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Reflecting Integrated Pest Management and constructing a Dynamic Resilience-based IPM framework

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Abstract
Integrated Pest Management has been championed for more than half a century as the rational middle ground between chemical-dependent crop protection and ecologically benign but knowledge-intensive alternatives. A vast body of evidence confirms that well-implemented IPM delivers measurable economic, ecological, and social benefits, yet its global adoption remains patchy and often symbolic, while reliance on broad-spectrum synthetic insecticides is stubbornly high. This paper conducts a critical multidisciplinary review to diagnose why a conceptually robust and evidence-rich paradigm persistently underperforms. We identify the root cause as a deep-seated mismatch between the static, optimization-oriented engineering logic embedded in conventional IPM thinking and the dynamic, nonlinear, self-organizing nature of agroecosystems. Drawing on resilience theory, adaptive co-management, and complex adaptive system perspectives, we articulate an original framework termed Dynamic Resilience-based Integrated Pest Management. DR-IPM replaces fixed economic thresholds with dynamic adaptive thresholds that couple real-time population signals, predator-prey ratios, crop compensatory capacity, weather forecasts, and market prices. It organizes responses across nested spatial scales from the field to the landscape, mandates strategic redundancy in control tactics, institutionalizes participatory adaptive learning loops, and valorizes ecosystem services through smart contracts and verified green credits. The framework is operationalized through an agricultural digital twin platform powered by multi-agent simulation and continuous stakeholder sensing. DR-IPM constitutes a shift from managing pest populations to stewarding the self-regenerative capacity of social-ecological systems, turning IPM from a prescriptive toolkit into an adaptive governance philosophy. We outline its implementation pathway, discuss differentiated trajectories for smallholder and large-scale agriculture, and propose a research agenda to empirically test the core hypotheses.

Keywords Integrated Pest Management; adaptive governance; social-ecological resilience; dynamic economic threshold; digital twin; agroecological transformation.

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1 Introduction

1.1 Background and the persistent puzzle

Integrated Pest Management crystallized as a formal concept in the late 1950s in response to the catastrophic failures of unilateral insecticide use, including target pest resurgence, secondary pest outbreaks, and environmental contamination (Stern et al., 1959; Carson, 1962; van den Bosch, 1978; Metcalf, 1980; Kogan, 1998). Since then, IPM has been codified by the Food and Agriculture Organization of the United Nations as the cornerstone of sustainable crop protection and embedded in national policies from Indonesia to the European Union (FAO, 2023; Kogan, 1998; De Schutter, 2011). The logic of IPM is compelling: combine biological, cultural, physical, and chemical tools in a manner that minimizes economic, health, and environmental risks while maintaining crop profitability (Zhang and Liu, 2023; Zhang, 2025). Despite this consensus, the actual transformation of pest management on the ground has been deeply uneven. Numerous surveys conducted across Africa, Asia, Latin America, and North America reveal that the majority of farmers still rely overwhelmingly on calendar-based applications of broad-spectrum insecticides (Parsa et al., 2014; Wilson and Tisdell, 2001; Oerke, 2006; Peshin et al., 2007, 2009, 2023; Zhang et al., 2011; Kumar et al., 2013; Jafarbeigi et al., 2014; Peshin and Zhang, 2014; Zhang, 2018b). Even when farmers report using IPM, scrutiny often reveals a pattern of label adoption, in which integrated elements are reduced to a single practice such as spraying a biopesticide instead of a synthetic one while the underlying decision architecture remains unchanged (Deguine et al., 2021). The central puzzle that motivates this study is therefore the following: why has a scientifically rigorous, logically coherent, and long-promoted knowledge system failed to dislodge the dominance of chemical-centric pest control?

Existing explanations point to diverse proximate barriers: high knowledge requirements, insufficient extension support, perverse subsidies, the lower and more visible cost of synthetics, and the psychological appeal of rapid insect kill (Morse and Buhler, 1997; Parsa et al., 2014; National Research Council, 2000). While these are all valid, they do not fully explain the phenomenon. After 50 years of refinement, the very persistence of these barriers suggests that a deeper structural or paradigmatic issue may be at play. This paper proposes that conventional IPM suffers from a hidden epistemological constraint: it conceptualizes the agroecosystem as a controllable mechanical device whose optimal state can be engineered through precise knowledge and efficient technology. This engineering mindset, inherited from the very industrial agriculture it sought to reform, frames pest management as a problem of optimal control under manageable uncertainty. In reality, agricultural landscapes are complex adaptive systems characterized by nonlinear feedbacks, threshold effects, cross-scale interactions, and inherent unpredictability (Liu et al., 2007; Holling, 2001; Zhang, 2016b, 2018). A paradigm optimized for stability in a predictable world becomes brittle when exposed to the amplified volatility brought by climate change, globalized trade, and landscape simplification (Raza et al., 2019; Meehan et al., 2011; Poppy et al., 2014).

1.2 Aims and significance

This paper pursues two interrelated objectives. The first is to provide a comprehensive yet critical synthesis of the impacts, technological advances, and persistent challenges associated with IPM, organized within a multidimensional evaluation system that goes beyond yield and pesticide reduction metrics. The second and more ambitious goal is to transcend the existing boundaries of IPM theory by constructing an original conceptual framework, Dynamic Resilience-based IPM, that redefines pest management as adaptive stewardship of social-ecological resilience. The significance of this endeavor is twofold. For the academic community, it offers a coherent, interdisciplinary lens that integrates insights from entomology, ecology, economics, social psychology, and complexity science. For policy makers, practitioners, and the agri-food industry, it provides a roadmap for designing pest governance systems that are robust under surprise, rather than merely efficient under normal conditions.

1.3 Research approach and methodological design

The study employs a progressive research design that moves from systematic synthesis to critical diagnosis and then to constructive theorization. The synthesis phase draws on a deliberately broad literature corpus spanning crop protection, landscape ecology, institutional economics, behavioral science, and computational modeling. The diagnostic phase applies meta-analytical reasoning to identify deep pattern failures that recur across geographical and commodity contexts. The theorization phase builds on resilience thinking, adaptive co-management, and complex adaptive systems to propose a coherent framework, complete with operational principles, mathematical formalisms, and an implementation methodology. Where equations are introduced, every variable is defined, and derivations are explicitly laid out in the Appendix. The framework is not presented as a finished prescription but as an auditable theoretical construct open to empirical testing and falsification.

1.4 Core innovations

The paper makes three primary contributions: (1) At the cognitive level, it reframes the IPM challenge away from deficient implementation and toward paradigmatic inadequacy, arguing that the field has reached the efficiency frontier of a static control logic and now requires a resilience logic. (2) At the theoretical level, it synthesizes resilience principles with pest management in an actionable way, introducing the concepts of dynamic adaptive thresholds, cross-scale modular response, strategic redundancy, participatory adaptive learning loops, and ecosystem service co-profitability. (3) At the methodological level, it specifies how a digital twin platform that integrates earth observation, IoT sensor networks, agent-based modeling, and social learning processes can translate these principles into daily decision making, thereby moving from a culture of prescription to a culture of adaptive experiment (Wolfert et al., 2017).

2 Literature review and intellectual architecture of IPM

2.1 Genealogy and paradigm evolution of IPM concepts

The idea of deliberately combining multiple control tactics predates the formal coinage of IPM, but the canonical starting point is Stern and colleagues who defined integrated control as the applied pest management that combines and integrates biological and chemical control (Stern et al., 1959). Economic entomologists then elaborated the notions of economic injury level (EIL) and economic threshold (ET), which became the quantitative core of decision making (Kogan, 1998). Over the following decades, the scope expanded. Kogan traced the historical trajectory from supervised control to IPM and then toward ecologically based IPM that emphasizes the understanding of the multitrophic interactions within the agroecosystem as the foundation for decision making (Zhang et al., 1996, 1997, 2014; Zhang, 2007, 2011, 2016b, 2018a, 2025; Jiang and Zhang, 2015; Iamba and Teksep, 2021). With the rise of sustainability science, IPM was repositioned within holistic farming systems and agroecology, leading to formulations such as Agroecological Crop Protection or Whole-System IPM that encompass soil health, biodiversity, and farmer empowerment (Lewis et al., 1997; Deguine et al., 2021; Holt-Giménez and Altieri, 2013). Each conceptual transition relaxed some of the implicit assumptions of the prior phase but never entirely abandoned the notion that sufficient knowledge and technological sophistication can bring pest problems under rational control.

2.2 The four pillars of classical IPM

The classical IPM knowledge system rests on four pillars, , as synthesized in major textbooks and reviews (Dent and Binks, 2020; Norris et al., 2003): (1) Regular pest population monitoring and forecasting, traditionally based on scouting and pheromone traps, which underpins the idea that interventions should be triggered by biological reality rather than calendar schedules. (2) The economic threshold concept that compares the cost of a control action with the value of the crop loss averted, thus providing an ostensible decision rule for when to act (Pedigo et al., 1986; Higley and Pedigo, 1996; Peterson and Hunt, 2003; Maleki et al., 2015). (3) The integration of multiple control tactics, hierarchically arranged from preventive measures such as host plant resistance and cultural practices to curative interventions such as biological control agents and, only as a last resort, selective chemical pesticides (Heong and Schoenly, 1998; Ehler, 2006; Horowitz and Ishaaya, 2004; Zhang, et al., 2009; Abdolmaleki et al., 2023; Singh, 2025a-b; Zhang, 2025). (4) The minimization of risks to human health and the environment, which legitimizes the entire approach (Zhang, 2025). This framework has been extraordinarily influential and has generated thousands of field trials demonstrating that IPM can reduce pesticide use by 30 to 70 percent while maintaining yield parity (Pretty and Bharucha, 2015; Way and van Emden, 2000). Yet the same literature regularly reports that adoption rates, especially of the more knowledge-intensive preventive practices, remain low (Parsa et al., 2014).

2.3 Contributions and blind spots of existing reviews

The existing review literature has mapped the technical landscape with increasing precision. Annual Review of Entomology papers, multi-country meta-analyses, and sectoral assessments have compiled evidence on the efficacy of specific tools, such as baculoviruses (Zhang et al., 1997), Trichogramma releases, neem extracts, and pheromone mating disruption (Chandler et al., 2011; van Lenteren et al., 2018; Dolati et al., 2013; Sanjaya et al., 2013). A smaller but growing body of work addresses the socioeconomic determinants of adoption, emphasizing farmer education, risk perceptions, and market incentives (Feder et al., 2004; Reardon et al., 2012). However, most reviews remain within the boundaries of the IPM framework itself: they ask how to better implement IPM, rarely whether the conceptual architecture of IPM itself requires fundamental reworking. A few critical voices have noted that the very language of control may be part of the problem, perpetuating a military metaphor that frames nature as an enemy to be subdued (van den Bosch, 1978). Others have pointed to the decoupling between IPM policy rhetoric and on-ground practices, attributing it to institutional inertia and political economy (Deguine et al., 2021; Vanloqueren and Baret, 2009). What is conspicuously absent is a systematic interrogation of the paradigmatic assumptions that lock IPM into a trajectory of diminishing returns. This gap is the entry point for the present study.

3 A systemic evaluation on multidimensional impacts of IPM

3.1 Economic impact: from plot-level margins to food value chains

At the field scale, well-designed IPM programs frequently lower variable costs through reduced insecticide purchases while maintaining or slightly improving yields, resulting in favorable marginal returns. Meta-analyses conducted on rice in Asia, cotton in West Africa, and vegetables in Latin America consistently demonstrate positive benefit-cost ratios when farmers’ own labor and learning investment are appropriately costed (Pemsl and Waibel, 2007; Pretty and Bharucha, 2015; Zalucki et al., 2012; Peshin et al., 2023). Yet the economic value of IPM extends beyond direct production economics. Compliance with IPM protocols is increasingly a prerequisite for accessing premium markets, including Global G.A.P. certification, organic labels, and supermarket private standards (Reardon et al., 2012; Rigby and Cáceres, 2001). The reputational and price premiums attached to such schemes can tip the calculus toward IPM even when short-term input savings appear modest. Moreover, the insurance value of diverse, biologically regulated systems becomes apparent when whole-farm risk is considered: farms with higher functional biodiversity exhibit lower yield variance across seasons (Zhang, 2025; Zhang, et al., 2014), a property that is undervalued in conventional financial analysis (Kremen and Miles, 2012; Tilman et al., 2002; Seufert et al., 2012).

3.2 Ecological impact: beyond pesticide load reduction

Reduction in the volume and toxicity of applied pesticides is the most commonly reported ecological metric of

IPM success, but it captures only a fraction of the ecological story. IPM programs that deliberately enhance floral resources, intercropping, and field margin vegetation can trigger cascading restoration of arthropod food webs (Altieri et al., 1984; Andow, 1991; Heong et al., 1991, 2007; Way and Heong, 1994; Altieri, 1999; Letourneau et al., 2011; Zhang et al., 2014; Jiang and Zhang, 2015; Iamba and Teksep, 2021; Tiwari et al., 2024). Species richness of natural enemies, including spiders, carabid beetles, syrphid flies, and parasitoid wasps, has been shown to increase significantly under IPM compared with conventional farms (Geiger et al., 2010; Letourneau et al., 2011; Hoy, 2011; Singh, 2025a-b). This rebuilding of the predator community translates into enhanced natural biological control, an ecosystem service that is self-replenishing and does not require recurring external inputs (Shepard et al., 1987; Crawley, 1992; Pimental et al., 1992; IRRI, 1998; Altieri, 1996, 1999; Schoenly et al., 1998; Altieri and Nicholls, 2004; Jiang and Zhang, 2015; Zhang et al., 2014; Zhang, 2025). At the landscape scale, IPM fields act as sources of beneficial organisms that colonize neighboring fields, generating positive spillover effects (Tscharntke et al., 2005). Pollination services also benefit from the reduced insecticide pressure and from the floral resources provided by companion plants, leading to improved fruit set and quality in pollinator-dependent crops (Klein et al., 2007; Kamel et al., 2013; Nicholls and Altieri, 2013; Khan et al., 2016; Willcox et al., 2023; Zhang, 2027a). These multifunctionality gains remain invisible in conventional cost-benefit analyses because they are not transacted in markets (Power, 2010; Zhang, 2027b).

3.3 Social and health impacts

The human health benefits of IPM are substantial and multi-layered. For farm workers and smallholder families, the reduction in exposure to organophosphates, carbamates, and other neurotoxic compounds lowers the incidence of acute poisonings and the burden of chronic diseases, including certain cancers and neurological disorders (Pimentel, 2005; Zhang et al., 2011; Mardani et al., 2017; Zhang, 2018, 2025). Epidemiological studies in developing countries have documented measurable declines in blood cholinesterase depression after the transition to IPM (Pimentel and Burgess, 2014). For consumers, the reduction in pesticide residues on food products alleviates a pervasive source of anxiety and, where enforcement is weak, genuine health risk. Beyond health, the participatory nature of quality IPM training, particularly the Farmer Field School approach, builds collective human capital (Peshin et al., 2023). Farmers who have undergone season-long experiential learning in agroecosystem analysis show improved observational skills, greater confidence in experimentation, and stronger social networks (Feder et al., 2004). These cognitive and social assets can spill over into other livelihood domains, making IPM an entry point for broader community resilience.

3.4 An emergent insight

Past studies reveals a pattern: the most durable and transformative IPM successes tend to occur when the program fosters systemic enhancements such as natural enemy conservation, soil health improvement, and farmer empowerment rather than when it merely substitutes one input for another (Settle et al., 1996; Zhang and Pang, 2009; Lu et al., 2012). This observation suggests that the benefits of IPM are best understood as emergent properties of a resilient social-ecological system, not as the direct output of a pest suppression algorithm. The insight will serve as the empirical foundation for the theoretical reconstruction that follows.

4 Frontier advances in technology, biology, and governance

4.1 Digital leap in sensing and decision making

Advances in sensor technology, artificial intelligence, and connectivity are transforming pest monitoring from episodic human observation to continuous, high-resolution digital streams. Automated camera traps equipped with deep learning algorithms can identify, count, and even sex pest insects in real time at the species level (Wolfert et al., 2017). Acoustic sensors and laser-based entomological lidars can quantify aerial insect densities. Satellite constellations with submeter spatial resolution and revisit times of a few days, combined with unmanned aerial vehicles, allow vegetation indices and stress signatures to be mapped over entire production landscapes. These data streams are being integrated into cloud-based decision support systems that forecast pest population trajectories using process-based and machine-learning models. The digital revolution makes it technically feasible for the first time to operationalize dynamic, spatially explicit pest management at scale.

4.2 Deep innovation in biological control and biotechnology

The biological control toolbox is expanding rapidly. Classical inoculative and augmentative release strategies are being supplemented by conservation biological control that explicitly manipulates habitat to support resident natural enemy communities (Jonsson et al., 2008; Wyckhuys et al., 2013; Eilenberg et al., 2001; Zhang et al., 2014; Jiang et al., 2015). At the molecular frontier, RNA interference pesticides offer a mode of action that can be designed to target specific pest species while sparing nontarget organisms. Gene drive systems based on CRISPR-Cas9 are being researched for the potential suppression or replacement of vector and pest populations, though their deployment raises profound ecological and ethical questions (Zhang and Pang, 2009; Jafarbeigi et al., 2014; Zhang et al., 2018b; Gould et al., 2018; Brookes and Barfoot, 2020). Semiochemicals, including aggregation and alarm pheromones, are being embedded in biodegradable dispensers that can be deployed across large areas via drones. The integration of microbial biopesticides based on entomopathogenic fungi, bacteria, and nematodes has improved substantially through advances in formulation, shelf-life extension, and application technology (Schoenly et al., 2003; Chandler et al., 2011; Sanjaya et al., 2013; Hajek and Eilenberg, 2018; Baker et al., 2020).

4.3 Agroecological engineering and landscape design

The ecological intensification of agriculture is generating practical design principles for pest-suppressive landscapes. Push-pull strategies, originally developed for cereal stemborers in Africa, have been refined to exploit a wider range of semiochemical and visual cues and have been adapted to multiple cropping systems (Khan et al., 2010; Khan et al., 2000). Habitat banks, beetle banks, flower strips, and hedgerow networks are being configured to maximize the connectivity of source habitats for natural enemies while minimizing edge-to-area ratios that could favor pest species (Altieri et al., 1984; Andow, 1991; Way and Heong, 1994; IRRI, 1998; Altieri, 1999; Landis et al., 2000; Zhang et al., 2014; Gurr et al., 2017; Paredes et al., 2015; Iamba and Teksep, 2021). At the landscape scale, the concept of ecological infrastructure is gaining traction, whereby non-crop habitats are deliberately planned and managed to deliver a bundle of ecosystem services, including pest regulation, pollination, and water purification, that support agricultural production (Cumming, 2011; Tscharntke et al., 2012; Perfecto and Vandermeer, 2010; Zhang et al., 2014; Willcox et al., 2023). The use of secondary plants and trap crops further exemplifies the design of agroecosystems that are inherently less susceptible to pest outbreaks (Shelton and Badenes-Perez, 2006; Parolin et al., 2012).

4.4 Institutional and behavioral advances

On the governance side, Farmer Field Schools have been complemented by social learning networks, video-mediated extension, and digital advisory services delivered via smartphones (Feder et al., 2004; World Bank, 2020). Behavioral nudges, such as simplified decision trees, peer comparison feedback, and conditional cash transfers, are being tested as means to accelerate the transition away from calendar spraying. Payment for ecosystem service schemes have begun to reward farmers for maintaining biological control capacity (Zhang, 2027b), while innovations in blockchain and smart contracts offer the possibility of transparent, low-transaction-cost verification of ecological outcomes. Participatory research frameworks, originally developed for plant breeding, are increasingly being adapted to pest management to strengthen local innovation capacity (Sperling et al., 2001). These advances collectively signal a shift toward more reflexive, multiactor governance arrangements, but they remain fragmented and unguided by an integrative paradigm (Armitage et al., 2008).

5 The Efficacy Paradox of IPM

5.1 Cognitive and technical: static logic confronts complex systems

The foundational decision rule of IPM, the economic threshold, was conceived in an era when insect population dynamics were viewed as roughly predictable and the main question was whether the cost of an insecticide application would be justified (Higley and Pedigo, 1996; Peterson and Hunt**,** 2003). The classic formulation sets ET equal to the control cost divided by the product of crop market value, damage per pest, and control efficacy. This formulation is inherently static and univariate. It assumes that pest damage accrues in a linear, additive manner and that the relationship between pest density at the time of scouting and ultimate yield loss is known and stable (Pedigo et al., 1986). In reality, crop plants exhibit tolerance and compensatory growth that vary with soil moisture, nutrient status, and weather conditions, rendering the damage coefficient a dynamic variable rather than a constant (Strand, 2000). Outbreaks of vector-borne plant pathogens, where a single aphid or whitefly can transmit a virus before any insecticide can act, expose the logical collapse of a threshold that waits for a critical population density to be reached (Lucas, 2020). Interactive effects among co-occurring pest species can generate nonlinear yield losses that a single-species threshold cannot capture (Gagic et al., 2016; Litsinger et al., 2011). The classical ET also ignores the collateral damage that a curative insecticide application inflicts on natural enemy populations, thereby setting the stage for subsequent pest resurgence (Rosenheim, 1998; Schowalter, 2017; Mardani et al., 2017; Faghani and Rahimian, 2018; Ali et al., 2026). In general, a static threshold cannot serve as an early warning of a system approaching a catastrophic regime shift.

5.2 Economic and institutional: structural disincentives

The political economy of pest management creates a powerful gravity toward chemical solutions. In many countries, pesticide subsidies lower the effective price of insecticides below social cost, while the negative externalities are borne by communities, health systems, and the environment (Wilson and Tisdell, 2001; Pimentel, 2005). The manufacturers, distributors, and retailers of chemical inputs form a dense, well-capitalized network that provides technical advice, credit, and marketing services that are bundled with pesticide sales (Vanloqueren and Baret, 2009). In contrast, the knowledge and ecological infrastructure required for IPM are public goods or common-pool resources that are systematically underprovided by the market (Ostrom, 2009). Ecosystem services such as natural pest regulation and clean water carry no price tag in farm budgets, making investments that generate these services appear unprofitable in the short term (Power, 2010; Zhang, 2027b). This structural asymmetry means that even when IPM is economically superior at the societal level, the private decision maker faces a tilted playing field.

5.3 Sociopsychological and extension: the knowledge-action gap

Human decision making under uncertainty is biased toward salient, visible, and immediate feedback. The rapid knockdown of insects observed after a broad-spectrum spray is a vivid, tangible outcome that reinforces the user’s confidence in the product. The gradual buildup of a parasitoid population over several weeks, in contrast, is invisible to the naked eye and requires a trained ecological imagination to appreciate. Conventional extension systems, often modeled on the linear transfer-of-technology paradigm, fail to cultivate the adaptive expertise needed to manage pests in a context-specific, dynamic manner (Feder et al., 2004; Morse and Buhler, 1997). Farmers receive prescriptions rather than diagnostic skills, leading to a hollowing out of local ecological knowledge and a dependency on external experts. The resulting knowledge-action gap persists even when farmers express positive attitudes toward IPM and understand its principles in abstract terms.

5.4 Amplifiers of perturbation: global change and novel uncertainties

Anthropogenic climate change is systematically eroding the predictability that conventional IPM presupposes. Warmer temperatures accelerate insect development, increase the number of generations per season, and expand the geographic range of many pest species poleward and to higher elevations (Raza et al., 2019; Savary et al., 2019; Rafiei, 2025; Zhang, 2026a-b). The brown planthopper in tropical Asia, for instance, illustrates how a secondary pest can become a primary threat under altered crop management and climatic conditions (Bottrell and Schoenly, 2012). Extreme weather events, such as droughts and floods, disrupt the delicate synchronization between pests and their natural enemies (Ragsdale et al., 2011). The globalization of trade introduces novel pests and pathogens at an unprecedented rate, confronting unprepared agroecosystems and regulatory systems with organisms against which no established IPM protocol exists (Oerke and Dehne, 2004). These trends mean that the baseline of static knowledge on which classic thresholds and calendars were built is dissolving, and even the best-designed IPM program of today may be rendered obsolete within a decade (Altieri et al., 2015).

5.5 A diagnostic conclusion

The evidence assembled across these dimensions converges on a single diagnosis. IPM is not failing because its individual tools are ineffective. It is failing because its underlying logic treats agricultural systems as stable, predictable, and controllable machines when in fact they are dynamic, nonlinear, and emergent systems (Holling, 2001). The pursuit of an optimal integrated control strategy within a static framework has reached the limits of its explanatory and operational power. The next stage of evolution requires a paradigm shift from engineering control to ecological adaptation, from optimization to resilience (Walker et al., 2004; Zhang, 2016a-b).

6 Original theoretical construction: the Dynamic Resilience-based IPM framework

6.1 Conceptual foundations and intellectual lineages

The DR-IPM framework draws on three intellectual traditions (Fig. 1). The first is social-ecological resilience thinking, originally articulated by Holling (1973) and subsequently elaborated by the Resilience Alliance. Resilience is defined not as the ability to return to a single equilibrium after disturbance but as the capacity of a system to absorb perturbations and reorganize while retaining essentially the same function, structure, and feedbacks (Holling, 1973; Folke, 2006; Zhang, 2016a-b). The second is adaptive co-management, a governance approach that treats policy as a series of deliberate experiments, linking scientists, resource users, and institutions in iterative learning cycles (Olsson et al., 2004; Armitage et al., 2008). Finally, the third is complex adaptive systems theory, which views large-scale patterns as emergent outcomes of local interactions among heterogeneous agents, with properties such as self-organization, tipping points, and path dependency (Liu et al., 2007; Zhang, 2016b). DR-IPM applies these insights to the specific domain of pest management, constructing a set of operational principles that turn resilience from a metaphor into a measurable and manageable property (Carpenter et al., 2001).

6.2 The five core principles of DR-IPM

Principle I: Dynamic Adaptive Thresholds

The classical economic threshold is replaced with a dynamic adaptive threshold that is a vector function of current pest population density, natural enemy density as a ratio, crop physiological status, weather forecasts, and market price signals. Formally, let $X(t)$ be a multivariate state vector including pest abundance $N(t)$, predator abundance $P(t)$, plant biomass $B(t)$, and soil moisture $M(\mathrm{t})$. The dynamic threshold is not a single number but a decision boundary $D(t)$ in the state space that separates the basin of autonomous regulation from the basin where intervention is required to prevent an irreversible shift. $D(t)$ is updated continuously via Bayesian inference that integrates prior probability distributions of damage functions with real-time sensor data. An early warning indicator is derived from the predator-prey ratio: when the ratio falls below a critical threshold θ_c, the system is deemed to be losing its regulatory capacity, and a preemptive, low-intensity intervention is triggered even if pest numbers remain below the conventional ET. The mathematical specification, including a transition probability model, is provided in Appendix.

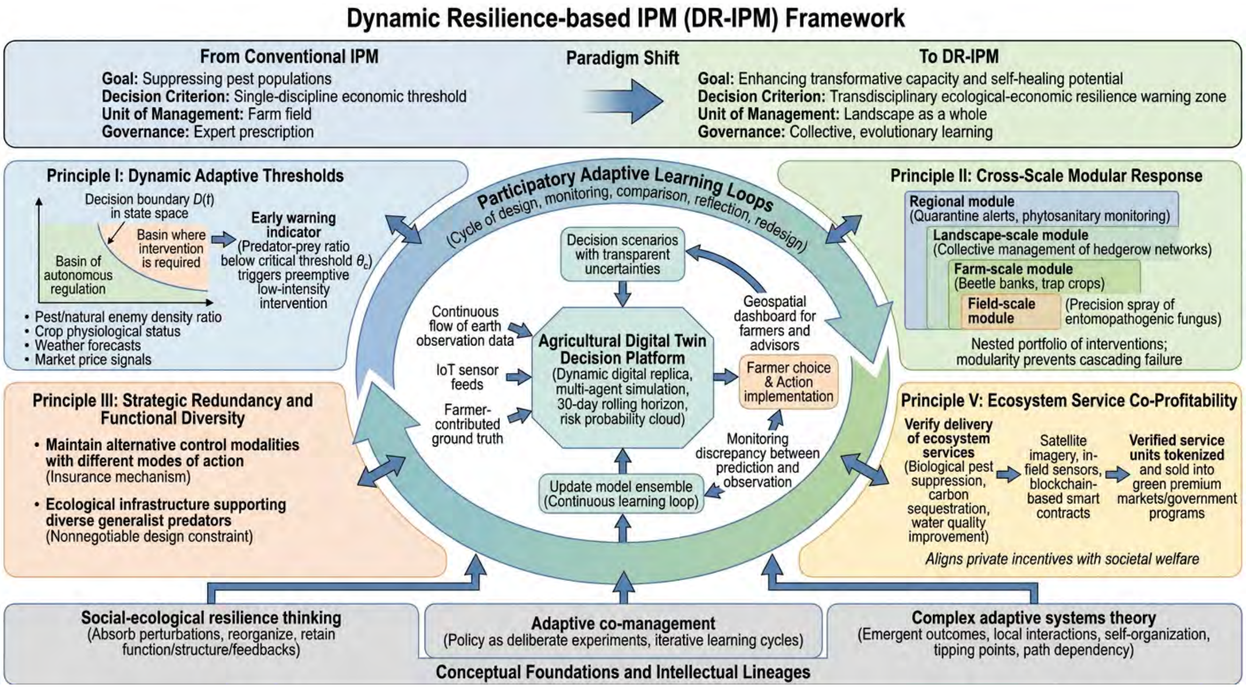

Fig. 1 Systematic diagram of Dynamic Resilience-based IPM framework.

Principle II: Cross-Scale Modular Response

Pest outbreaks are scale-crossing phenomena. A field-level infestation may originate from a landscape-level simplification that removed overwintering habitats. Under DR-IPM, any decision event triggers a simultaneous assessment at the field, farm, landscape, and regional scales, generating a nested portfolio of interventions. The field-scale module might deploy a precision spray of an entomopathogenic fungus; the farm-scale module activates beetle banks and trap crops; the landscape-scale module coordinates collective management of hedgerow networks through a local cooperative; and the regional module initiates quarantine alerts and phytosanitary monitoring. The principle of modularity ensures that a failure at one scale does not cascade to the whole system and that responses are tailored to the processes operating at each scale (Schellhorn et al., 2015; Cumming, 2011).

Principle III: Strategic Redundancy and Functional Diversity

Conventional IPM seeks to optimize by selecting the single most cost-effective tactic. DR-IPM deliberately maintains functional redundancy in the control portfolio. Even if at a given moment a synthetic insecticide appears cheapest, the farmer is required to maintain and periodically exercise at least two alternative control modalities with different modes of action, such as a microbial antagonist and a physical barrier (Zhang and Liu, 2023). This redundancy functions as an insurance mechanism. In the event that a sudden pest evolution overcomes one mode of action, the backup mechanism is already active and ready to be scaled up. Functional diversity in the landscape is similarly treated as a nonnegotiable design constraint: a minimum proportion of farm area must be managed as ecological infrastructure that supports a diverse guild of generalist predators (Landis et al., 2000; Letourneau et al., 2011; Zhang et al., 2014; Zhang, 2025).

Principle IV: Participatory Adaptive Learning Loops

Instead of a linear sequence of research-extension-adoption, DR-IPM organizes pest governance as a continuous cycle of design, monitoring, comparison, reflection, and redesign. All stakeholders, including farmers, extension agents, researchers, and market actors, participate in a structured process of collaborative inquiry. Mobile applications and digital dashboards allow farmers to upload observations, photographs, and decisions, which are aggregated and visualized for the community. Seasonal debriefing workshops compare model predictions with actual outcomes, update model parameters, and renegotiate shared thresholds and rules. This transforms the governance system into a social learning community in which adaptive expertise is cultivated and distributed rather than concentrated in a central authority (Olsson et al., 2004; Armitage et al., 2008).

Principle V: Ecosystem Service Co-Profitability

DR-IPM embeds pest management in a value-capture architecture that monetizes the positive externalities of resilient practices. Using satellite imagery, in-field sensors, and blockchain-based smart contracts, the framework verifies the delivery of ecosystem services such as biological pest suppression, carbon sequestration, and water quality improvement (Zhang, 2027b). Verified service units are tokenized and sold into green premium markets, government environmental programs, and corporate supply chain sustainability commitments. This co-profitability mechanism reverses the perverse economic logic that currently penalizes IPM adopters (Zhang, 2027b). By making resilience visible and tradable, DR-IPM aligns private incentives with societal welfare (Power, 2010; Kremen and Miles, 2012; Zhang, 2027b).

6.3 Operationalization: the agricultural digital twin decision platform

The operational heart of DR-IPM is an agricultural digital twin: a dynamic, digital replica of the focal agroecosystem that ingests a continuous flow of earth observation data, IoT sensor feeds, and farmer-contributed ground truth. The twin runs a multi-agent simulation in which virtual pest and natural enemy populations interact across a spatially explicit landscape under multiple climate scenarios (Zhang et al., 1997; Müller et al., 2013). For a given current state, the platform simulates a 30-day rolling horizon for each candidate intervention portfolio, generating a risk probability cloud for economic loss, yield, and ecological service provision. Farmers and advisors interact with the twin through a geospatial dashboard that presents not a single recommendation but a set of decision scenarios with transparently communicated uncertainties. The farmer makes a choice, the outcome is monitored, and the discrepancy between prediction and observation is fed back to update the model ensemble through a continuous learning loop (Wolfert et al., 2017). The process embeds the adaptive learning cycle in daily operations and gradually reduces the structural uncertainty of the models.

6.4 Paradigm shift: from control to adaptive stewardship

The transition from conventional IPM to DR-IPM represents a paradigm shift in the Kuhnian sense. The goal redefines from suppressing pest populations to enhancing the system’s transformative capacity and self-healing potential (Walker et al., 2004). The decision criterion shifts from a single-discipline economic threshold to a transdisciplinary ecological-economic resilience warning zone. The unit of management expands from the farm field to the landscape as a whole (Tscharntke et al., 2005). And the governance process transitions from expert prescription to collective, evolutionary learning. This framework elevates IPM from a methodology for pest control to an adaptive governance philosophy for social-ecological systems (Folke et al., 2005; Zhang, 2016b).

7 Prospects: future pathways and systemic transformation under DR-IPM

7.1 Frontier technologies in service of resilience

Robotic embodied intelligence will in the near future be able to patrol fields autonomously, deploy redundant control tactics with millimeter precision, and collect high-frequency data on crop and insect physiology. Synthetic biology may soon deliver designer plant defense circuits that are inducible, tunable, and transferable across crop species, providing a novel form of endogenous, energy-efficient resilience. The convergence of these technologies with the DR-IPM framework could automate a significant part of the monitoring and tactical execution while keeping strategic decision making in the hands of a well-informed human collective.

7.2 Institutional and market reconstruction

The policy architecture required for DR-IPM differs fundamentally from current agricultural support. It includes a green resilience subsidy and insurance system that rewards farms achieving predefined levels of functional diversity and cross-scale coordination, reducing premiums as proof of system robustness accumulates. A pest resilience governance zone, delineated on ecological rather than administrative boundaries, could coordinate monitoring, establish shared thresholds, and pool resources for landscape-scale interventions (Schellhorn et al., 2015). Certification schemes and commodity roundtables can integrate DR-IPM indicators into their standards, creating demand pull from the downstream supply chain (Reardon et al., 2012).

7.3 Differentiated trajectories in a globalized world

The implementation pathways will necessarily differ between regions. In smallholder-dominant contexts of Sub-Saharan Africa and South Asia, a lightweight digital DR-IPM that relies on mobile phones, community-based facilitators, and oral tradition enhanced by simple decision heuristics may be more appropriate than a capital-intensive digital twin. Here, the emphasis falls on building human and institutional resilience (Pretty et al., 2011). In large-scale mechanized farming systems of the Americas, Europe, and Oceania, the full digital twin platform can be deployed, integrated with precision agriculture machinery and corporate sustainability accounting. In both cases, the core principles of dynamic thresholds, modularity, redundancy, and learning remain invariant.

7.4 Research agenda for validation

The DR-IPM framework is a theoretical construct that requires empirical confrontation. Priority hypotheses to test include: whether the dynamic adaptive threshold provides significantly earlier warning of vector-borne pathogen outbreaks than the static ET; whether farms that maintain strategic redundancy exhibit faster recovery of pest regulation after extreme climatic events; and whether tokenized ecosystem service payments alter farmer decision making more effectively than conventional subsidies. Open-source, low-code community resilience modules need to be developed and tested in living laboratories across diverse agroecologies. Long-term, comparative, whole-system experiments that benchmark DR-IPM fields against conventional IPM fields under both ambient and perturbed conditions will be essential to move from plausible reasoning to evidence-based practice.

8 Conclusion

8.1 Summary of the investigation

This paper has systematically evaluated the scientific record on Integrated Pest Management, documenting its tangible impacts on profitability, biodiversity, and human health, while simultaneously diagnosing the deep structural, cognitive, and paradigmatic constraints that limit its transformative potential. I argued that the root cause of the persistent gap between IPM's promise and its performance lies in a static control paradigm that is fundamentally mismatched with the dynamic complexity of agroecosystems under global change.

8.2 Contributions and practical value

In response, I constructed the Dynamic Resilience-based IPM framework, an original synthesis of resilience theory, adaptive co-management, and complex systems thinking (Zhang, 2016b). DR-IPM supplies five actionable principles: dynamic adaptive thresholds, cross-scale modular response, strategic redundancy, participatory adaptive learning loops, and ecosystem service co-profitability. It offers an operational methodology centered on an agricultural digital twin that turns pest governance into a continuous, participatory, and evidence-rich adaptive cycle. For policy makers, DR-IPM provides a blueprint for designing agricultural policies that generate positive feedback between ecological regeneration and economic prosperity.

8.3 Limitations and critique

DR-IPM is predicated on access to data streams, institutional coordination, and sustained investment that are currently unevenly distributed. In resource-poor regions, the full digital-twin vision may be aspirational rather than immediately actionable. The framework remains a theory until validated through empirical research. It may also contain blind spots inherited from the very resilience thinking it champions, such as an underappreciation of power asymmetries and political conflict in shaping which system states are deemed desirable. A critical and reflexive posture must accompany the operational deployment of DR-IPM to ensure it empowers rather than marginalizes the farmers it intends to serve.

Appendix

Formal specification of the Dynamic Adaptive Threshold

The dynamic adaptive threshold is derived from a stochastic economic injury model extended with an ecological resilience indicator. The classic economic injury level *EIL* is given by:

$$EIL = C / (V \times D \times K)$$

where *C* is the cost of the control action per hectare, *V* is the farmgate price per unit of crop product, *D* is the yield loss per pest individual per unit area, and *K* is the proportion of the pest population killed by the control action. The static economic threshold *ET* is typically set at some fraction below the *EIL* to account for the time lag between scouting and action.

In DR-IPM, we recognize that *D* is not a constant but a function of crop physiological status, soil water potential, and prior damage history. Moreover, pest population impacts on yield are mediated by the functional response of the natural enemy community. We therefore define a state-dependent damage function:

$$D(t) = D_0 \times f(B(t), M(t)) \times g(P(t)/N(t))$$

where $B(t)$ is the crop biomass or leaf area index, $M(t)$ is a soil moisture index, $P(t)$ is the density of effective natural enemies, $N(t)$ is the pest density, and g is a sigmoid function that takes values near 1 when the predator-prey ratio is low and approaches a lower asymptote when the ratio is high, indicating effective biological regulation. The function g can be parameterized from field cage or exclusion experiments.

The instantaneous expected loss over a future time horizon *T* is:

$$L(t) = \int_t^{t+T} V(\tau) \times D(\tau) \times N(\tau)\, d\tau$$

The dynamic adaptive threshold boundary is defined by the condition that the expected loss over the horizon exceeds the cost of a diversified intervention portfolio I that includes at least one tactic from each functional group. However, rather than waiting for this condition to be met, DR-IPM computes a resilience early-warning index:

$$RWI(t) = P(t) / N(t) - \theta_c$$

Where θ_c is a critical threshold derived from local empirical relationships. When $RWI(t)$ drops below zero, the system is considered to be approaching a loss of regulatory capacity, and a preemptive, low-intensity redundant intervention is triggered even if current pest density is below the conventional *ET*.

The parameters D_0, f, g, and θ_c are continuously updated through Bayesian hierarchical modeling. At the beginning of each season, prior distributions are specified based on historical data. As real-time sensor and farmer reports flow in, posterior distributions are computed, and the dynamic threshold $D(t)$ is recalculated on a rolling basis. The digital twin uses these posteriors to perform multi-agent simulations that generate forecast probability clouds for each management scenario, which are presented to the farmer participatory group for collective deliberation. This approach embodies the principle that in complex adaptive systems, the optimum is transient and learning is perpetual (Zhang, 2016b).

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