion to the use of pesticides that carry greater risks. Resistance has been documented across weeds, arthropods, and fungal pathogens. Globally, there are more than 250 weed species that have developed resistance to over 150 herbicides (Moss et al., 2019), and weeds have shown adaptation to 23 of the 26 herbicide modes of action (Heap and Duke, 2018). Over 500 species of arthropods have evolved resistance to one or more insecticides (Siddiqui et al., 2023) and fungicide resistance evolves so rapidly that use of single-mode fungicides are either capped to limit total applications (Lázaro et al., 2021) or professional guidance instructs users to rotate modes of action after limited uses (FRAC, 2025). Compounding the problem is the limited development of new pesticide modes of action, particularly in herbicides. In the past three decades, only a small number of novel chemistries have been introduced (Westwood et al., 2018), even though weed management is the largest pest management expense nationally (US EPA, 2015). The discovery and registration of new modes of action is both costly and time-intensive, making rotation of existing modes of action, monitoring emerging resistance issues, and ultimately, reducing reliance on chemical control, critically important strategies for long term pesticide efficacy. Moreover, pesticide use leads to short- and long-term environmental and human health impacts such as biodiversity loss, water contamination, and public health issues

(Figure 1d) (Bourguet and Guillemaud, 2016; Pimentel and Burgess, 2014; Pretty et al., 2001). These negative impacts are referred to as externalities because these costs are not internalized by the market, in other words they are not reflected in the price of agricultural products (Pretty et al., 2001). If properly accounted for, they would more likely be absorbed at the production level—as part of total production costs or offset elsewhere in the production system, particularly in life cycle and sustainability assessments (Pajewski et al., 2020). Negative externalities occur when the environmental and social costs of industrial or commercial activities are not reflected in the final cost of goods or services. These include contamination of soil and water, health impacts on applicators (Tudi et al., 2022), and damage to off-target organisms (Leach and Mumford, 2011). Instead of being paid by the producers or by the consumers directly, the costs are absorbed by the surrounding community and broader society with the public ultimately bearing the burden (Pajewski et al., 2020). These externalities encompass a wide range of impacts, from direct environmental issues such as exceeding ecosystem carrying capacity, deforestation, loss of natural habitat, declining soil quality (Rehman and Farooq, 2023), to larger systemic issues like climate change and waste generation, all of which are notoriously difficult to quantify (Macháč et al., 2021).

A prominent example of such externalities is the widespread use of neonicotinoids (neonics), a class of neurotoxic insecticides that exhibit lower toxicity to non-targets including mammals, birds and fish than organophosphate and carbamate insecticides (Kurwadkar and Evans, 2016). Neonics were developed as a low-dose, broad-spectrum pesticide that could be easily applied in multiple ways (e.g. foliar spray, seed coating, or soil treatment). Their effectiveness against arthropod pests, ease of use, and perceived safety led to rapid adoption, particularly in high-value specialty crops and as seed treatments in row crops (Jeschke and Nauen, 2008; Thompson et al., 2020). However, over time, the extensive use of neonics has revealed unexpected environmental persistence and significant off-target impacts on insects including high-profile species such as the Monarch butterfly *Danaus plexippus* (James, 2019; Klingelhöfer et al., 2022; Knight et al., 2021; Singla et al., 2021). In particular, several sub-lethal impacts of exposure to neonics in bees have been discovered, including abnormal foraging behavior, impaired brood development, neurological deficiencies, and colony collapse disorder (Lu et al., 2020). In response to mounting environmental concerns, litigation, and evidence of harm to pollinators, regulatory bodies moved to limit the use of insecticides, including neonics, during bloom periods and in residential settings (Marchand, 2023; Obama, 2014; Thompson et al., 2020). The story of neonics illustrates the recurring cycle of rapid adoption, followed by the emergence of non-target or unforeseen risks, subsequent regulatory restrictions, and the eventual rise of resistance against effective modes of action described by the Pesticide Quandary. The cycle is often driven by the unrealistic hope that the next "new" pesticide will finally offer a lasting solution to pest pressures without introducing additional negative externalities.Beyond the negative impacts on insects, pesticide use has been shown to have a significant negative impact on biodiversity, particularly among invertebrates, with losses recorded up to 42% in European studies (Beketov et al., 2013). In the U.S., declining bird populations have been partially attributed to pesticide exposure, which can impair mating success, physical mobility, and flight orientation (Stanton et al., 2018). The intensification of pesticide use increases the risks of exposure through drift, surface runoff, forage contamination, and leaching into groundwater (Travlou et al., 2024). Moreover, declining biodiversity associated with habitat loss and pesticide exposure can create a feedback loop, where reduced populations of natural enemies, such as parasitoids and predators, lead to greater pest pressures and consequently a higher need for pesticide use (Sánchez-Bayo, 2021). Conserving natural enemies through intentional habitat management and selective pesticide use improves pest management efficiency (Naranjo and Ellsworth, 2024), highlighting the importance of integrating ecological principles into pest management strategies. These impacts underscore a critical dimension of the Pesticide Quandary: biodiversity loss is rarely accounted for in economic assessments of pesticide use, despite its economic and agricultural consequences (Dallimer et al., 2012).

Societal concern surrounding the widespread use of pesticides (Figure 1e) plays a crucial role in shaping public discourse and influencing regulatory changes. Growing awareness of pesticide-related risks has prompted individual engagement through advocacy groups, and environmental organizations to take action aimed at reducing pesticide externalities. One proxy for measuring both social concern and the necessity of pesticides is the volume of comments submitted during EPA registration reviews or related regulatory actions. Social concern is evident for highly hazardous pesticides such as chlorpyrifos (69,301 comments) and atrazine (227,134 comments) but pesticides with low mammalian toxicity and widespread use such as glyphosate (523,736 comments) and neonics including imidacloprid (898,505 comments) and clothianidin (309,287 comments) often receive a greater quantity of comments (U.S, 2025). These figures suggest that public concern is not solely driven by toxicity profiles, but also by perceived environmental impacts, media attention, and scale of use.

Consumer behavior, such as preference for organic produce (Figure 1f), has emerged as a powerful force to impact both producer behavior (Carlson, 2023) and political decisions impacting pesticide use (Constance, 2009; Birch et al., 2011). For instance, research has shown that organic produce has fewer pesticide residues (Baker et al., 2002) but organic production does not necessarily have fewer environmental impacts due to higher application rates (Bahlai et al., 2010). Consumers have been willing to pay a premium for organic apples, demonstrating the potential of market-driven incentives to reduce pesticide reliance or reduced residues (Connolly and Klaiber, 2014). While consumer choices enable individuals to support production systems which create more environmental benefits (Durham and Mizik, 2021) and less pesticide residue on the environment (Geissen et al., 2021) through their purchasing power, another avenue for expressing social concern over pesticide externalities is through legal mechanisms (Figure 1G). In these cases, environmental groups leverage the court system to compel government agencies to strengthen environmental protections (Schmandt, 1984). A notable example includes recent litigation under the Endangered Species Act, which has pressured the Environmental Protection Agency (EPA), the regulatory body that governs pesticide registration, to develop mitigation strategies to be imposed across broad categories of pesticides (Kimbrell et al., 2021) (Figure 1H). Other high-profile cases have targeted specific pesticides such as dicamba, a herbicide known for its volatility and propensity to drift; glyphosate, linked by litigants to non-Hodgkins lymphoma in civil cases; and atrazine, a herbicide designated as restricted-use due to its environmental persistence and toxicity (Kimbrell et al., 2021). Environmental advocacy groups' use of litigation and the regulatory response can both reduce risks (by restricting or banning pesticides) and increase risks by reducing the amount and diversity of active ingredients in the producer toolbox, leaving higher-risk or less effective pesticides as limited options. Glyphosate could be considered the 'poster child' of this issue, as mounting litigation has raised concerns that the registrant, Bayer, may eventually withdraw the product from the U.S. market.

Regulatory agencies with authority over pesticide oversight must balance the need to protect environmental and human health with the need to protect food and fiber production, operating on a risk-benefit framework. The EPA is directed by executive order (Reagan, 1981) to evaluate actions using risk-benefit analysis, balancing the social, environmental, and economic benefits of the pesticide against the scientific risks to human and animal health as well as risk to ground and surface water (US EPA, 2013). The EPA develops and maintains sophisticated risk assessment models (EPA, 2025) and comprehensive databases such as The ECOTOX Knowledgebase (Olker et al., 2022) to perform this function. To inform EPA decisions, the United States Department of Agriculture (USDA) Office of Pest Management Policy works with a diverse group of stakeholders including producers, commodity groups, and Extension to ensure that the needs of producers are considered (USDA-OPMP, 2025) in pesticide policy.

Looking towards possible solutions, in the original conception of The Pesticide Quandary, IPM was envisioned as the brake that slows down the negative feedback cycle of pesticide use, environmental degradation, human health impacts and societal concern (Magarey et al., 2019). The story of IPM traces back to October 1959, when the journal *Hilgardia* published the landmark "The Integrated Control Concept." Led by Vernon M. Stern, the authors laid out the foundations of IPM (USDA, 2018) that continues to shape modern pest management: economic thresholds, biological and cultural control, and strategies to reduce chemical inputs and pesticide resistance (Stern et al., 1959). IPM is a holistic approach that integrates biological, physical, cultural, and chemical controls to manage pests while minimizing risks to human and environmental health (Naranjo and Ellsworth, 2009). IPM, which initially focused on decision support and reducing off target impacts, has evolved towards system thinking, including management considerations, business operations, and sustainability (Dara, 2019).

Despite its potential, several aspects of IPM have made measurement, evaluation, and widespread adoption challenging (Deguine et al., 2021). Since the creation of IPM, the definition has been inconsistent across research or regulations. Bajwa and Kogan (Bajwa and Kogan, 2002) have documented over sixty different definitions, with variations ranging from minute semantic differences to broader conceptual differences. Some definitions emphasize ecological integrations while others focus on social or economic benefits. This definitional ambiguity reflects the complexity of agriculture, which involves diverse crops, pests, and management strategies (Stenberg, 2017). While there is a statutory definition in the United States Code at 7 U.S.C. § 136r, it is broad (defining IPM as a sustainable pest management approach using biological, physical, and chemical tools to minimize risk) which makes its use in research and assessment challenging. At a research level, scientists often narrow the scope of IPM, such as Integrated Weed Science (Damalas and Koutroubas, 2024) or Biologically Integrated Farming Systems (Brodt et al., 2004) which adds to the definitional confusion. As a result, there is no universally standard definition of what constitutes IPM adoption (Deguine et al., 2021), which makes measurement and evaluation challenging (GAO, 2001). While many studies have demonstrated that IPM can reduce pesticide use in agriculture (Pecenka et al., 2021; Trumble et al., 1997; Zalucki et al., 2009), other research has found inconsistent or negligible reductions (GAO, 2001; Maupin and Tech, 2010; Norton and Mullen, 1994).

Currently, measurement of IPM adoption is frequently based on the percentage of producers who use specific IPM practices (Farrar, 2023). While these statistics are valuable, reductions in pesticide externalities through IPM practice adoption largely remain unquantified. Likewise, the mass of pesticides applied is also a poor metric since IPM programs may result in the substitution of relatively toxic pesticides such as organophosphates with less toxic ones such as petroleum oil, bio-pesticides, mating disruptors and other lower-risk alternatives (Biddinger et al., 2014; Gentz et al., 2010; Goldberger et al., 2013; Naranjo and Ellsworth, 2024). The absence of suitable metrics results in an "IPM Catch-22" (taken from Joseph Heller's famous antiwar novel meaning a "no-win" situation) where a lack of clear metrics to measure IPM progress hinders funding for IPM research and adoption. In the absence of stronger IPM support, many producers prefer calendar-based spray schedules or prophylactic treatments due to limited alternatives, perceived convenience, or to reduce economic risk (Fabre et al., 2007; Hurley, 2016). As a result, one of the original promises of IPM, to meaningfully reduce the human and ecological health risks, has not been fully realized. While IPM principles and practices remain useful and offer value to consumers and producers, IPM has not succeeded as a stand-alone solution to the complex, systemic challenges embedded in the Pesticide Quandary.

3 Eco-efficiency as solution to the pesticide quandary

Eco-efficiency presents as a promising method for incentivizing IPM in systems where its impact has been historically marginalized (Table 1). The concept of eco-efficiency emerged from the recognition that traditional cost-benefit analyses often omit environmental damages and other externalities (Huppes and

TABLE 1 Eco-efficiency solutions to IPM challenges and issues.

Issue	Current state of IPM in regard to issue	Potential eco-efficiency solutions
IPM is poorly defined	Defining IPM adoption or practice is hard to determine, with a very broad statutory or federal definition (Stenberg, 2017).	Eco-efficiency values, can be clearly defined based on crop production and toxicity levels
	IPM is challenging to define as a practice and varies by pest, crop and season (Wyckhuys et al., 2023).	Using products that are more eco-efficient would be easy to show, especially when interacting with consumers.
	IPM, economic thresholds are challenging to compute and use from season to season (Peterson et al., 2018).	Eco-efficiency can be used in and with a variety of systems, regardless of the framing.
IPM adoption is difficult to measure	Consistently measuring IPM adoption is difficult (Benjamin and Wesseler, 2016) and lacks standards (Farrar, 2023).	Eco-efficiency, as a measurement or assessment tool, is standardized across uses.
	As IPM practices change with environmental and pest changes, measurements are not consistent across times and seasons.	Eco-efficiency values are standardized across chemical pesticides.
	IPM tools and techniques available to producers change with cost, opportunity, needs, and crop, creating a challenging and multi-pronged measurement (Lane et al., 2023).	Eco-efficiency standards would remain useful to producers regardless of changes in income, IPM tool access, or changes in crop or production systems.
Data and recordkeeping for IPM adoption or certification is labor intensive	IPM, having a myriad of practices and techniques, can be an administrative burden to the producer (ie. IPM certifications) (Xerces Society, 2023).	Eco-efficiency values which can be easily integrated into existing pesticide record keeping management systems.
	Chemical pesticide use in weight or volume is not reflective of levels of risk or damage (GAO, 2001).	Risk to human and ecological health is integrated into eco-efficiency values in a standardized way which reflects increased or decreased risk.
Regulatory Systems are stressed	The United States regulatory system is facing uncertainty and flux due to political realities, litigation and judicial rulings.	Eco-efficiency values can be determined at quasi-public institutions such as non-profits, universities, or institutes with publicly available data.
	Regulatory solutions are often slow-moving; this allows time for active participation for stakeholders but also slows implementation of effective solutions.	Eco-efficiency is lightweight, where values can quickly be integrated into DSS (Decision Support Systems) and other management systems, added on pesticide labels or marketing, and disseminated to producers, extension, and crop consultants.

IPM v EE; current issues, EE solutions, resources.

Ishikawa, 2007). Eco-efficiency allows complete economic and environmental analysis when making cost-effectiveness decisions on environmental policies (Huppes and Ishikawa, 2005) as well as incentivizing technological innovation in environmental protection (Andersen and Kemp, 2004). As a framework, eco-efficiency offers a way to integrate previously disregarded environmental costs into a decision-making process that has long prioritized economic output (Caiado et al., 2017). Defined as the ratio of economic value produced to the environmental impact incurred, eco-efficiency enables the comparison of production systems based on both profitability and sustainability (Huppes and Ishikawa, 2007; Kicherer et al., 2007). In an agricultural context, eco-efficiency aims to sustainably increase agricultural productivity while simultaneously minimizing ecological harm (Boulanger and Mainguy, 2010).

History shows that as economic activity increases, environmental degradation tends to increase as well (Huppes and Ishikawa, 2007). While regulatory efforts have led to some progress in restricting the use of harmful pesticides, environmental degradation linked to pesticide use continues to escalate on a global scale (World Health Organization and Convention on Biological Diversity, 2015). If environmental impacts were fully internalized into regulatory frameworks, policy goals, and economic expectations, it is likely that pressure on ecological systems could be reduced substantially. Looking to a different industry with clearer environmental impacts and regulatory frameworks, waste disposal is a useful example of the impact of internalizing environmental costs also known as externalities. If these costs were correctly accounted for (fully internalized) via higher taxes on waste disposal, advance disposal fees (ADFs), and increased producer responsibility for damages, there might be less waste leading to less environmental damage (Matheson, 2022). This is seen in microcosm with plastic bag policies, where consumers having to pay for bags reduced the amount of bags consumed (Nishijima and Nakatani, 2024). While full sustainability has not been achieved in most industries, eco-efficiency has proven to be an invaluable tool for moving industries, such as BASF's methodology for environmental and economic impacts in chemical production, towards sustainable development through production improvement (Caiado et al., 2017; Saling et al., 2002). Eco-efficient policies and actions provide a pathway towards sustainability by maximizing the production of goods and services while minimizing inputs and environmental harm. For example, the use of eco-efficiency metrics such as tons of production or profit per KWh or KG greenhouse gas emissions can lead to more efficient production practices (Müller et al., 2015; Wang et al., 2022; Müller et al., 2015). Eco-efficiency can also be determined by multiple weighted criteria such as environmental impacts, life cycle cost, and societal factors (Heijungs, 2022). Via these metrics, co-efficiency helps illuminate environmental and economic trade-offs that are often overlooked.

Returning to the Pesticide Quandary (Figure 1), IPM is reimagined as a positive counter-cycle (Figure 1 bottom half) driven by incentives to meet eco-efficiency standards and targets. This positive feedback loop is focused on research, Extension, IPM adoption and sustainability certification that lead to measurable improvements in environmental and human health outcomes. Eco-efficiency addresses the IPM "Catch-22" by providing measurable metrics that demonstrate progress, helping to secure support for IPM initiatives. Applying eco-efficiency framework to the Pesticide Quandary offers a way to integrate ecological externalities into pest management practices through an easy-to-understand, standardized tool (Magarey et al., 2019). The process begins by channeling public and environmental advocacy, while helping generate funding support (Figure 1i), ultimately driving research and development. This investment into research and development (of both newly developed IPM practices and chemical active ingredients) enables the creation of eco-efficiency standards (Figure 1j) and improved IPM practices and tools (Figure 1k) designed to reduce pesticide risks and associated externalities. Next, Extension can assist in disseminating more eco-efficient practices to producers (Figure 1l). Eco-efficiency can also provide an alternative or additional metric to IPM practice adoption as a validation for IPM certification schemes. Adoption of these more eco-efficient practices (Figure 1m) can reduce societal concern while also stimulating market demand for crops grown using certified IPM systems (Figure 1n), a dynamic that is known as market-based mechanisms (Green, 2008; Lefebvre et al., 2015).

The foundation for the eco-efficiency counter-cycle is the ability to measure baseline conditions and track progress (Figure 1j) towards reducing the externalities associated with pesticide use. One example of an eco-efficiency index is the total mass of crop production divided by an indirect measure of pesticide externalities, the Total Applied Toxicity (TAT) (Love et al., 2025). The TAT is a simplified risk quotient that calculates the ratio between the mass of pesticide applied and its corresponding toxicity endpoint (Peterson, 2006; Schulz et al., 2021). Toxicity levels or endpoints, also referred to as Regulatory Threshold Levels (RTLs, are specific to various terrestrial and aquatic species groups, such as mammals, birds, arthropods, plants, invertebrates, and fish (Schulz et al., 2021). Eco-efficiency metrics provide a mechanism to deliver toxicity endpoints often buried in databases, such as the EPA's ECOTOX Knowledgebase, into a format that stakeholders can use to inform pesticide use decision making. In addition to the TAT, the area of land to which certain pesticides have been applied is also a variable that is used in some eco-efficiency indices (Kniss et al., 2025).

Eco-efficiency scores offer a practical, quantitative way to measure progress in IPM, while also capturing the human and ecological health impacts often treated as externalities. In contrast to adoption statistics for individual IPM practices, which can be difficult to link directly to changes in pesticide-related risks, eco-efficiency indices provide a more direct and integrated measure of these impacts. This enables goal setting and progress tracking in ways that traditional IPM regulations, policies, and reporting systems including those that rely on tracking pesticide mass applied or IPM practice adoption often cannot. While eco-efficiency is not yet widely used in the context of pest management, several studies have begun to apply the concept. For example, Kniss et al. (2025) evaluated pesticide use in soybean and corn systems with respect to potential impacts on honey bees (Kniss et al., 2025) and (Bonfiglio et al., 2017) assessed the eco-efficiency of Italian arable farms using pesticide toxicity indicators. Two other studies have explored eco-efficiency using pesticide production and pesticide use (Zhu et al., 2014) while some focus on application mass without incorporating toxicity metrics (Van Grinsven et al., 2019).

4 Adoption of eco-efficiency in pest management

In this section, barriers and solutions to eco-efficiency implementation in agriculture are discussed. These barriers include: i) Stakeholder acceptance; ii) Data availability; and iii) Specific mechanisms for implementation of eco-efficiency scoring.

The first barrier is stakeholder acceptance. While stakeholders are not familiar with eco-efficiency in the context of pesticide use, many are already acquainted with life cycle analysis (LCA) or sustainability metrics (Sieverding et al., 2020). LCA is defined as the process of "evaluating the potential environmental impacts throughout the whole life cycle of a product or service" (Vásquez-Ibarra et al., 2020). LCAs examine a wide range of factors including raw material inputs, carbon and energy usage, packaging, distribution, end-of-life disposal, and other elements typically excluded from conventional economic evaluations. This approach, which echoes the process of determining eco-efficiency metrics, supports more informed decisions aimed at reducing environmental impacts while maintaining economic value (Konstantas et al., 2020). Life cycle and eco-efficiency analyses illuminate opportunities to reduce waste, carbon footprints, and other negative externalities (Andersen and Kemp, 2004; Martinelli et al., 2020). Eco-efficiency in pesticide use builds on this foundation to reduce ecological impacts and resource consumption in ways that align with the planet's environmental limits.

One notable example of LCA is the Field to Market Fieldprint Calculator which has been developed for multiple agronomic crops (Field to Market, 2021; Gillum et al., 2016). Developed through collaboration among diverse agricultural stakeholders, the Fieldprint tool engages producers, industry leaders, consumers, processors, advocacy organizations, retailers, and Extension agents to collaboratively assess sustainability (Konefal et al., 2022). The Fieldprint Calculator measures eight environmental metrics, (1) land use, (2) soil conservation, (3) irrigation water use, (4) energy use, (5) greenhouse gas emissions, (6) soil carbon, (7) water quality, and (8) biodiversity. These metrics are visualized in a multi-dimensional graphic that enables users to compare producers and products using standardized sustainability indicators (Hartley, 2020; Strube et al., 2021). Importantly, major stakeholders in the cotton industry have utilized Fieldprint metrics to guide sustainability efforts (Field to Market, 2021; Gillum et al., 2016). While surveys assessing environmentally beneficial practices offer valuable insights for guiding research outreach efforts (Farrar, 2023; Field to Market, 2020), they do not directly address the measurement of pesticide environmental externalities. Currently, the Fieldprint scores do not incorporate pesticide externalities, representing a gap that could be filled by a pesticide-specific eco-efficiency metric or analysis.

The second barrier is pesticide toxicity data. Data availability which is a major limitation in the implementation of eco-efficiency frameworks in agriculture. One critical research need is to estimate toxicity level values for commonly used pesticides in the United States, especially for specialty crops. A recent study (Love et al., 2025) found that while 94% of pesticide active ingredients used in soybeans had associated toxicity level values, only 55% of those used in vegetable and fruit crops had associated toxicity level values. The lack of toxicity values for specialty crops is likely a reflection of their lower market share which impacts pesticide research and registration. Although most pesticide active ingredients, with the exception of recently registered products, are likely to have the ecotoxicity data available in official databases such as the ECOTOX Knowledgebase (US EPA, 2024), the process of calculating and standardizing toxicity level values is labor intensive. As such, dedicated funding is needed to support the estimation, validation, and digital archiving of these values, ensuring they are accessible for use by researchers, policymakers, producers, and other key stakeholders.

Another limitation to implementing eco-efficiency scoring is the availability of reliable and consistent pesticide usage data. The USDA National Agricultural Statistics Service (NASS) Chemical Use Program pesticide usage dataset (USDA, 2025) is likely adequate for many applications, including the development of eco-efficiency metrics for individual crops at the state level. However, it would likely not be adequate for more granular studies such as those at county or smaller spatial scales. Currently, only California maintains a detailed pesticide database which could be used to power eco-efficiency calculations at fine, spatial scales for specific crop or commodity groups. For eco-efficiency indices to be widely deployed, progress would need to be made towards a system where pesticide use data at the producer level could be shared with organizations, apps or tools that could standardize the data and calculate relevant metrics at multiple scales.

An additional constraint associated with eco-efficiency scores is the difficulty of fully assessing environmental and human health impacts. While Total Applied Toxicity offers a standardized and accessible method for measuring environmental impact, it remains a simplistic proxy. In real-world applications, actual exposure levels are influenced by multiple mitigating factors. For example, human exposure is significantly reduced through the use of enclosed mixing containers and tractor cabs, while aquatic exposure may be mitigated by vegetative buffers, drainage structures, or other landscape features to reduce runoff into waterways (Teed et al., 2024). Similarly, spray drift, a major route of non-target exposure, can be minimized through application nozzle selection, use of adjuvants, and the presence of windbreaks. Moreover, simple eco-efficiency metrics based only on applied mass and toxicity fail to consider other critical factors of pesticides such as environmental persistence, volatility, and mobility in soil and water systems. Likewise acute toxicity does not cover other health impacts such as chronic exposure.

Additionally, another key limitation of simplistic eco-efficiency scores is that they do not account for real-world variability, such as climate conditions, pest pressures, and emergence of new or resistant pests. These dynamic factors can cause substantial changes in pesticide use from year to year. As a result, a change in eco-efficiency score may reflect changes in external pest-related pressures rather than improvements or regressions in pesticide decision-making. Without contextual information, it becomes difficult to determine whether a shift in eco-efficiency reflects a true management improvement or a response to changing conditions in the production environment.

The third barrier is the lack of specific mechanisms for delivering eco-efficiency scores. While the concept of setting crop-specific eco-efficiency targets holds promise, there is currently no formal forum to engage industry stakeholders in discussion around pesticide eco-efficiency baselines for a given crop. One potential mechanism for this engagement is through Pest Management Strategic Plans (PMSPs) (Boudwin et al., 2022). Pest Management Strategic Plans are comprehensive documents that outline pest management practices for specific crops within a defined region. These plans are developed through stakeholder workshops that include participation from producers, crop consultants, researchers, and regulatory agencies. A key function of these workshops is to establish regulatory, Extension, and research priorities, making them ideal venues for introducing and discussing current eco-efficiency scores for a given crop. Incorporating eco-efficiency discussions into these workshops could follow a structured approach. First, stakeholders could review current eco-efficient metrics for a given crop. Second, they could identify the pests and pesticides that present the greatest challenge to improve those scores. Finally, the group could establish targeted research, Extension, and regulatory priorities aimed at either improving eco-efficiency scores or establishing targets for improvement. Because higher eco-efficiency scores are associated with lower human and environmental health externalities, funding to achieve these targets could justifiably come from sources beyond traditional agriculture. Grants aimed at reducing environmental externalities, improving public health outcomes, or supporting climate-smart practices could help advance eco-efficiency goals, especially when benefits extend across sectors.

Another emerging avenue for the implementation of eco-efficiency scores is through sustainability or IPM certification programs, which have gained significant traction in recent years. These certifications involve third-party evaluation of vendors' IPM practices across produce, cut flowers, and live plant products, and are increasingly required by major retailers, including Walmart, Whole Foods, and Kroger (Kroger, 2024; "Meijer Community - Pollinator Health, 2024; Newell and Mader, 2024; Walmart, 2021; Whole Foods, 2024). Collectively, these retailers make up almost 40% of the U.S. grocery market (Schaul and Peiser, 2024), giving them substantial influence over production standards and practices. To maintain access to these markets, producers must undergo a time intensive application process and on-site inspections to secure certification, all at their own expense with no financial benefit beyond market access. This often includes travel costs for auditors, program-specific fees, and ongoing re-certification fees. While most certifications accepted by retailers are non-profit organizations or private companies, the USDA Organic certification program remains the only federally evaluated option. Importantly, USDA Organic is the only certification option offering incentives and cost-sharing opportunities for participating producers.

Examples of other certification programs include non-profit organizations such as the Xerces Society for Invertebrate Conservation and Pollinator Partnership, as well as international standards such as Global Good Agricultural Practice (GAP) Integrated Farm Assurance and Florverde Sustainable Flowers (Walmart, 2021). The price for certification varies, from the more economical Xerces Society Bee Better Certification starting at $400 plus auditor's fees to well into the thousands for Rainforest Alliance certification. These fees are in addition to any landscape, management, or system changes needed to attain the certification.

While horticultural operations generated nearly $14 billion dollars in sales of specialty produce, live plants, and cut flowers in 2019 (Letterman, 2020), this market remains relatively small compared to commodity crop sales, which reached $541 billion dollars in 2022 (Rossi, 2024). Additionally, over half of horticultural producers are individually or family-owned operations (USDA, 2021), making the burden of certification significant. Retailers requiring IPM certification do not cover the associated labor, administrative, or certifying costs, and currently, there are no available metrics to demonstrate whether these programs actually lead to increased IPM adoption or reduce pesticide risks.

Integrating eco-efficiency scores into these programs offers a promising solution to streamlining the certification process. Because these scores can be calculated directly from producers' pesticide use records, they could reduce the requirement for extensive documentation of IPM practices currently required. If retailers incorporated eco-efficiency thresholds into their sourcing requirements, this approach could simplify compliance, reduce administrative burden, and potentially encourage broader adoption of IPM practices. Moreover, eco-efficiency scores provide a transparent, quantifiable link between production practices and environmental externalities, enabling consumers to make more informed purchasing decisions rather than relying solely on the assumption that certification equates to more sustainable pest management. The potential for eco-labelling of produce and the advantages of performance-based metrics over practice-based metrics has been informally discussed elsewhere (WIPMC, 2017).

Another promising mechanism for delivering eco-efficiency scoring is through the use of Decision Support Systems (DSS). DSS are computer or app-based platforms that allow producers to input field-specific data and receive tailored recommendations on pest management, nutrient applications, and other farm management decisions (Matthews et al., 2008). These tools help producers streamline and organize complex information, enabling them to make more informed, data driven decisions (Ara et al., 2021). DSSs have been a useful tool in integrating some externalities into already complex pesticide decision making but have challenges in adoption and long-term use (Rossi et al., 2023). Integrating eco-efficiency scores as an additional metric that producers could optimize in addition to pesticide price and efficacy can help reduce pesticide externalities on their farms. When IPM principles and practices are integrated within easier-to-use tools such as DSS systems, they have been shown to influence pesticide application behavior and lead to more sustainable outcomes (Gent et al., 2011). For example, IPM-integrated DSS tools have been used to prevent plant disease epidemics in wheat crops (Rabbinge and Rijsdijk, 1983), reduce waste in agricultural irrigation systems (Todorovic et al., 2016), and reduce the amount and frequency of fungicide applications (Lázaro et al., 2021). Another example is a cotton Extension publication that helps cotton producers select insecticides with the least harm to natural enemies. Over time the use of IPM strategies including selective pesticides in Arizona cotton has resulted in reduced pesticide use, especially the toxic pesticides such as organophosphates (Naranjo and Ellsworth, 2024). Integrating eco-efficiency scoring into DSS platforms would provide producers with real-time feedback on the environment and human health impacts of pesticide choices, further encouraging low-risk, high efficiency pest management strategies.

5 Adoption of eco-efficiency in urban pest management

Beyond agriculture, urban pest management represents a significant portion of overall pesticide use, including applications for controlling urban pests such as rats, cockroaches, and bedbugs, as well as residential treatments for lawns, gardens, recreation areas, and rights-of-way spaces (Budd, 2010). Residential applications, particularly in homes and gardens, suffer from the same misuse, overuse, and development of pesticide resistance, and use exceeded 66 million pounds of active ingredient, making up eight percent of national pesticide use (Bush, 2015). Urban pest management is responsible for the critical management of pests such as cockroaches, mosquitos, and fleas that vector human diseases (Gondhalekar et al., 2021; Namias et al., 2021). Like agricultural pesticides, urban uses contribute to waterway and forage contamination, posing risks to biodiversity and non-target organisms (Md Meftaul et al., 2020). These applications are plagued with inefficient and ineffectual use by homeowners, leading to detrimental environmental impact including pollinators and other beneficial insects (Hernke and Podein, 2011).

Service-based approaches offer potential to improve eco-efficiency by providing for pest management companies profit pathways that do not rely sole upon pesticide sales (Chappell et al., 2019). This has ready potential in urban pest management where IPM practices have been shown to be both efficient and economical. The direct impacts of cockroach infestation are well-known, as direct exposure with cockroaches, their feces, and secretions contributes to asthma, mental distress, allergies, food contamination, and even the spread of antibiotic-resistant bacteria (Sever et al., 2007). The less obvious, indirect effects of cockroach infestation resemble the challenges observed in agricultural pesticide use including the use of incorrect or ineffective pesticides, development of insecticide resistance, and overexposure due to improper application methods such as foggers or direct sprays (DeVries et al., 2019). Baits are more efficient and pose less risks, but many pest control companies continue to use sprays due to their immediate and visible impact (Brenner et al., 2003). Studies have shown that using bait-based methods significantly reduces human pesticide exposure and the amount of insecticides entering waterways and urban drainage systems while providing more effective control (DeVries et al., 2019; Jiang et al., 2016). In both professional and do-it-yourself scenarios, a combination of public education campaigns and the implementation of eco-efficiency standards could encourage the adoption of safer, more effective practices (Sever et al., 2007).

6 Discussion

This paper explores the systemic challenges posed by pesticide use, emphasizing the "Pesticide Quandary" as a social-ecological trap where pesticide dependence perpetuates a negative feedback loop of pesticide resistance, environmental, and public health externalities. A solution is a multi-pronged strategy to introduce eco-efficiency as a tool for quantifying, tracking and incentivizing IPM practices that mitigate pesticide-related externalities and promote sustainable agricultural practices (Table 2). Specifically, developing standardized eco-efficiency scoring and establishing a centralized repository of eco-efficiency data (Peterson, 2006; Schulz et al., 2021) are critical initial steps, as they provide the necessary infrastructure for consistent measurement and comparison of pesticide impacts. Without these metrics, the ability to measure progress or incentivize better practices would remain limited.

To help conceptualize how eco-efficiency impacts sustainability outcomes, this paper adapts the social-ecological adaptive cycle as a visual framework (Figure 2). The adaptive cycle represents the dynamics of complex systems in which human societies and ecosystems are interconnected and co-evolve. It consists of four phases—growth (exploitation), conservation, release (collapse), and reorganization—that describe the typical trajectory of change and adaptation (Holling, 2001). Here, the cycle is applied to agricultural sustainability, mapping resource use, connectivity, productivity, and information content (Magarey and Chappell, 2025). Figure 2 plots eco-efficiency examples in four quadrants: a stable ecosystem (green), an exploitative system that sacrifices environmental stability for productivity (purple), an archaic system where poor information limits productivity (blue), and a remnant system with poor environmental and production outcomes (red). This framework illustrates the range of possible trajectories for agricultural systems striving for eco-efficiency. Translating these conceptual insights into practical action requires collaboration, regulatory alignment, and market incentives to guide agricultural systems toward the more desirable eco-efficiency trajectories.

Engaging stakeholders through forums such as Pest Management Strategic Plans workshops (Boudwin et al., 2022) could offer a collaborative platform for setting crop-specific eco-efficiency baselines and establishing goals. Regulatory integration, resembling the Insecticide Resistance Action Committee or mode of action classifications, would allow these metrics to be available to the largest population of producers, and would streamline incorporation of these values into DSS and other tools. Market-based incentives, such as requiring eco-efficiency metrics in IPM certifications and consumer labeling of urban pest management services, could also rapidly drive adoption.

While the benefits of eco-efficiency are clear, several challenges must be addressed for effective adoption. Data availability remains a primary hurdle, as eco-efficiency scoring requires robust datasets on pesticide toxicity and use rates. Producers can be skeptical of information-sharing with government agencies (Sullivan et al., 2024; Zhang et al., 2021), especially in light of transparency issues in data privacy, portability, and liability (Wiseman et al., 2019) Although tools like the USDA-NASS surveys and ECOTOX Knowledgebase offer partial coverage, gaps will continue to persist, particularly for specialty crops and newer active ingredients (Love et al., 2025). Stakeholder acceptance is another concern, especially since many producers and policymakers are unfamiliar with eco-efficiency concepts, even though they might be familiar with similar frameworks like LCA (Vásquez-Ibarra et al., 2020). To help stakeholder adoption, DSS that integrate eco-efficiency metrics could provide producers with actionable insights, reducing overreliance on high-risk pesticides while maintaining productivity (Gent et al., 2011; Lázaro et al., 2021). Similarly, in urban pest management, transitioning from high-risk sprays to more eco-efficient solutions such as bait-based strategies could reduce health risks while maintaining effective pest control (DeVries et al., 2019).

The radical and ill-conceived pesticide ban implemented by Sri Lanka serves as a cautionary case of policy overcorrection (Nadeeka Kumari and Pushpa Malkanthi, 2024). While motivated by public health concerns, the severity of a complete agrochemical ban contributed to unintended consequences such as severe crop losses and economic instability. Had eco-efficiency assessment been available and integrated into decision-making along-side other data-driven considerations along-side other data-driven considerations, it might have provided policymakers with a more balanced approach: such as phasing out high-risk pesticides where safer alternatives exist, while maintaining crop yields through lower-risk options, or being able to track progress over time.

Eco-efficiency offers opportunities for various stakeholder groups. For agrochemical companies, eco-efficiency metrics offer

TABLE 2 Eco-efficiency recommendations for pest management.

Category	Recommendation	Implementation strategy
Eco-effciency	Develop standardized eco-efficiency scoring	Create a repository of eco-efficiency metrics data including toxicity levels for pesticides
Stakeholder Collaboration	Engage stakeholders through PMSP (Pest Management Strategic Plans) workshops.	Measure crop specific eco-efficiency baselines and set targets for improvement.
Market Incentives	Use eco-efficiency in IPM certification and consumer labeling.	Encourage major retailers to require eco-efficiency metrics for supplier certification.
Decision Support Tools (DSS)	Incorporate eco-efficiency metrics into DSS for pest management.	Develop DSS that visualize eco-efficiency progress and recommend lower-risk pesticides.
Regulatory Integration	Include eco-efficiency metrics in EPA risk assessments.	Advocate for eco-efficiency scoring in pesticide registration and re-registration.
Public Education & Outreach	Raise awareness about eco-efficiency practices.	Develop educational materials and training for producers and urban pest managers.
Research and development	Increase research and extension efforts to increase eco-efficiency	Include eco-efficiency as a reportable metric for funded projects in USDA NIFA-CPPM* grant programs
Urban Pest Management	Encourage pest management companies to self-report eco-efficiency metrics	Encourage bait-based strategies over spraying for lower-risk pest control.

*Crop Protection and Pest Management.

an opportunity for showcasing safer, lower-toxicity innovations. Since the metrics support efficiency they offer companies the leverage to obtain regulatory or marketing advantages through improved stewardship using approaches such as service-based strategies (Chappell et al., 2019). For the environmental lobby, it provides opportunities to advocate for government programs or consumer products that support eco-efficiency improvements instead of focussing on pesticide bans that can often be counterproductive. For the agriculture industry, it offers opportunities to better coordinate and communicate sustainability outcomes to consumers. For regulators, eco-efficiency programs can complement existing EPA efforts and provide additional data for understanding pesticide use and regulatory needs. Eco-efficiency metrics could be integrated with programs designed to protect the health and safety of children, especially to encourage adoption of IPM in schools. Finally, for IPM researchers, eco-efficiency offers additional metrics to report positive research outcomes beyond pesticide sprays and dollars saved.

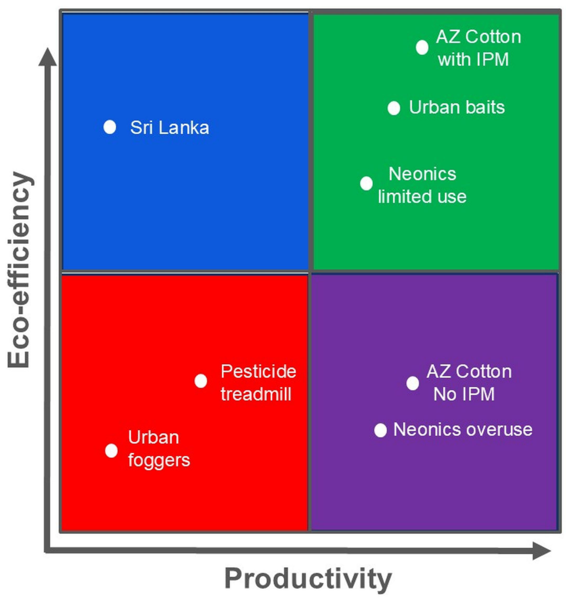


FIGURE 2
Quadrant graph illustrating trade-offs between productivity and eco-efficiency. Each quadrant represents a different ecosystem state in a social-ecological adaptive cycle with various levels of sustainability and productivity based on information content (Magarey and Chappell, 2025). Eco-efficiency examples mentioned in the text are plotted in four quadrants representing a stable ecosystem (green), an exploitive ecosystem that sacrifices environmental stability for productivity (purple), an archaic ecosystem where lack of information ensures low productivity (blue) and a remnant ecosystem that has poor environmental and production outcomes (red).

7 Conclusion

The unique contribution of this paper to the literature is to comprehensively describe eco-efficiency based solutions to the pesticide quandary (Magarey et al., 2019). Eco-efficiency has the potential to reshape global pest management by offering structured policies and data-driven methods for balancing agricultural productivity with environmental health. Eco-efficiency metrics can complement existing regulatory frameworks such as the EPA's risk assessments (US EPA, 2024) and pesticide registration processes; policymakers could better address pesticide externalities while maintaining food security. Even in the absence of regulatory adoption, eco-efficiency offers a valuable tool for communicating the benefits and risks of pest management strategies. By using accessible, data-driven metrics, such as pesticide toxicity levels, it helps translate complex environmental trade-offs into terms that are easier for stakeholders to understand. Engaging stakeholders in future pilot programs and working with existing crop production systems represents non-policy pathways for applying the eco-efficiency framework. Overall, this policy review underscores the importance of adopting eco-efficiency scoring as a core component of modern pest management strategies. Prioritizing data standardization, stakeholder collaboration, and market-driven incentives can collectively drive the shift towards sustainable agriculture. Future research should focus on refining eco-efficiency indices, expanding data availability, and testing eco-efficiency integration into existing decision support systems.

Author contributions

LK: Conceptualization, Writing – review & editing, Writing – original draft. RM: Funding acquisition, Supervision, Writing – review & editing, Visualization, Writing – original draft, Conceptualization. ML: Writing – review & editing, Writing – original draft. DC: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. AI was used in the editing and research of this paper, including sentence structure, grammar, and word choice. All data and language in this paper was reviewed and corrected by human beings.

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