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Pest management research is not geared toward transformability

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From the earliest origins of farming, agri-food production has undergone transformational changes. These have permitted a steady output of nutrient-dense farm produce to feed ever-growing human populations and to advance societal development. Crop domestication and breeding, agricultural mechanization, agronomy, irrigation and chemically synthesized fertilizers and pesticides have all progressively lifted productivity levels (Pingali, 2012; Scott, 2017). Since the mid-1900s, substantial yield gain has been achieved by deploying improved crop varieties under input-intensive management schemes, for example, during the so-called "Green Revolution." Although such packaged "seed × chemical" technologies became hallmark features of global agriculture, depressed food prices and thereby alleviated poverty, they also induced undesirable social-environmental externalities (Pingali, 2012). In the world's bread baskets, yields of prime food staples are now stagnating while total factor productivity drops (Ramankutty et al., 2018). Overreliance upon petroleum-derived inputs is broadening the environmental footprint of global agriculture (Rockström et al., 2020), triggering biodiversity loss, undermining resilience and promoting resistance to pesticides, while crops are increasingly under pressure from pests and diseases, weather anomalies and a fast-degrading natural resource base. There is growing global concern that the current status quo of input-intensive agri-food production is insupportable (Dalin and Outhwaite, 2019).

Globally, food production relies on synthetic pesticides to tackle crop pests, diseases, and weeds. The manufacture, distribution and application of these compounds is highly energy-intensive, generating up to 6% of the greenhouse gas emissions from the world's cropland (Wyckhuys et al., 2022a). Since the 1940s, pesticide mass, usage intensity and toxicity loading have progressively increased and these patterns are currently exacerbated in the Global South (Bernhardt et al., 2017; Shattuck et al., 2023). Pesticide-intensive agriculture is characterized by weakened trophic interactions and ecosystem function and consequently it is vulnerable to climatic disruptions and pest shocks (Davis et al., 2021; Bullock et al., 2022). Meanwhile, climate change deepens biotic losses by facilitating the expansion of pest distributions, increasing pest survival and fostering pesticide resistance, thereby constraining the efficacy of the crop protection tool most favored by farmers (Ma et al., 2021). Thus, given fast-progressing global change, pesticide intensive pest management is becoming ever more untenable.

Since the late 1980s, scientists and world leaders have stressed the importance of implementing sustainable practices to secure current food production without compromising natural capital (Brundtland et al., 1987). In 1996, a conceptual framework was designed to analyse and implement a global transition toward the adoption of agroecological practices (Hill and Macrae, 1996). This approach is now widely used to position farming systems along an ecological intensification trajectory that ranges from increased *efficiency* of input use (i.e., shallow sustainability) through input *substitution* to a radical, wholesale *redesign* of the entire production system (i.e., deep sustainability). Here, we use this framework to gauge how sustainable pest management science has evolved over the past 50 years by examining relevant research outputs for a devastating crop pest of global significance.

Endemic to the Neotropics, the fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) is a debilitating pest of forage and food crops such as maize, rice, sorghum, and pasture grasses (Montezano et al., 2018). For as long as we know, FAW has affected maize production in its center of domestication and diversity. Since 2016, the pest has successively invaded the African, Asian and Oceania continents and in each, maize has been the most impacted crop (Day et al., 2017; Yan et al., 2021; Volp et al., 2022). Crop losses of more than US$9 billion per annum have been inflicted in Africa alone (Kenis et al., 2022). Its voracious feeding habits, long-range migration and capacity to evolve resistance to xenobiotics have made FAW one of the world's most notorious pests. Pesticide-centered management is increasingly challenging, as FAW currently presents 257 cases of resistance against 45 different insecticide active ingredients worldwide (Mota-Sanchez and Wise, 2024). Thus, FAW offers a unique opportunity to understand how the scientific endeavor has pursued its sustainable management over space and time, allowing for an in-depth analysis of the emerging research foci as the pest makes its appearance in new geographies.

We conducted a systematic literature review to characterize global scientific progress on FAW pest management. Using the search string TS = [(Spodoptera frugiperda) AND (pest*)], we interrogated the Web of Science (WoS) Core Collection for articles published from the beginning of 1980 to 30 September 2023. For each literature record, we logged geographical focus as that of the first author's principal affiliation. In addition, 100 publications prior to 1980 were added manually by screening reference lists in the existing literature collection for key publications with the highest numbers of citations. Prior to 1980, the WoS database did not include authors' addresses and it was thus impossible to geographically delineate the published research. Studies that were not relevant to our investigation (i.e., those that did not investigate a particular aspect of pest management) were excluded. We also excluded works from Europe as FAW is not established there (Kenis et al., 2022) and our objective was to compare practices in regions where FAW has recently invaded and become problematic (i.e., Africa, Asia, and Oceania) with those in its native range. For each retained publication, we methodically screened the abstract to capture the type and nature of the pest management practice investigated. Next, we categorized this focal practice using the sustainability framework of Hill and Macrae (1996), positioning the practice along the framework's efficiency-substitution-redesign continuum.

Studies that implemented adjustments to reduce agrochemical inputs, particularly pesticides, were considered to represent *efficiency*, step 1 on the continuum. These comprised studies addressing novel pesticide application modes e.g., ultra-low volume spraying, seed coating or drone-based pesticide delivery, pest detection or surveillance to better target pesticide application, pesticide resistance monitoring or outreach efforts. Studies that replaced synthetic chemical products or practices with more environmentally benign alternatives that promoted natural pest regulation were defined as *substitution* (step 2); many publications in this domain promoted biological pest control by a range of microbial, invertebrate, or vertebrate agents. Finally reports of research that radically modified conventional practices through a wholesale re-building of the agri-production system were defined as *redesign* (step 3). These comprised more extensive changes in the farming system through crop diversification, reduced tillage, ecological infrastructures to attract beneficial arthropods, and conservation practices which consider the benefits of the natural landscape (Wezel et al., 2013; Pretty, 2018). Lastly, investigations that generated baseline biological and/or ecological insights without specifically addressing in-field pest management, though important, were not considered part of the sustainability framework *per se* (step 0).

Our initial literature corpus contained 2,364 publications, covering North America ($n = 678$), South America (562), Central America (16), Main Asia (=Asia- excluding Southeast Asia; 638), Southeast Asia (25), Africa (163), Middle East (15), Oceania (25), and Europe (242). After excluding irrelevant works, a final collection of 1,929 publications was obtained. Of these 39.6% were categorized as reporting step 0 research while the remainder ($n = 1,136$) reported on the three steps along the ecological intensification continuum; *efficiency* (9.3%), *substitution* (48.3%) and *redesign* (2.7%) (Figure 1A). Research on *efficiency* has mostly been conducted in North America ($n = 51$) and Main Asia ($n = 76$), while progress on *substitution* has been primarily within South America ($n = 345$ publications) and North America ($n = 291$), consistent with the long biological control research trajectory in the pest's native range (Wyckhuys et al., 2024). Lastly, research on farming system *redesign* has mainly been conducted in North America ($n = 18$) and Africa ($n = 13$). A generalized linear model ($R^2 = 0.5485$) revealed how overall scientific output (i.e., average number of publications) was determined by three variables (1) ecological intensification ($F = 22.441$, $P < 0.0001$), (2) continent ($F = 7.190$, $P < 0.0001$), and (3) publication year ($F = 1.506$, $P = 0.0269$).

Globally, invertebrate biological control, biopesticides (microbial and botanical) and pest-resistant crop varieties have received critical amounts of scientific attention for the management of FAW (Table 1). Since the earliest literature record analyzed in this study (published in 1968), global scientific output has gradually increased over time producing an average of 126.1 publications per year over the decade 2013–2022. Temporal increases in scientific output are most prominent for the *substitution* step in the Americas (Figure 1B). Although maize-bean polycultures, widely implemented during pre-Columbian times, suffer far less pest problems than crops managed under pesticide-intensive methods (Altieri et al., 1978), such "redesigned" systems barely feature in the global FAW literature. This with the notable exception of Africa where locally designed push-pull technologies developed for the management of other cereal pests have been adapted to provide cost-effective non-chemical control for FAW (Midega et al., 2018). Importantly, research in the pest's invasive range, particularly in Asia, has focused on substitution and efficiency of pesticide application (Table 1), largely mirroring that in the

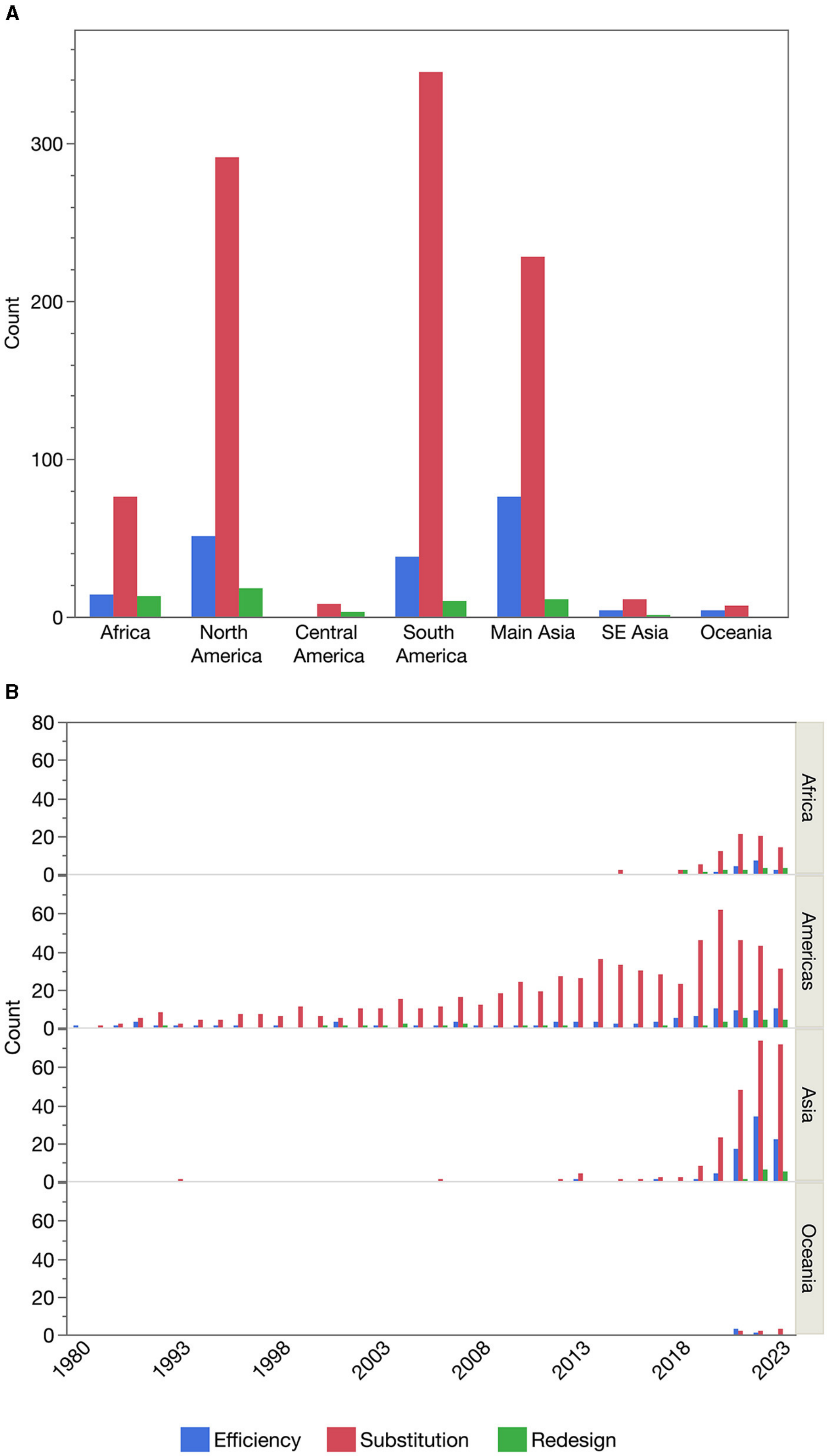

FIGURE 1
Spatio-temporal alignment of FAW pest management science with the efficiency-substitution-design continuum. **(A)** Depicts a continental breakdown of the total number of publications in three domains: enhanced efficiency, input substitution and farming system redesign. **(B)** Shows temporal patterns in publication outputs along the above continuum for Asia, Africa, Latin America and Oceania. Note that Asia only includes Main Asia and SE Asia.

TABLE 1 Continental-scale breakdown of the most extensively researched FAW management practices in the Americas, Asia, Africa, and Oceania.

Farming approach	Practice	Number of publications					Ranking (top 10) by continent			
		Total	Americas	Asia	Africa	Oceania	Americas	Asia	Africa	Oceania
Substitution	Biopesticides - botanical	177	137	28	12	0	1	3	4	-
Substitution	Bt transgenics	144	128	11	4	0	2	-	8	-
Substitution	Biological control - parasitoids	90	47	30	13	0	5	2	3	-
Efficiency	Pesticide application methods	77	33	41	3	0	8	1	9	-
Substitution	Resistant varieties	70	53	9	8	0	3	-	5	-
Substitution	Bt insecticidal protein	64	51	12	1	0	4	10	-	-
Substitution	Biopesticides - entomopathogenic fungi	58	29	24	5	0	9	4	7	-
Substitution	Biopesticides - virus	49	36	10	3	0	7	-	9	-
Redesign	Crop habitat management	47	23	10	14	0	10	-	2	-
Substitution	Insecticide Resistance Management	45	20	17	3	6	-	8	9	1
Efficiency and Substitution	IPM	41	13	11	15	2	-	-	1	2
Substitution	Effect of pesticides on beneficials	40	37	2	1	0	6	-	-	-
Substitution	Highly efficient pesticides	40	16	19	5	0	-	6	7	-
Substitution	Biological control - predators	39	22	11	6	0	-	-	6	-
Substitution	Highly selective insecticides	33	11	20	1	1	-	5	-	3
Substitution	Biological control - entomopathogenic nematodes	29	13	14	2	0	-	9	10	-
Efficiency	Improved diagnostic methods	28	6	18	2	2	-	7	10	2

Farming approaches are listed by declining scientific attention across all four regions combined. Columns 2-5 report the number of times that a given pest management practice is cited in each of the regions. The four columns at the right show the ranking of the 10 most common approaches in each region.

Americas decades previously (Figure 1B). However, positive effects from these approaches, can easily become exhausted if they are not integrated with or replaced by a larger set of ecologically sound practices. Given the rapid chemical intensification of Asia's farmland, these developments are cause for concern and warrant remediation, especially as research on *highly efficient pesticides* regardless of their secondary effects is still prioritized (Table 1). Similarly, the recent arrival of FAW in Oceania has seen research focus on managing pesticide resistance (Table 1). Improved efficiency of pesticide-centered approaches and management of the resistance problems that typically ensue will not lead to the required system changes needed to promote the adoption of agro-ecological approaches and sustainability. Given the above, bold awareness raising, regulatory caps and creative incentive schemes are required to put crop protection more firmly on the required agro-ecological track.

Pesticides are well recognized as drivers of biodiversity loss and ecosystem collapse (Carson, 1962). An effective harnessing of biodiversity and agroecological processes for crop protection at field, farm and agro-landscape scales can greatly reduce our reliance upon pesticidal entrants and bolster agro-ecosystem resilience, even in the face of climate change (Heeb et al., 2019; Bullock et al., 2022). Our work shows that the requisite research to implement ecologically based pest management is steadily increasing (Figures 1A, B). However, this progressive approach must be interpreted with important caveats: (1) substitution research is typically repeated as an invasive pest moves across the globe (Figures 1A, B, cf. Asia and Africa and the Americas).

Responses to recent outbreaks of *S. frugiperda* in newly invaded areas in Africa, Asia and the eastern hemisphere follow the same reductionistic approaches that have been applied for decades in the Americas, denying opportunities to rethink and innovate into more sustainable forms of pest, crop or farm management. (2) There is little effort to integrate these methods into redesigned systems. Overall, research tends to study the constituent components of a farming system in isolation, overlooking the myriad of interactions and critical services that healthy ecosystems can provide and thereby missing out on ways to transform a globally defunct model of agri-food production.

All pieces are in place for a transition toward resilient, pest-suppressive farming systems (Wyckhuys et al., 2022b). However, the present-day scientific effort is constrained by conceptual and thematic impediments. Not only is pest management science hampered by abstraction and geared toward single-factor solutions (Wyckhuys et al., 2023), but it also does not pursue transformability. Transformation of present-day farming systems and the necessary research to underpin it require significant cultural and institutional shifts. These must acknowledge the profound changes to the scientific enterprise and the funding models that are needed to support it (Vanloqueren and Baret, 2017; Ickowitz et al., 2022; Wyckhuys and Hadi, 2023). Historically, science has compartmentalized problems, resulting in disjointed research agendas or so-called "silos" that tackle the various components of the broader issue in isolation rather than in an integrative, holistic manner. Instead, to effectively transform farming systems, future endeavors must bring together stakeholders from all sectors (consumers, producers, scientists, economists, social scientists and policy makers), consciously bridge social and natural science disciplines and work across (ecologically) relevant spatial and temporal dimensions. By doing so, one can operationalize the concept of ecological intensification and increase the odds of achieving a much-needed redesign of food production systems at scale. Supportive policies, cross-regional South-South learning and technology transfer can consolidate documented gains and take crop protection science beyond this critical transition zone (Tittonell, 2014). An unprecedented opportunity presents itself for scientists and farmers to double down on efforts to take globally relevant yet locally appropriate practices to scale. Now is the time to co-learn, rethink and redesign climate-resilient and pest-suppressive agroecosystems and strive together for our common future (Brundtland et al., 1987).

Author contributions

MM: Data curation, Formal analysis, Writing – original draft. KW: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. YD: Writing – review & editing, Project administration. MF: Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Project administration.

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Conflict of interest

KW was employed by the company Chrysalis Consulting.

The remaining 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.

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