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Pest management science often disregards farming system complexities

Kris A. G. Wyckhuys[1,2,3✉], Fiona H. M. Tang[4,5] & Buyung A. R. Hadi[6]

Since the 1940s, pesticide-intensive crop protection has sustained food security but also caused pervasive impacts on biodiversity, environmental integrity and human health. Here, we employ a systematic literature review to structurally analyze pest management science in 65 developing countries. Within a corpus of 3,407 publications, we find that taxonomic coverage is skewed towards a subset of 48 herbivores. Simplified contexts are commonplace: 48% of studies are performed within laboratory confines. 80% treat management tactics in an isolated rather than integrated fashion. 83% consider no more than two out of 15 farming system variables. Limited attention is devoted to pest-pathogen or pest-pollinator interplay, trophic interactions across ecosystem compartments or natural pest regulation. By overlooking social strata, the sizable scientific progress on agroecological management translates into slow farm-level uptake. We argue that the scientific enterprise should integrate system complexity to chart sustainable trajectories for global agriculture and achieve transformative change on the ground.

[1] Chrysalis Consulting, Danang, Vietnam. [2] Institute for Plant Protection, China Academy of Agricultural Sciences (CAAS), Beijing, China. [3] School of Biological Sciences, University of Queensland, Saint Lucia, Australia. [4] School of Environmental and Rural Science, University of New England, Armidale, NSW, Australia. [5] Department of Civil Engineering, Monash University, Clayton, VIC, Australia. [6] Food and Agriculture Organization (FAO), Rome, Italy.
✉email: kagwyckhuys@gmail.com

Worldwide, animal herbivores reduce crop yields by 18% and cause important post-harvest losses[1]. Individual herbivore species account for 5–10% losses in the world's primary food crops[2], exerting the most pronounced impacts in food-insecure regions with fast-growing populations e.g., Sub-Saharan Africa[3]. The economic repercussions of pest attack are substantial and annually amount to tens of billions of US dollars in foregone productivity and management-related costs[4], while their broader societal impacts routinely remain occluded[5]. Inter-twined global change drivers such as climate warming, biodiversity loss and biocide resistance aggravate those pest-induced losses and compromise global food supplies[6–8].

An overwhelming faith in human's ingenuity to exert top-down control[9,10] and a 'siren call' for easy solutions[11] have spawned ineffective response modes to these systemic pest challenges and deepened their social-environmental impacts. Since the 1940s, synthetic pesticides have become the default tool to safeguard crop harvests from herbivore attack. This has resulted in escalating pesticide usage intensity[12] and toxicity loading[13]; dynamics that are further enforced by a simplification of agroecosystems[14]. By mimicking ecological processes such as natural biological control, pesticides force agro-ecosystems into a suspended state of 'coerced' resilience i.e., a system's natural capacity to endure and adapt under continual change or perturbation[15]. This overreliance on therapeutic chemical control has caused vast environmental contamination[16,17], lowers total factor productivity[18], negatively affects producer and consumer health[19,20] and undermines ecosystem functioning[21]. The above impacts feature among the main externalities of the global food system[22] and the current crop protection regime contributes notably to its 'hidden' costs, which currently amount to US$ 12 trillion[23]. In different parts of the Global South e.g., Asia and Latin America, pest- and pesticide-related costs are manifest though irregularly quantified[12,17].

To mitigate the above impacts, a paradigm shift is required in crop protection and agri-food production worldwide. Agroecology and biodiversity-based tactics feature prominently in a new, more desirable paradigm[24,25]. Transformative approaches and a far-reaching farming system redesign are needed to reconstitute resilience and offset systemic vulnerabilities across scales and sectoral boundaries[26–29]. A system approach is pivotal to the above endeavor[23,30], in which one explicitly accounts for farmland ecosystems as dynamic, intricate and self-regulating systems[9,10,15]. System redesign can ultimately result in more adaptable, knowledge-intensive and resource-frugal ways of producing food that uphold planetary health[18]. New agricultural knowledge economies are required[31], where (participatory) science and a real-time monitoring of food system processes foment collective societal learning and drive transformation[32,33]. To fully account for the diverse social-ecological facets of agriculture, inter- or trans-disciplinary science is vital[34,35]. A cross-disciplinary understanding between ecology, agronomic decision-making and the social-behavioral sciences equally helps to generate actionable knowledge and maximize the contribution of the scientific enterprise[36,37]. Likewise, a solid scientific foundation needs to be laid to efficiently and effectively harness ecological processes such as predation, parasitism or (bottom-up) plant-based defenses at field, farm and landscape scales[21,38,39]. Agro-ecological science however cannot bud serendipitously but instead needs to progressively accrue along a multi-step pathway emanating from the foundational principle of biodiversity[40]. Hence, in order to trace trajectories towards sustainable pest management in particular farm or geographic contexts, it is essential to methodically chart the respective scientific landscape and core knowledge domains[41].

In the Global South, agricultural science is prospering though exhibits inter-country and inter-regional variability in its forward linkages into a global societal learning process[42,43]. Equally, many countries have laid a scientific foundation for sustainable forms of pest management e.g., integrated pest management (IPM), agroecology and biological control[44]. As a universal decision framework founded upon agroecological principles, the original concept of IPM resonates well with broader resilience thinking yet has failed to curb pesticide usage over a span of six decades[45,46]. Though (context-appropriate) knowledge *in principle* is available to transition towards more sustainable forms of crop production and protection[31], no fine-resolution mapping has been conducted. Systematic literature reviews in Western countries have unveiled conceptually skewed research agendas and critical gaps in basic or applied pest management science[47]. As scientific agendas in the Global South have not been methodically charted, it remains unknown to what extent national research progresses along particular technological trajectories[48,49] and whether science-based innovations are likely to either fit-and-conform or stretch-and-transform crop protection regimes[50]. In order to effectively transform pest management practice, it is thus essential to gain robust, quantitative insights into the type, maturity and breadth of scientific inquiry.

In this study, we employ bibliometric analyses to quantitatively define the scientific underpinnings of pest management in the Global South. More specifically, we systematically analyze literature output of 65 developing countries in Africa, Latin America & the Caribbean, Southeast Asia and the Middle East over a 10-year time frame. Without diminishing localized scientific activity, our work centers on indexed English publications within global bibliographic databases. Following an in-depth screening of abstracts, we log the identity of target biota and crops, research type, core IPM themes, relative coverage of system-level variables and degree of inclusion of (plant, animal) companion biota. We use farming system stratification as an analytical lens to dissect science and explore opportunities for interdisciplinarity[51]. Thus, our analyses uncover how science is shaped by varying cognitive contexts and potentially informs (non-)academic learning, policy and practice. Our work illuminates the conceptual base and general methodology of crop protection science in the Global South, and the degree to which it may either enable or obstruct the envisioned global food systems transformation.

Results

Web of Science queries yielded an initial literature corpus composed of 1135 (Southeast Asia), 2117 (Latin America and the Caribbean), 593 (West Africa) and 2079 (Middle East) indexed publications. After abstract screening and removal of irrelevant studies, a respective total of 614; 1362; 327 and 1149 publications were retained. Removal of duplicates among the four sub-regions yielded a final literature corpus of 3,407 international peer-reviewed publications. Country-level research output varied substantially ranging from 0–459 publications over the 10-year timeframe.

Across sub-regions, 881 (species- or genus-level) herbivore taxa are covered in 2,891 instances. Given that all taxa engage in herbivory and may attain pest status in agricultural settings, eventual other feeding modes e.g., omnivory were not logged. Single taxa are covered in 57.4% of the studies, while the remainder either address multiple taxa or do not specify the focal organisms. Common herbivores include cosmopolitan pests of cereal grain or horticultural commodities such as *Bemisia tabaci* (Insecta: Hemiptera; 110 studies), *Spodoptera frugiperda* (Insecta: Lepidoptera; 94), *Tuta absoluta* (Insecta: Lepidoptera; 80), *Tetranychus urticae*

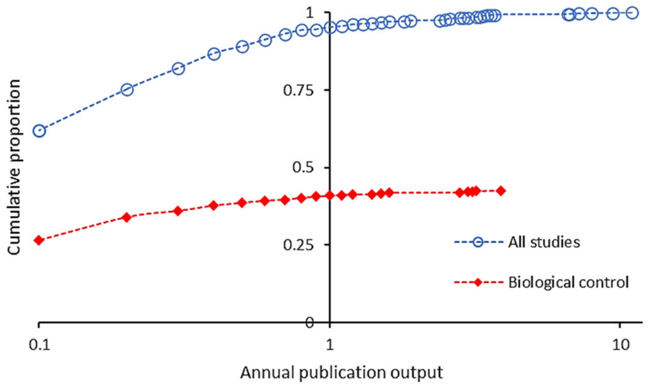

Fig. 1 Relative degree of scientific attention to different herbivore taxa and their associated biological control agents in 65 developing countries over 2010–2020. We show the cumulative proportion of (species- or genus-level) herbivore taxa that is receiving varying degrees of scientific attention i.e., expressed by the yearly number of peer-reviewed scientific publications (*X*-axis). Taxon-level publication output is plotted on a log-scale and differentiated between all studies and those addressing biological control.

(Arachnida: Trombidiformes; 72) and *Helicoverpa armigera* (Insecta: Lepidoptera; 67). Overall, limited amount of research attention is specifically geared towards individual taxa, with 94.6% of all (881) herbivore taxa featuring in less than one publication per year and only 0.6% taxa receiving more than five publications per year (Fig. 1). For 43% of the (881) herbivore taxa, research covers biological control agents (BCA). Out of these, 95.4% of taxa feature in less than one publication per year; BCAs are most commonly addressed for *T. absoluta* (3.9 studies per year), *S. frugiperda* (3.2) and *T. urticae* (3.2). Taxon-level scientific attention increases with incidence of insecticide resistance (IR) ($F_{1,98} = 68.075$, $p < 0.01$; $R^2 = 0.41$; Supplementary Fig. 2), though newly invasive pests e.g., *S. frugiperda* or *T. absoluta* notably divert from this pattern. Similarly, prominent herbivores with high IR incidence e.g., *Spodoptera exigua* and *Spodoptera litura* (Insecta: Lepidoptera) are comparatively understudied. Overall, scientific attention goes primarily to cereal grains (17.6% studies), fruits (17.3%) and non-starchy vegetables (15.1%). Though scientific effort for food crops is in line with their relative share in the global reference diet (Pearson's $r = 0.925$, $p < 0.01$), it diverts from their proportional contribution to global insecticide mass or total insecticide hazard load (Spearman Rank's $\rho = 0.462$, $p = 0.13$; $\rho = 0.315$, $p = 0.32$; Fig. 2, Supplementary Fig. 3).

Out of all studies, 47.9% involve laboratory or desktop research and 7.8% literature reviews, while a respective 6.2% and 49.0% is conducted at a greenhouse (or semi-field) and field level. Several studies involve more than one research type. Out of eight integrated pest management (IPM) thematic areas[52], studies primarily address bio-ecology, preventative and curative non-chemical management (Fig. 3). Themes such as host plant resistance (HPR), sterile insect technique (SIT) and the development or field-level validation of decision thresholds feature in a respective 7.7%, 1.1% and 0.5% of studies. Botanical insecticides are covered in 5.9% studies, BCAs in 32.5% studies, while only 11 publications (0.3%) cover preventative chemical management. In terms of organismal focus, 45.5% of all studies omit (animal, plant; crop, non-crop) companion biota and 36.6% solely consider one or more target pests. The 2,086 management-centered studies account for 1.2 ± 0.5 ($\bar{x} \pm$ SD) types of tactics i.e., comprising either preventative or curative, chemical or non-chemical management. Out of these, 1674 studies (80.2%) only evaluate one type of tactic and 28.6% involve curative chemical control. In studies involving synthetic insecticides, 22.2% evaluate their (non-target) impacts on or compatibility with BCAs. Lastly, yield and farm-level revenue are used as endpoints in merely 9.3% and 2.4% studies.

Next, we employed hierarchical stratification[51] to assess the extent to which scientific inquiry aligns with the social-ecological strata of a farming system and the processes or (animal, plant) biota therein. Specifically, we accounted for 15 farming system variables at increasing levels of spatial scale and complexity, accounting for space, time and gene dimensions[39,53]. For the 1832 publications that comprise greenhouse and (semi-)field research, farming system variables and companion biota are covered to varying extent (Fig. 4). Studies merely account for 1.8 ± 1.0 (out of 15) system variables, and 0.6 ± 0.8 (out of 6) companion biota. Target herbivores (81.1% of the studies), pest management regime (29.0%) and crop genetics or phenology (21.0%) feature prominently in field research, while ample attention is given to inter-specific diversity in space i.e., intercropping (6.5%). Conversely, system variables such as inter-specific plant diversity over time (i.e., rotation schemes; 1.4%), soil moisture or irrigation (0.9%) and intraspecific plant diversity (0.2%) are regularly disregarded. Certain variables within a given stratum (e.g., soil, farm or landscape) or across strata (e.g., soil x crop diversity) are often considered concurrently (Fig. 4). Similarly, companion biota such as BCAs (34.7%) and non-crop plants (7.6%) are commonly investigated as compared to pollinators (1.6%), soil fauna and flora (3.1%) or plant pathogens (4.5%). BCA organisms comprise vertebrates (1.2% studies), invertebrate predators (16.5%), invertebrate parasitoids (15.9%), microbiota (8.5%) and viruses (1.0%). Pest management type affects the number of system variables (ANOVA, $F_{2,937} = 73.634$, $p < 0.001$) and proportional coverage of system strata (soil: $X^2 = 47.761$, $p < 0.001$; plant: $X^2 = 140.070$, $p < 0.001$; field: $X^2 = 111.288$, $p < 0.001$; farm: $X^2 = 32.383$, $p < 0.001$; landscape: $X^2 = 24.389$, $p < 0.001$; social: $X^2 = 91.209$, $p < 0.001$) (Fig. 5).

For the five main cosmopolitan herbivores, taxa-level scientific attention differs geographically (Chi square $X^2 = 182.903$, $p < 0.001$; Supplementary Fig. 4). Taxa such as *T. urticae* are primarily studied in the Middle East, while *S. frugiperda* research is largely restricted to Latin America. Most publications cover laboratory and desktop research, representing 77.8% studies for *T. urticae*. Meanwhile, (semi-)field or greenhouse research make up a respective 18.1% and 25.8% of studies for *T. urticae* and *S. frugiperda*. Across the above five taxa, bio-ecology invariably represents the most popular theme (range 37.5–55.9% studies), while curative and preventative non-chemical management equally receive high coverage. Overall (chemical, non-chemical) curative measures feature in a respective 31.0%, 14.3%, 86.4%, 100.0% and 19.0% more studies than preventative non-chemical ones for *B. tabaci*, *S. frugiperda*, *T. absoluta*, *T. urticae* and *H. armigera*. Moreover, curative non-chemical measures are covered more frequently for four herbivore species. Scientific coverage of biological control differs between taxa ($X^2 = 10.544$, $p = 0.032$), with BCAs featuring in 28.2% (*B. tabaci*) up to 48.8% (*T. absoluta*) of all studies. Meanwhile, botanical insecticides appear in 6.3–13.9% of studies. Greenhouse or (semi-)field studies primarily center on the pest management regime (for *T. absoluta*, *T. urticae* or *H. armigera*) or crop genetics and phenology (for *S. frugiperda* and *B. tabaci*; Fig. 6) in addition to a 'focal pest' variable, which features in 94.3–100.0% of studies. Scientific attention is primarily directed towards plant- and field strata, constituting up to 42.8% and 21.6% of studies respectively (Fig. 6). Higher level strata (i.e., social, farm- or landscape-level) and below-ground processes receive consistently less attention. Lastly, in field studies, the number of system variables and companion biota do not differ between taxa ($H = 2.484$, $p = 0.648$; $H = 5.338$, $p = 0.254$) and ranges between 1.8–2.0 and

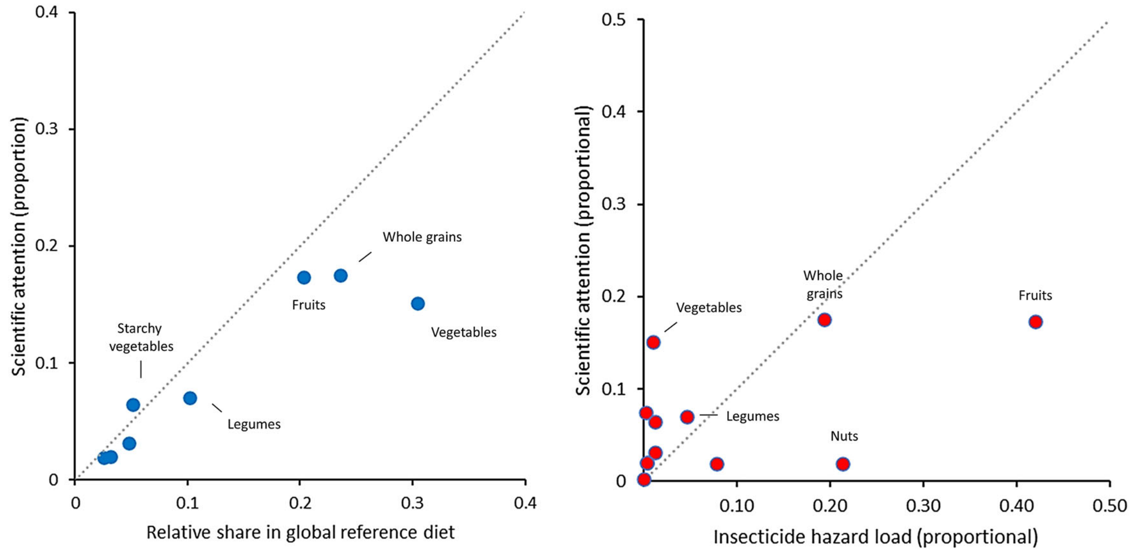

Fig. 2 Degree of scientific attention for the main crop categories versus their relative contribution to a global insecticide reference diet or total insecticide hazard load. Per food crop category, scientific attention is expressed as the proportional share of international, peer-reviewed publications from 65 developing countries over 2010–2020. In the left panel, the relative contribution of each crop category to a global reference diet with target intake of 2500 kcal/day is plotted[22]. Data are only shown for eight food crop categories: whole grains, root & tuber crops (i.e., starchy vegetables), vegetables, fruit crops, legumes (i.e., beans, lentils, peas, soy, peanut), tree nuts, palm or vegetable oil crops, and sugar crops. In the right panel, scientific attention is contrasted with proportional insecticide hazard load. Hazard load (kg body weight) indicates the human or non-target organism mass required to absorb the applied insecticides without experiencing an adverse effect. The dotted line in both graphs indicates a 1:1 ratio.

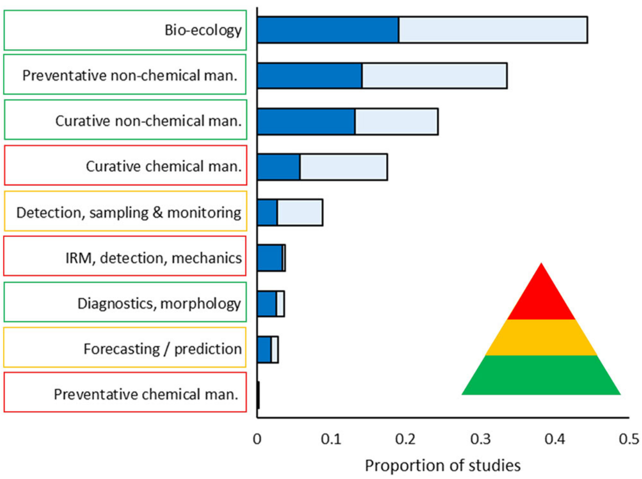

Fig. 3 Prevailing thematic foci of pest management science in 65 developing countries. Patterns are derived from a systematic literature review of 3407 publications over a 2010–2020 time frame. Stacked bars visually differentiate laboratory or review studies (dark blue) from greenhouse or (semi-)field studies only (light blue). Themes refer to core components of the integrated pest management (IPM) conceptual framework[52], with one single publication regularly covering multiple thematic areas. Non-chemical avoidance strategies constitute the basis of the 'IPM pyramid', while effective chemical use is deemed a 'measure of last resort'. Preventative non-chemical management covers a diverse set of practices e.g., crop sanitation, cultural control, intercropping, varietal resistance[39]. IRM refers to insecticide resistance management.

0.6–1.0, respectively. Even for insect vectors such as *B. tabaci*, plant diseases or their causal (viral) pathogens only feature in 17.6% of field studies (N = 51) and 14.5% of all studies (N = 110).

Herbivore taxa for which either of 10 less common system variables were examined (i.e., omitting focal pest, crop, management regime, landscape and social facets) receive higher overall research output as compared to all taxa ($H = 220.178$, $p < 0.001$). Similarly, taxa for which either of the 5 types of companion biota (except for BCAs) were studied feature on comparatively more publications ($H = 158.062$, $p < 0.001$). Hence, farming systems research and multi-guild studies are consistently geared towards herbivores that receive a critical amount of scientific attention across the 4 focal geographies.

Discussion

In the mid-1900s, a chemical era dawned for global agriculture. With the advent of synthetic insecticides, trained entomologists prescribed spray regimes against single pests at a scale of individual fields[54]. As adverse side-effects became apparent in the 1950s, calls for a total overhaul of this 'supervised control' approach emerged[45] and an integrative systems-approach was advocated as guiding premise for sustainable pest management[30,55,56]. Yet, failure to refine and deploy such system-centric management over the past decades lies at the core of pervasive social-environmental problems. In this study, we unveil how developing countries generate vast scientific knowledge, but this is fragmented by disciplinary specialization, centered on a fraction of herbivore taxa, geared towards the study of phenomena in simplified 'microworlds'[57] and focused on curative control. Specifically, 48% of studies are conducted within laboratory confines, 46% disregard companion biota or host plant effects, and 83% field research addresses two or less system variables (out of 15). Even for mobile, polyphagous herbivores such as *S. frugiperda* and *H. armigera*, farm- and landscape strata are only considered in 3–8% of field studies while social layers are routinely omitted. Though IPM foundational themes such as pest bio-ecology receive major scientific attention, management tactics are examined in an isolated fashion in > 80% of studies. Organismal foci reflect a skewed scientific attention towards insecticide-resistant (IR) herbivores and recent invasives, while nutrient-rich, pesticide-intensive crops are under-studied. Though ecological regulation and ecosystem service providers are commonly addressed, taxon coverage is restricted. Our

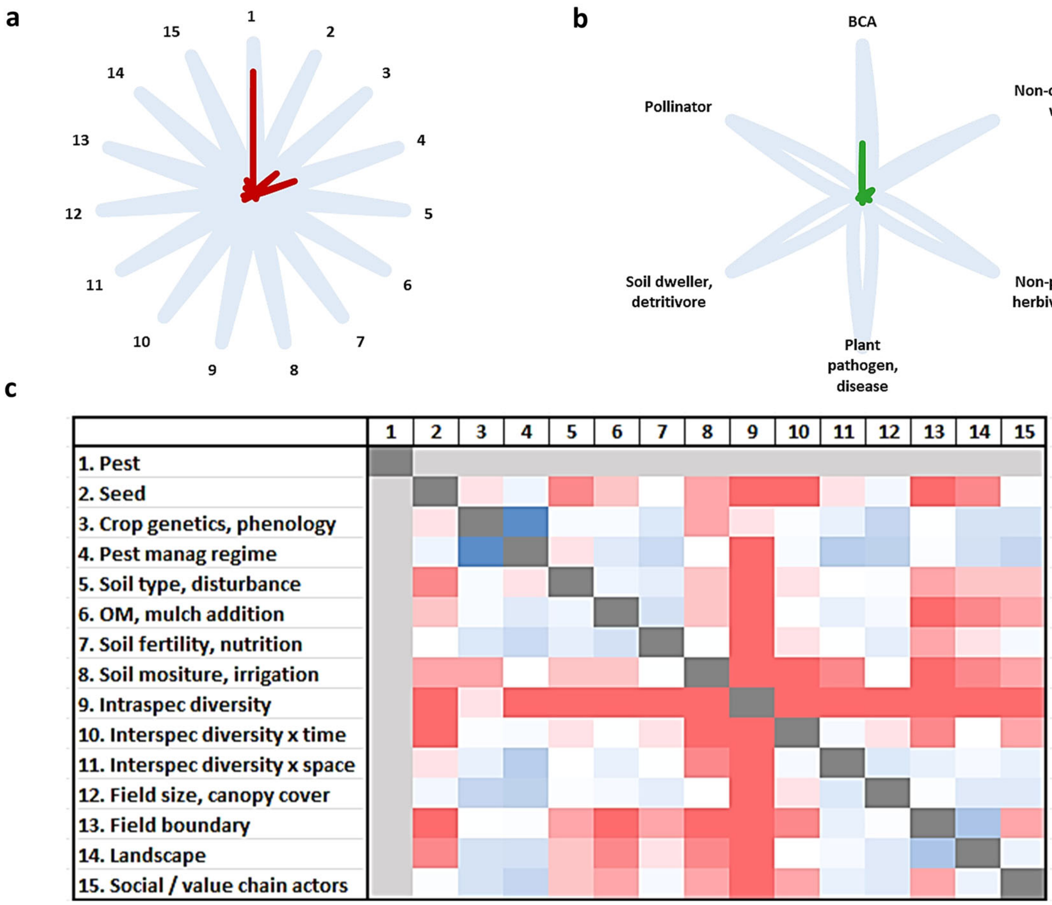

Fig. 4 Relative coverage of 15 system-level variables and 6 companion biota in (semi-)field research. Radar charts indicate the proportion of peer-reviewed publications over 2010–2020 that address a particular system-level variable (**a**) or companion biota (**b**), in which one single publication regularly covers multiple variables. The length of each radius is proportional to the magnitude of the variable (range 0–1). Data are exclusively shown for 1832 published (semi-)field or greenhouse studies. Numbered variables in panel a refer to components or strata of a farming system, ranging from a (focal) pest, seed or crop to entire landscapes or social facets e.g., farmers. A heatmap (**c**) reflects the extent to which system-level variables, excluding the focal pest (#1), are simultaneously addressed in field research. Distinction is made between gene, space and time dimensions of crop diversification[53]. OM refers to organic matter, and BCA to biological control agent.

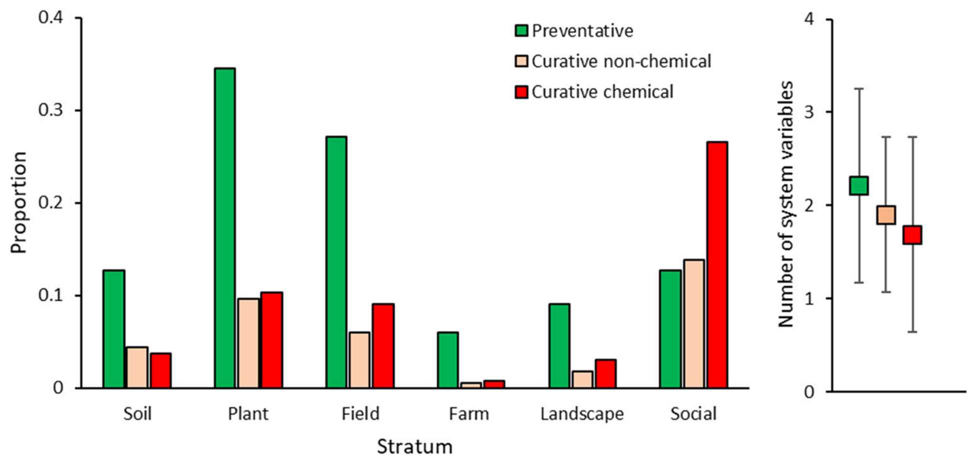

Fig. 5 Pest management type affects the number of farming system variables and proportional share of social-ecological strata. Data are plotted for the 1832 (semi-)field and greenhouse studies. The right panel represent the number (mean ± SD) of system variables that is covered by studies addressing either of three management types. For each management type, relative coverage of six farming system strata is plotted. Studies covering more than one single management type are excluded from analysis (data in the text).

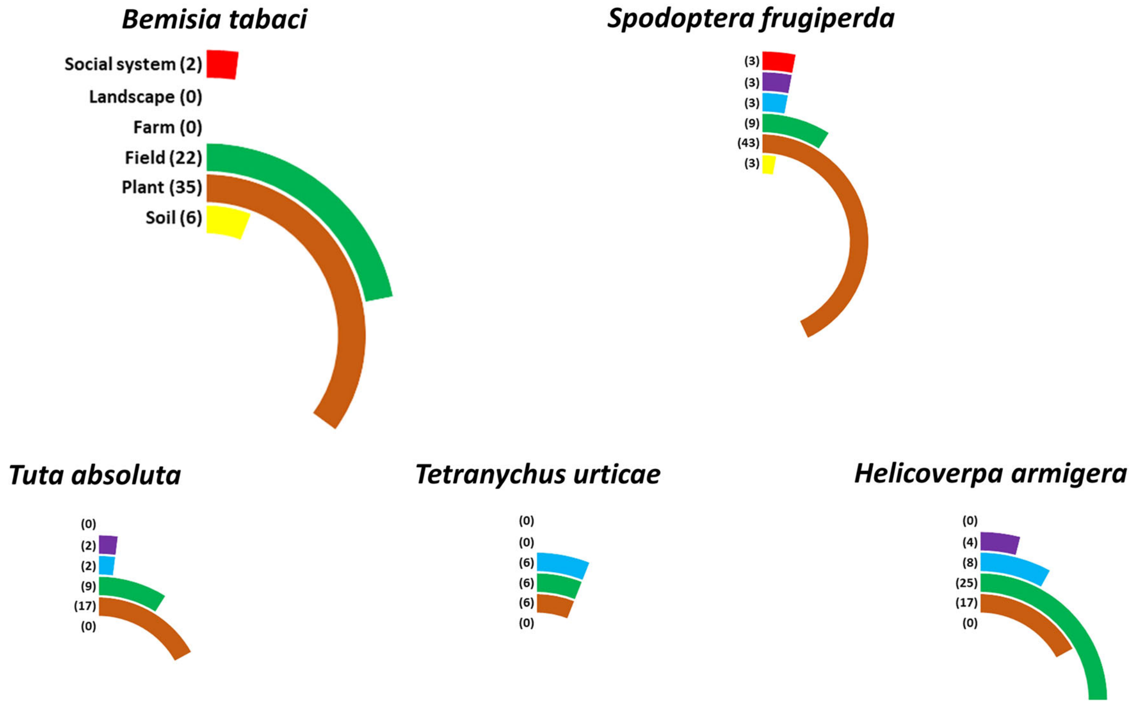

Fig. 6 Relative coverage of 6 different farming system strata in scientific publications addressing either of the five most studied arthropod pests. Data reflects scientific output in 65 developing countries over 2010–2020. Within the concentric donut chart, the exact circumference of each loop mirrors the percentual scientific coverage of a given farming system stratum in the total research output for a specific pest species (total circumference equals 100%). The exact number of scientific publications covering a given stratum is indicated between brackets next to the respective loop. Patterns are individually plotted for each pest species. Soil, field and plant strata comprise multiple system-level variables.

pioneering attempt to methodically dissect pest management science in the Global South signals that this undertaking remains highly reductive, pest-centric, and geared towards single-factor solutions. We argue that the current scientific enterprise contributes little to holistic resilience thinking or 'integrated' pest management, and thus falls short of being a problem-driven tool for transformative action.

Ecologically-centered pest management is knowledge intensive and imposes in-depth, context-specific insights into the biology of target herbivores, co-existing biota and associated ecological processes[24,46]. In order to effectively harness trophic regulation, biodiversity discovery and description have to proceed in parallel with an empirical validation and manipulation of process-based mechanisms[40,58]. For instance, in Asian paddy rice, a thorough understanding of herbivore identity, ecology and trophic interactions allows for a preventative management of pest outbreaks[59]. This has enabled drastic pesticide phasedown at a regional level, in some cases leading to diversification into rice-fish systems, while preserving or even improving yield[60,61]. In the Global South, merely 5% and 2% of herbivore taxa receive a critical amount of attention (i.e., min. 1 paper/year) in terms of general scientific inquiry or studies involving biological control agents (BCA). As such, baseline bio-ecology information is missing for the majority of agricultural herbivores of legumes or cassava—vital constituents of healthy diets e.g., in Africa and the Americas[62]. Considering how traditional, biodiverse farming systems are increasingly dismantled, chemically intensified or embedded in simplified landscape matrices, it is crucial to assess how ecological regulation underpins resilience and prevents herbivores from attaining pest status[21,63]. Doing so can help to anticipate, forestall or even reverse trophic cascades, regime shifts and pest outbreaks that result from plant, animal or habitat diversity loss. For instance, a broader organismal focus beyond the initial target herbivores could have precluded secondary outbreaks of sap-feeding hemipterans in transgenic Bt crops—the latter geared towards lepidopteran pest control[64]. Further, an in-depth study of ecological mechanisms in invasive pests' native range can yield nature-friendly mitigation options[65]. Equally, scientific activity needs to be bolstered on nutrient-dense, pesticide-intensive crops such as fruits, legumes and (starchy) vegetables e.g., potato. Whether the added emphasis on IR pests is merited i.e., a genuine reflection of (farm-level) organismal priorities or an attempt at symptomatic control of pesticide-induced issues is unclear. Further, BCA-related studies are geared towards a sub-set of invertebrate parasitoids and predators, as compared to vertebrates or pathogens[66,67]. Cross-disciplinary cooperation e.g., with pathologists or pollination ecologists is limited with only 1–5% of all studies covering plant pathogens or pollinators. Especially for insect-vectored pathogens, this is counterintuitive as the distinct (tri-trophic) defenses against either stressor ideally are studied in sync. Similarly, scant attention is given to companion biota such as weeds and soil fauna that uphold tri-trophic defenses[39,68]. One drawback of our study however is that it omits the large, high-quality and visible scientific output of Western countries and other nations in the Global South e.g., China or Brazil[42,43], which may be relevant for cosmopolitan herbivores such as *B. tabaci*. Nonetheless, our findings are reminiscent of those in Australian grain systems where a lack of taxonomic resolution, shallow scientific knowledge of key pests and a deficient understanding of the regulation potential of BCAs hinder sustainable crop protection[47]. Given the above, the desire to further scientific understanding of a small slice of biota i.e., to 'dig deeper' likely exerts a stronger gravitational pull than that of actually remediating their in-field management[47]. These obstacles are not inherent to crop protection science; comparable blind spots exist in soil biodiversity and ecosystem function research[69,70] and in the global study of invertebrates across ecosystems[58]. Fundamental research along taxonomy, biology and ecology fronts is thus critically lagging. Considering how global change intensifies pest problems through negative impacts on upper trophic layers, food webs and ecosystem functions[8,41,63], these knowledge gaps should be filled.

For decades, scientists have pursued an 'illusion' of IPM while supervised control is continually reinvented[71]. This is manifest in our analyses. First, curative measures receive consistently more scientific attention and are covered in 37% of studies (vs. 31% for preventative non-chemical ones). For five globally-important herbivores, curative tactics feature in up to 100% more studies than non-chemical preventative ones (Supplementary Fig. 4). Though non-chemical alternatives such as invertebrate or microbial BCAs receive ample attention, there is a tendency to direct scientific research towards their use as commoditized therapeutic tools in a prescription-like manner[30]. This trend however carries distinctly fewer risks than chemical control and may nurture systems back to resilience[30]. Other non-chemical tactics such as botanicals merit critical investigation into their non-target impacts. Second, fewer than 20% studies treat multiple component technologies in an 'integrated' fashion in viable production systems i.e., as per the founding principles of IPM. This is surprising, as a tactical integration of multiple non-chemical preventative measures (e.g., crop diversification) across spatial or temporal scales, improves the productive performance of cropping systems[72]. Third, while decision thresholds are core IPM features that guide farm-level management action[46,73], studies that develop or validate them are virtually non-existent. In such absence of context-specific decision aids, farmers lack basic rules of thumb of what represents a yield-limiting pest or when management action is economically warranted. Lastly, a mere 18% and 0.3% studies involve the curative or preventative use of insecticides. This is well beyond the 0.5% of pesticide-related papers in mainstream ecological journals[12], but juxtaposes with the ubiquity of synthetic insecticides in global agroecosystems[74] or the rapid proliferation of 'insurance' pest management using insecticide-coated seeds or soil drenches[75]. Though a heightened attention to invertebrate or microbial biological control is praiseworthy, this practice is only adopted on less than 1% farmland globally[76]. Yet, microbial BCAs in particular are steadily gaining a foothold into conventional or organic farming systems[77]. Beneficial fungi, bacterial inoculants, (myco)viruses or bacteriophages all wait to be integrated with e.g., behavior-modifying chemicals or protein-based tactics to provide non-chemical pest control. Other forms of non-chemical control both curative and preventative are plausibly implemented on the 77.4 million ha under organic production i.e., 1.6% of global farmland or a mere 0.7% in the Global South[78]. Meanwhile, the unrelenting global proliferation of chemical control[12,44,74,75] reflects an inability to capitalize on the sizable research progress in non-chemical preventative management. Lagging uptake of those practices signals how the underlying areas of scientific inquiry are poorly calibrated and conceptualized. Indeed, by skipping one or more steps in the sequential process to harness the power of biodiversity[36,40], agroecological research irregularly spawns desirable outcomes. Overall, as the scientific enterprise continues to focus on curative tactics while discounting the pivotal role of decision aids or the broader enabling environment, it is questionable whether it will ever break the IPM mirage. Troubleshooting BCA or agroecology science and resolving its socio-technical adoption hurdles is thus imperative to maximizing the potential of science to transform practice[36,44].

An interdisciplinary systems-approach is essential to bolster food system resilience and mitigate pesticide-related externalities[23], but scientists' ability to treat farming systems as a 'whole' is impeded by deeply rooted pest- or crop-centric (vs. process-centric) approaches[26,49,79]. Our literature analyses reveal how science is paralyzed by abstraction, rarely covering system variables or biota beyond the focal pest, crop or (imposed) management regime. Laboratory settings or greenhouses regularly constitute the locus for microworlds, where phenomena are conditionally dependent upon simplified observational contexts[57]. The remaining studies are confined within plant, crop or field delimitations and rarely consider (above- or below-ground) ecosystem compartments or social strata. The bulk of field studies do not address more than two system variables especially those pertaining to different hierarchical strata e.g., soil x crop diversity. Also, despite their powerful contributions to sustainable crop protection[80], intraspecific diversification or rotation schemes receive anemic degrees of attention. Though diversification in multiple (space, time, gene) dimensions is not always necessary[53], omitting these measures from the onset carries implications for the pest management solutions space. Molecular biologists, plant breeders or soil ecologists primarily operate at a micro-scale[29] even when their pest targets exhibit long-range dispersal and only sporadically colonize ephemeral crop patches. Equally, scientists that act at meso- or macro-scales commonly disregard (ecological, management-induced) processes at seed, crop or soil levels[25,39]. Lastly, as only 2% of studies cover decision-relevant metrics such as revenue or multi-year benefit:cost ratios, effectively convincing the envisioned end-users i.e., farmers becomes a predicament[24,36,73]. This spatial mismatch, failure to perform wholeness-oriented science and incapacity to meaningfully link to people e.g., by intersecting with the behavioral sciences results from disciplinary specialization and large conceptual divides within agrifood science[49]. A landscape-level framing of pest issues *in se* can help to remediate this by integrating cross-scale ecological and social dynamics[81,82]. However, scientists struggle to slot such complexity into traditional experimental set-ups or cope with needs for extra labor, costs and cross-disciplinary engagement under short-cycle projects and 'publish or perish' imperatives[83,84]. To complicate matters further, interdisciplinary science faces lower funding success and outright penalization by scientific peers[85,86].

Anchored in specialization, pest-centric mindsets and simplification[49], current pest management science appears unfit to redress the myriad social-environmental externalities of present-day crop protection. Scientists' pursuit of single-factor remedies, without due consideration of ecological processes at relevant spatial or organizational scales, is unlikely to result in disruptive impacts on science and farm-level practice[26,63]. Even in the face of moderately high scientific output in preventative non-chemical management, failure to build a cross-disciplinary understanding with the social sciences is bound to stall action on the ground[36,40]. This, regrettably, is the present-day reality. The bulk of farmers resort to pesticides because they are cheap, easy and quick, while steering clear of agro-ecological practices because of their (perceived) cost, complexity and risk or a simple lack of knowledge. Hence, to ensure that pest management science becomes a true learning process with and for society[50], its cognitive (i.e., societal, intentional and observational) context merits close scrutiny. Novel decision frameworks such as the biodiversity 'spiral' approach, hierarchical stratification or integrative food web analytics can put science more firmly on the interdisciplinary track[40,41,51]. The above could be tied to prioritized research portfolios, revamped incentive schemes[87], enabling policies[83], bold awareness raising and revitalized public sector funding e.g., for agroecology and other scientific avenues to shore up preventative measures[88]. To avoid inaction due to overwhelming complexity, multi-stakeholder platforms e.g., farmer-scientist co-learning alliances prove an appealing way to generate tractable solutions[9], as has been achieved through UN-endorsed farmer field schools in the Asia-Pacific[89]. By closely engaging farmers in discovery-based learning, the latter attained sharp yet transient cuts in pesticide usage on millions of farms. Given that pesticide-inflicted harm has progressively worsened over the span of more than half a century[12], the implications of today's scientific enterprise are colossal. Self-reflection is in order and scientists need to ask whether minute additions to a global stockpile of knowledge are sufficient measures of progress or whether society needs readjustments that equate with scientific revolution[90]. Only when pest management science duly and fully accounts for the multiple farming system variables and strata can we expect to see real-world impacts in safeguarding food security, halting biodiversity loss and upholding human health.

Materials and methods

We used bibliometric approaches and multi-method analyses to characterize pest management science over a 10-year time frame in 65 countries in the Global South (Supplementary Fig. 1). The geographical focus encompassed all countries within 4 sub-regions: Southeast Asia (11 nations), Latin America and the Caribbean[20], West Africa[16] and the Middle East[18]. Brazil was excluded due to its exceptionally high literature output over the study period. A stepwise process was followed for bibliometric analysis, database curation, study categorization and statistical analysis (Supplementary Fig. 1).

First, we used the Web of Science (WoS) online database to build an initial literature corpus covering the 2010–2020 time frame. Literature searches were defined to access publications that made clear inferences to applied pest management science i.e., the actual implementation of scientific results to crop protection within standing (agricultural) fields or crops. Topic searches were conducted using the following WoS search string: TS = ((field OR crop*) AND (pest*) AND country) in which the latter parameter was replaced with the exact name of each of the 65 focal countries. As such, publications were retrieved that were either conducted in a particular country or co-authored by scientists from this country. Both elements sensibly (though distinctively) impact country-level crop protection practice. Also, topic searches permitted screening the study title, abstract and keywords. The WoS Core Collection database (1900–2022) was queried using a University of Queensland staff subscription between August 1 and October 15, 2022.

Next, titles and abstracts of the 5924 retrieved studies were individually screened for relevance. Specifically, we excluded studies that covered animal or human pests, urban pests such as cockroaches or house flies (except for termites, given their impact on agricultural crops) and zoonotic or vector-borne disease vectors e.g., mosquitoes. Meanwhile, publications addressing storage pests were included given that their infestation pressure and mitigation is mediated by field-level management action. Studies that addressed pesticide handling, use of personal protective equipment (PPE), residue detection, (eco-)toxicity, (in-field or laboratory-based) dissipation or degradation kinetics were equally removed. Equally, studies that validated analytical methods for pesticide detection in particular matrices were excluded. Meanwhile, studies that evaluated the susceptibility (or resistance) of target herbivores to specific pesticidal compounds under laboratory, semi-field or field conditions were retained. Lastly, any duplicate publications were marked and removed from analyses e.g., those considering global vs. regional or country-level datasets. This process yielded a smaller final literature corpus, which was subject to further categorization and statistical analysis (Supplementary Fig. 1). The number of publications that each country generated was indicative of its overall research output on pest management science over the study period.

For each publication (or study) within the above literature corpus, the abstract was thoroughly screened and classification was performed in the following categories: focal (herbivore, crop) biota, type of research study, integrated pest management (IPM) thematic areas, farming system variables and companion biota. Focal crops were organized into 14 different categories, which expanded upon the Indicative Crop Classification (ICC) by the Food and Agriculture Organization (FAO) and included a separate category for studies that either addressed multiple crop types or did not specify the exact crop focus. Further, the relative degree of scientific attention to particular (food) crops was contrasted with their overall share in the global reference diet[22] and contribution to the annual insecticide mass and total insecticide hazard load. The hazard load (HL) was calculated based on a similar concept as the total applied toxicity indicator (TAT[91];), as $HL = \sum[M_i/(NOAEL_i \times 365)]$, with M_i being the annual applied mass of insecticide i and $NOAEL_i$ being the no-observed adverse effect level of insecticide i in mammals and birds. The annual insecticide applied mass was calculated based on the crop-specific insecticide application rates were accessed through the PEST-CHEMGRIDS database for 2015[68], whereas the values of NOAEL used were tabulated in Supplementary Data 3 of Tang et al.[92]. For target herbivores, the scientific name and taxonomic classification (i.e., sub-class or order) was recorded for maximum 6 listed biota. As these organisms were variably listed at the genus or species level, we refer to them as 'taxa' instead of alluding to a particular taxonomic resolution. Studies that either listed more than 6 herbivore taxa or that left focal herbivores unidentified were analyzed in a separate category. Further, the relative degree of scientific attention to the 100 most studied (arthropod) herbivore species was plotted against their respective incidence of insecticide resistance (IR)[93].

Depending upon the type of research, studies were then classified as laboratory and desktop, reviews, greenhouse and semi-field, or field research. A single publication occasionally reported on more than one research type. Next, we logged whether each publication covered one or more of eight core IPM themes[52]: (1) Diagnostics and morphology; (2) Detection, sampling and monitoring e.g., trap validation; (3) (Model-based) forecasting and prediction; (4) Bio-ecology e.g., population dynamics and geographical distribution; (5) Preventative non-chemical management e.g., mass trapping, mating distribution; (6) Curative non-chemical management e.g., botanical insecticides, augmentation biological control; (7) Preventative chemical management e.g., insecticidal seed coatings; (8) Curative chemical management e.g., (chemical) bait sprays. Five more categories provided finer resolution insights into certain thematic areas i.e., (1) Host plant resistance (HPR) including transgenics; (2) Sterile insect technique (SIT); (3) Insecticide resistance management (IRM), mechanics and detection; (4) Botanical insecticides; and (5) Development and field-level validation of decision thresholds e.g., economic or action thresholds and injury levels. Considering how (bacterium-derived) spinosad or spinetoram pose high environmental risk[94], those compounds were invariably classified as chemicals instead of biopesticides. For (semi-)field studies only, we further recorded which of 15 different farming system variables were taken into account. Variables covered multiple facets of a farming system at increasing levels of spatial scale and complexity, while accounting for the space, time and gene dimensions of diversification[39,53]. Variables ranged from an individual seed or target crop to the entire field, farm, agro-landscape mosaic or interlocked social system. Similarly, we noted which of the following 6 companion biota were covered in each (semi-)field study i.e., (1) Weed or non-crop plant; (2) Plant pathogen or disease e.g., aflatoxigenic fungi; (3) Non-pest herbivore; (4) Soil dweller, detritivore or rhizosphere fauna and flora; (5) Pollinator; and (6) Biological control agent (BCA). The latter group of companion biota was further categorized into vertebrate BCAs, invertebrate predators, invertebrate parasitoids, microorganisms (i.e., bacteria, fungi, nematodes) and viruses. Per study, we equally logged the number of system variables and companion biota that were covered. Heat maps were drawn to visualize which system variables were often considered simultaneously, while radar plots captured the relative coverage of system variables and companion biota across field studies. Lastly, an in-depth assessment of geographical coverage, research type, system variables and companion biota was conducted for publications that addressed either of the five most studied arthropod pests i.e., *Bemisia tabaci*, *Spodoptera frugiperda*, *Tuta absoluta*, *Tetranychus urticae* and *Helicoverpa armigera*. For these taxa, we visualized the extent to which pest management science is aligned with a hierarchical stratification of the farming system[51] by grouping 13 farming system variables into six strata: soil, plant, field, farm, landscape and the social system. In this stratification, we excluded the focal pest and imposed pest management regime.

Prior to statistical analysis, all data were checked for normality and homoscedasticity. Data that did not abide to the above assumptions were transformed by log normal transformation, or were analyzed with non-parametric tests. Linear regression analysis was used to relate taxa-specific research attention to IR incidence. Non-parametric Kruskal-Wallis tests were used to compare the number of system variables and companion biota that were studied between the four sub-regions. Chi square analyses were employed to detect any geographical biases in the study of five particular (arthropod) herbivores, or taxa-specific differences in the coverage of different research types, IPM themes or system variables. IBM SPSS Statistics version 29.0 was used for all analyses.

Data availability

All data underlying this manuscript are available to readers in a public repository through the following links: https://doi.org/10.5061/dryad.fqz612jwq and https://doi.org/10.6084/m9.figshare.23514552.

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Correspondence and requests for materials should be addressed to Kris A. G. Wyckhuys.

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