

Perspective Paper

Beyond Pesticides: Harnessing Artificial Intelligence, Digital Technologies and Nature-Based Solutions to Reinvent Crop Protection

From reactive pesticide control to predictive, microbiome-informed and agroecological crop protection

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Abstract

The transition towards agriculture without reliance on harmful chemical pesticides requires more than the substitution of conventional products or the digital optimisation of spraying. Drawing on six synthesis and Virtual Mobility reports prepared within COST Action CA21134, this perspective integrates breakthroughs in multi-scale sensing, molecular diagnostics, artificial intelligence (AI), predictive modelling, autonomous non-chemical weed management, microbiota-based protection, new microbial biopesticides, insect chemical ecology and plant immunity. Its central proposition is that the unit of crop-protection innovation must shift from the individual pesticide application to the functioning agroecosystem: risks are anticipated, resistance is cultivated in plants and microbial communities, pest behaviour is redirected, non-chemical interventions are targeted, and outcomes are measured across seasons. The reports identify major advances, but also show that laboratory model accuracy, biological antagonism and technical proof of concept do not automatically translate into dependable field outcomes. This paper therefore proposes eight interconnected paradigms and an operational Observe-Diagnose-Predict-Prevent-Intervene-Learn framework. It distinguishes established practices from emerging research directions, sets out an evidence-based programme for cross-border demonstration and regulation-aware deployment, and recommends outcome indicators based on avoided harmful pesticide exposure, yield and quality, ecological effects, financial viability and resilience. Digital technologies and microbiome-informed biology should be treated not as competing innovations but as complementary foundations for preventive, accountable and increasingly pesticide-independent European cropping systems.

Keywords: zero-pesticide agriculture; precision crop protection; artificial intelligence; digital plant pathology; weed robotics; microbiota; synthetic microbial communities; microbial biopesticides; entomopathogens; semiochemicals; decision-support systems; agroecology.

Introduction - Executive perspective: what must change

The most consequential result of the six reports is conceptual. Precision technology can reduce pesticide consumption by treating only selected plants or zones; microbiological agents can replace selected synthetic treatments; and resistant varieties can lower baseline susceptibility. Yet no single innovation demonstrates that an entire cropping system can function without harmful chemical pesticides across different years, climates, pest complexes and farm economics. The UK synthesis states this limitation explicitly, and the weed-management synthesis connects it to the TOP-AGRI Memorandum of Understanding: input efficiency is an intermediate step, whereas substantial or complete withdrawal of pesticides requires redesign of the production system (Yang, 2026; Božić, 2026).

The proposed direction is a networked, prevention-first crop-protection system. It combines diverse crop rotations and cultivar mixtures; beneficial soil, plant and insect microbiota; specific microbial products and bioactive signals; automated surveillance of pathogens, pests and weeds; models that explain the probability

and consequence of outbreaks; and interventions whose efficacy and ecological effects are measured. In this perspective, “zero pesticide” is a strategic ambition, not a claim that all biocontrol products are legally or scientifically non-pesticidal. A microbial active substance registered to control a harmful organism is itself a plant protection product. TOP-AGRI’s distinctive aspiration is agriculture free of synthetic pesticides and nature-derived pesticides that negatively affect the environment and human health, while safeguarding productivity and the farm economy (TOP-AGRI-Network, official project description).

The six contributions address complementary dimensions of this transformation: digital plant health monitoring (Tsitsigiannis, 2026), digital and preventive weed management (Božić, 2026), precision farming and implementation experience in the United Kingdom (Yang, 2026), microbiota-based protection and postharvest antagonistic yeasts (Öztekin, 2026), microbiota, entomopathogens, chemical ecology and host immunity (Ince, 2026), and microbial-product regulations, soil health and practical barriers to adoption (Bokszczanin, 2026). Their integration gives rise to a research agenda in which digital tools decide when, where and why action is justified, while ecology and biology expand the feasible range of actions beyond conventional pesticides.

1. Strategic context: from risk reduction to agroecosystem redesign

Crop pathogens, insect pests and weeds reduce yield, product quality, marketability and food-system stability. Risks are altered by long-distance trade, changes in crop production and climate extremes, while the repeated use of limited chemical modes of action fosters resistance and can generate environmental externalities (Ristaino et al., 2021; McDonald and Linde, 2002). Conventional diagnosis and field scouting remain indispensable but can be episodic and localised. A changing crop-protection system therefore needs better knowledge of the biological hazard, the host’s capacity to tolerate it and the ecological consequences of management.

The European Farm to Fork Strategy established non-legally binding 2030 ambitions to reduce the use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50%. The proposed Sustainable Use Regulation, which would have introduced binding provisions, was withdrawn in March 2024; Directive 2009/128/EC remains in force. It is therefore incorrect to describe the 50% strategy target itself as a currently legally binding reduction obligation. Equally, a 50% reduction cannot be equated with pesticide-free farming, nor do sales-based indicators alone capture local exposure, resistance, biodiversity or disease outcomes (European Commission, official sustainable-use and pesticide-target webpages). This clarification matters because science should evaluate both intermediate reduction pathways and the deeper transformation envisaged by TOP-AGRI.

Three principles frame the ensuing analysis. First, prevention/prophylaxis must have priority over response: crop diversity, healthy soils, resistant hosts, sanitation, surveillance and prophylactic biological protection can reduce the frequency and intensity of outbreaks. Second, interventions should be conditional on evidence: a sensor anomaly is not a confirmed infection, and the presence of an insect or weed is not automatically an economically damaging population. Third, deployment must be evaluated as a system over time: apparent first-season success can conceal a rising weed seedbank, replacement pest, disrupted microbiome or unsustainable cost. These principles reconcile the technological optimism of digital agriculture with the ecological ambition of the Action (Figure 1).

2. Layered, multi-scale surveillance of plant pathogens

The first major scientific breakthrough is the combination of complementary observations into layered diagnosis. Field symptoms, microscopy, culturing and molecular assays remain essential to causal attribution. Polymerase chain reaction (PCR), quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP), recombinase polymerase amplification (RPA), CRISPR-assisted assays and portable sequencing expand the possible speed and sensitivity of pathogen detection. On-site and point-of-care approaches are illustrated by the portable detection and CRISPR literature included in the digital report; metagenomic sequencing has also supported strain-level characterisation of pathogens in tomato wilt samples (Aman et al., 2020; Marcolungo et al., 2022; Paul et al., 2025; Abdelrazek et al., 2025).

These techniques solve only part of the monitoring problem. A diagnostic result is biologically specific but ordinarily attached to a limited number of sampled plants. Remote and proximal sensors solve the inverse

problem: they can rapidly map variation, but stress signals are rarely etiologically unique. RGB systems identify visible lesions, defoliation or colour changes; multispectral and hyperspectral sensors detect changes in reflectance linked to pigments and physiology; thermal imaging measures temperature shifts associated with transpiration and stomatal function; chlorophyll fluorescence reveals photosynthetic perturbations; and LiDAR describes canopy structure. The literature cited by Tsitsigiannis documents applications in grapevine leafroll, *Verticillium* wilt, blackleg in potato and other plant diseases, without implying that spectral separation alone confirms a pathogen (Pérez-Bueno et al., 2019; Bendel et al., 2020; Mahlein et al., 2019; Franceschini et al., 2024; Zhang et al., 2023).

A future surveillance workflow is hierarchical rather than technology-centred: satellite imagery or an environmental-risk model identifies a suspicious zone; a UAV and ground sensor refine the location and timing; AI ranks the competing diagnoses; an agronomist collects representative samples; laboratory or portable tests confirm pathogen identity; and the georeferenced results update a dynamic field-risk map. The combined system distinguishes screening from diagnosis and allocates scarce sampling capacity to the most informative locations. Multi-scale sensor reviews underscore that temporal continuity, calibration and platform complementarity are more important than adding sensors without a decision purpose (Alexopoulos et al., 2023; Trippa et al., 2024; Pereira et al., 2025) (Figure 1).

Connected weather stations and Internet of Things (IoT) networks fill a critical temporal gap. Temperature, leaf wetness, humidity, precipitation and soil moisture can change over hours, creating short infection windows that weekly scouting may miss. Automated spore surveillance and camera-equipped insect traps provide another stream of near-real-time evidence (Tao et al., 2021; Ahmed et al., 2024; Tummon et al., 2024). The paradigm is therefore not “AI diagnosis instead of plant pathology”, but “biologically verified, spatially explicit surveillance at the scale and frequency needed for preventive action”.

3. AI becomes a decision and learning system

Deep learning is increasingly effective at recognising patterns in leaf images, trap photographs, crop canopies and UAV imagery. Convolutional neural networks and object detectors, including YOLO architectures, support disease classification, pest localisation and small-target detection. The literature includes small-insect detection algorithms and reviews of imaging and data augmentation (Tian et al., 2023; Shorten and Khoshgoftaar, 2019; Pereira et al., 2025). However, technical accuracy measured on curated datasets is not equivalent to valid farm-level advice: image labels may be uncertain, disease and drought may resemble each other, and models trained on one geography, cultivar, season or sensor may fail under another.

More ambitious applications link observations to interpretable epidemiological and population models. Process-based models represent causal mechanisms such as host susceptibility, temperature-dependent infection, inoculum availability and insect degree-days. Statistical and machine-learning models can capture complex interactions and learn from new field data. Hybrid systems should combine them, quantify uncertainty and translate risk into explicit decisions: no action, inspect, confirm diagnostically, intervene biologically, or use a carefully delimited last-resort measure where relevant to a transition-stage IPM system. An intervention rule needs a validated threshold, a specified forecast horizon, the likely cost of a false alarm and a description of who is responsible for the decision.

The UK report provides an important caution about the transfer of apparently relevant models. JULES-crop represents crop responses to weather and soil, CARDAMOM uses Bayesian model–data fusion, and UFLUX upscales carbon, water and energy fluxes from observations. These frameworks are valuable as environmental context and exemplars of uncertainty-aware fusion, but they do not constitute pest-specific forecasting or proof of pesticide savings. Their contribution should be measured only once linked to validated biological risk models and actual decisions (Osborne et al., 2015; Bloom and Williams, 2015; Myrriotis et al., 2021, 2022; Zhu et al., 2023a, 2023b, 2026; Yang, 2026).

An AI-enabled decision-support system (DSS) should answer five questions legibly: What is observed? What competing explanations remain? How likely is a damaging event, and when? Which prevention or control options are compatible with the crop and local constraints? Did the selected action work, without disproportionate environmental or economic cost? The resulting workflow is observation → diagnosis → risk

and uncertainty → action → efficacy measurement → model update. Without the last two steps, digital crop protection is simply monitoring; with them, it becomes adaptive management (Figure 1).

4. Digital weed ecology enables herbicide-independent management

Weed management provides a particularly powerful test case because weed species and densities vary sharply within fields, damage depends on crop competition and weed emergence, and the seedbank carries consequences into future seasons. Ground cameras, satellite and UAV imagery, machine vision and site-specific maps enable detection at the scale of individual plants or weed patches. UAV multispectral mapping of black-grass in cereals and other approaches described in the UK and weed reports demonstrate the feasibility of mapping problem populations, but not automatic economic justification of the resulting intervention (Cox et al., 2023; Božić, 2026; Yang, 2026).

The familiar precision-farming approach converts these maps into site-specific herbicide application. This is relevant to near-term risk reduction, yet it maintains dependence on herbicides and may not reverse resistance selection. A more radical development uses the same detection and navigation technology to operate precise non-chemical devices. RTK-GNSS-guided machines and autonomous robots can perform inter-row or intra-row mechanical disturbance; machine vision can position laser, electrical or thermal treatments on detected weed tissue; and electric weed-control systems provide a commercial example of an alternative physical mechanism (RootWave, n.d.; Božić, 2026). These methods vary in performance, energy demand, crop injury risk, capacity and cost. Present evidence does not justify a universal ranking among them.

The real paradigm shift occurs when algorithms optimise seedbank trajectories rather than one-day weed mortality. Multi-year weed maps can be linked to crop rotation, cover-crop history, cultivation, seedling emergence, sowing date, species biology, resistance records and previous intervention results. A DSS can then recommend competitive crop cultivars, spatial crop arrangements, false seedbeds, altered sowing windows, targeted cultivation, or prevention of seed production in persistent hotspots. Site-specific intervention becomes a component of agroecological design, not a substitute for it. As the weed synthesis emphasises, the decisive sequence is detect → identify → map → assess risk → decide → intervene → evaluate → plan next season (Božić, 2026).

Validation must extend beyond weed-detection precision or treated-area percentages. Relevant measures include survivor frequency, seed return, changes in the viable seedbank, resistance risk, crop damage, soil disturbance, operation speed, energy use, labour and total cost per hectare. A treatment that appears highly effective from imagery may be inadequate if it fails to prevent reproduction in a small resistant population. Conversely, leaving low-density noncompetitive plants untreated may protect biodiversity without compromising yield. Decision thresholds should recognise these ecological and economic differences.

5. Smart pest surveillance converges with chemical ecology

For insect pests, smart camera traps and connected networks can quantify population changes, while object-detection algorithms automate counting and improve spatial coverage (Ahmed et al., 2024; Tian et al., 2023). But a count is not a control decision. Pest biology, life stage, crop phenology, damage thresholds, natural enemies and spatial connectivity must be interpreted together. Digital surveillance becomes transformative when it supports timely deployment of selective biological and behavioural tools rather than routine broad-spectrum treatment.

Chemical ecology provides those tools. Foundational pheromone research showed that defined molecules coordinate insect behaviour, while studies of plant volatiles established that herbivore-attacked plants can recruit predators and parasitoids (Karlson and Lüscher, 1959; Karlson and Butenandt, 1959; Dicke and Sabelis, 1988; Turlings et al., 1990). Insect host selection responds to mixtures of volatile compounds rather than a single generic odour; the “odorscape” concept describes those blends across space and time (Bruce et al., 2005; Conchou et al., 2019). These discoveries underpin mating disruption, mass trapping, push–pull cropping and trap crops (Cook et al., 2007; Khan et al., 2016; Hokkanen, 1991).

A digitally mediated odorscape strategy would monitor target insect abundance and stage, forecast dispersal or attack windows, and adapt placement or timing of pheromone dispensers, trap crops and biological agents. It could also measure whether natural-enemy populations respond as anticipated. Plant volatiles

may themselves prime defence: citrus studies cited in the chemical-ecology report connect exposure to selected green-leaf volatile compounds with changes in defence-associated signalling and pest interactions (Pérez-Hedo et al., 2024; Ortells-Fabra et al., 2025). Such interactions are context-dependent; induced defences can have costs or unintended effects on beneficial arthropods (Pappas et al., 2017).

The breakthrough is therefore a shift from pest mortality alone to the management of ecological information: pest orientation, host recognition, immune priming and natural-enemy recruitment. Its promise is selectivity, but field performance requires realistic dispenser economics, weather-sensitive deployment, crop-specific validation and monitoring of non-target effects. Digital timing can improve the targeting of semiochemical strategies; it cannot, by itself, guarantee that complex insect communities respond predictably.

6. The plant holobiont becomes a unit of crop protection

Plants interact continuously with microbiota in the rhizosphere, root tissues, leaves, stems, flowers and fruits. The holobiont concept treats the plant and its associated microbial communities as a functional ecological system influencing nutrition, stress tolerance and immunity (Vandenkoornhuyse et al., 2015; Compant et al., 2025). High-resolution studies of the *Arabidopsis* root microbiome established that structured microbial assemblages can be characterised, while synthetic-community methods create a route from correlation to causal experimentation (Lundberg et al., 2012; Vorholt et al., 2017).

Beneficial microorganisms reduce disease through mechanisms that act together rather than in isolation: competition for nutrients and colonisation sites; siderophore-mediated iron limitation; antibiosis and inhibitory metabolites; lytic enzymes; mycoparasitism; disruption of pathogen signalling; and the priming of plant immunity. Bacteria in the rhizosphere can induce systemic resistance involving jasmonate- and ethylene-associated pathways (Van Loon et al., 1998). Mycorrhizal associations can also prime local and systemic responses to soil-borne pathogens, and *Trichoderma* species combine antagonism with induced resistance and changes to the microbial environment (Cordier et al., 1998; Pozo and Azcón-Aguilar, 2007; Liu et al., 2026).

Single-strain selection is still useful for formulation, quality control and regulatory identification. Nevertheless, multi-strain consortia and engineered synthetic microbial communities (SynComs) create a route towards functional complementarity: different organisms may occupy different niches, exploit distinct nutrients or respond differently to stress. The microbiota report highlights beneficial bacteria such as *Bacillus* spp. and *Pseudomonas* spp., mycoparasitic fungi including *Trichoderma* spp., and antagonistic yeasts such as *Metschnikowia* spp., *Meyerozyma* spp., *Aureobasidium* spp. and *Hanseniaspora* spp. (Öztekin, 2026; Compant et al., 2025). The key scientific challenge is to demonstrate that consortium members remain compatible, viable and protective in actual plant-soil systems rather than merely coexisting in the laboratory.

There is also an alternative to adding microorganisms: create conditions in which resident protective microbiota function better. The regulatory/microbial synthesis discusses disease-suppressive soils, crop-residue and substrate amendments, chitin-based defence elicitors and the potential roles of biochar, humic substances and spent mushroom substrate in structuring microbial communities (Bokszczanin, 2026). These materials are not equivalent in mechanism, efficacy or regulatory classification. Their value should be tested through measurable changes in community function and disease risk, not inferred solely from altered microbiome composition. A host-associated community is not automatically beneficial; pathogenic, neutral and mutualistic organisms coexist and their effects can change with climate and management.

The resulting paradigm is functional microbiome management: define protective functions, identify causal organisms and mechanisms, support their establishment, measure persistence and relate the microbiome to disease suppression. Multi-omics, field microbiology and AI can help prioritise candidates, but biological ground truth remains necessary. The relevant endpoint is not the number of detected taxa but the reliability of a protective phenotype in a specific crop and environment (Figure 1).

7. Next-generation biopesticides and postharvest biological protection

Microbial biopesticides are no longer solely a proof of concept. Registered or historically commercialised products use *Bacillus* spp., *Pseudomonas* spp., *Trichoderma* spp., *Beauveria* spp. and antagonistic yeasts against particular pathogens or insects; baculovirus products can target codling moth and other susceptible

lepidopteran pests. The underlying actions range from pathogen antagonism and induced resistance to host-specific insect infection (Bokszczanin, 2026; Lacey et al., 2015). Their ecological advantage is often selectivity, but this does not exempt them from case-by-case safety assessment or confirm that they will perform under all field conditions.

The postharvest fruit sector provides tangible evidence of scientific translation. Three decades of research have led from screening antagonist isolates to commercial biological preparations and sophisticated mechanistic analysis (Droby et al., 2025). Antagonistic yeasts can colonise fruit wounds quickly, deny nutrients and space to pathogens, and sometimes restrict iron through chelating metabolites such as pulcherrimin. Studies and reviews in the supplied microbiota synthesis emphasise green mould of citrus and mandarins, pathogenic *Penicillium* species and the potential for yeast combinations to complement single-strain control (Öztekin and Karbancioglu-Guler, 2023; Oztekin et al., 2023; Godana et al., 2026).

Postharvest biological control is scientifically distinctive because it must work across harvest, handling, transport and cold storage. Temperature changes, humidity, fruit wounds, microbial compatibility, shelf life and residues of other treatments can all shape performance. The field-to-shelf challenge thus provides an ideal test of both formulation robustness and microbiome-informed deployment. It also links crop health to food safety: mycotoxigenic fungi threaten product quality, and selected biological strategies may help prevent colonisation or modify toxin fate. Claims of detoxification must nevertheless verify the chemical identity and toxicological safety of degradation products, rather than rely only on a falling analytical signal (Oztekin et al., 2023; Godana et al., 2026).

Emerging tools include defined multi-strain or cross-kingdom consortia; microbial metabolites or elicitors that stimulate immunity; endophytic entomopathogenic fungi able to affect both pests and host defence; and selectively acting insect viruses. Reports cite *Beauveria* spp. and *Metarhizium* spp. as organisms whose endophytic lifestyles can modify plant-insect interactions and, in particular experimental settings, infect pests within plant tissues (González-Mas et al., 2021; Aguilera Cuenca et al., 2026). Targeted virus engineering is discussed as an exploratory research frontier, not an approved operational solution (Ince, 2026). Claims about biosafety, host range, environmental persistence and effectiveness must be established separately for each candidate and use case.

A further paradigm shift is to move from “replace a fungicide or insecticide with one commercial product” to “assemble a reliable package of biological functions”. Such a package can include host resistance, habitat management, a microbial inoculant, a semiochemical signal and surveillance-led timing. It must be compatible with local regulation, production logistics and the ecology of the crop, and its success should be judged against untreated and conventional reference treatments in independently replicated trials (Figure 1).

8. Genetic resistance and functional biodiversity supply durable prevention

Biological crop protection extends beyond inoculants and products. The gene-for-gene framework and the two interacting layers of pattern-triggered and effector-triggered immunity explain important aspects of pathogen recognition and plant defence (Flor, 1971; Jones and Dangl, 2006). Resistance durability is a population-level property: the capacity of pathogen populations to evolve, disperse and reproduce determines whether a resistance trait retains value over time (McDonald and Linde, 2002). Genotype diversity, resistance-gene deployment and mixtures therefore matter as much as the presence of a single high-performing gene.

The widely cited rice variety-mixture experiments demonstrated how within-field diversity can reduce blast severity and decrease fungicide dependence, offering unusually direct evidence for a prevention-first approach (Zhu et al., 2000; Wolfe, 2000). Modern genome-editing research also demonstrates the possibility of modifying susceptibility loci: editing wheat MLO alleles has conferred heritable powdery-mildew resistance under research conditions (Wang et al., 2014). These are conceptually distinct routes -ecological diversity and genetic modification- but both shift the burden of crop protection away from repeated external chemical intervention.

Preventive resistance is not cost-free. Plant defences can trade off with growth or ecological interactions, and pathogen pressure may select for virulence even when a cultivar initially performs well (Sheldon and Verhulst, 1996). Emerging work in holobiont-aware breeding should therefore test genotype × microbiota ×

environment × management interactions: breeding for a plant that recruits or retains beneficial microbiota could potentially strengthen resistance durability, but this remains a research agenda rather than an established production recommendation. Climate resilience and compatible natural-enemy communities must be part of the evaluation.

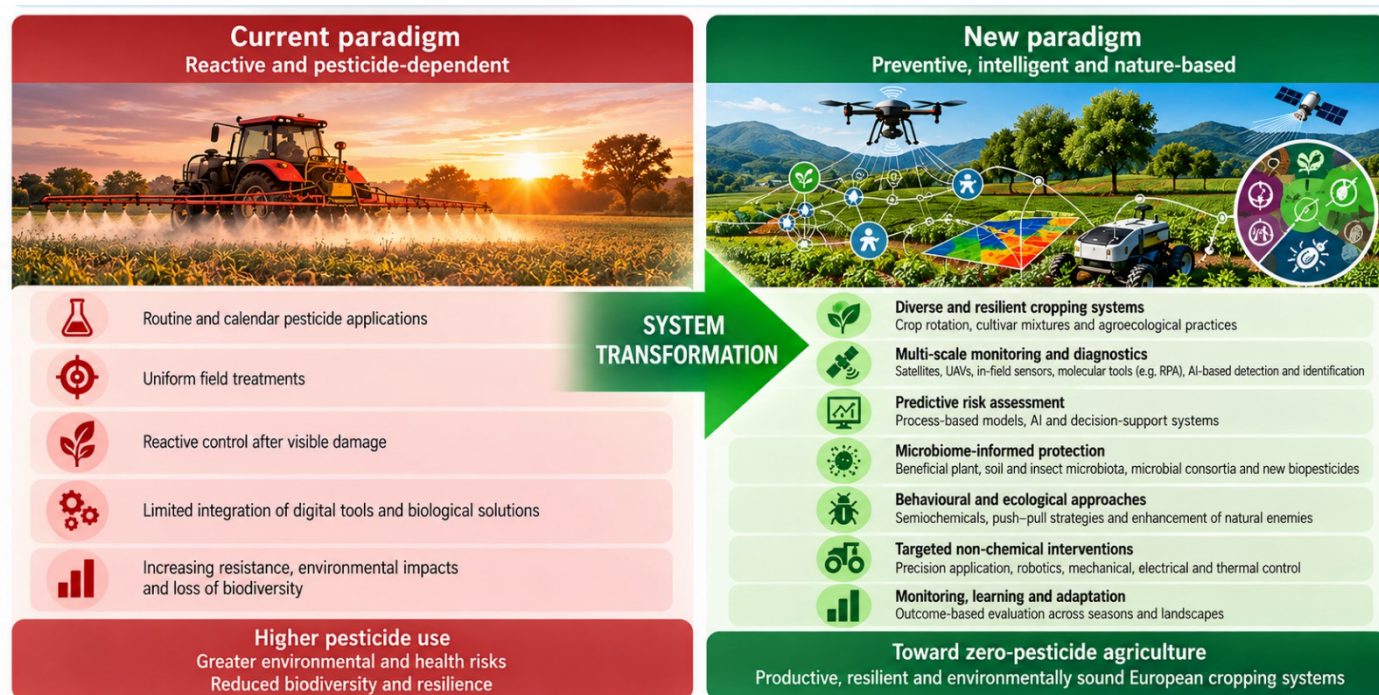


Figure 1. A New Paradigm for Crop Protection: From reactive pesticide use to preventive, intelligent and nature-based crop protection.

9. An integrated architecture: Observe-Diagnose-Predict-Prevent-Intervene-Learn

The synthesis suggests a practical architecture built on six recurring functions. **OBSERVE:** monitor vegetation, pathogens, insect populations, weed communities, beneficial organisms and microclimate at appropriate spatial and temporal scales. **DIAGNOSE:** connect candidate anomalies to laboratory-confirmed pathogen identity, pest species, weed biology and differential diagnosis. **PREDICT:** combine mechanistic and AI models to estimate incidence, severity, population dynamics, uncertainty and likely losses. **PREVENT:** recommend rotations, resistant varieties, vegetation diversity, soil or microbiome management, sanitation, semiochemical programmes and other measures that lower the probability of an outbreak. **INTERVENE:** select the least harmful effective action, which may include a specific biological agent, physical weed removal or strategically timed monitoring rather than any treatment. **LEARN:** measure outcomes, identify errors and recalibrate subsequent decisions.

Every step requires traceable data: geolocation, crop and cultivar, phenological stage, intervention and cost, diagnostic confidence, weather, management history and verification of outcomes. A data architecture should support common terminology, accessible metadata, interoperability between software and machinery, and explicit farmer consent and permissions. The decision interface must express confidence and limitations in comprehensible language. A high-risk alert without an explanation or available response pathway is not an operational innovation.

The UK North Wyke Farm Platform illustrates the value of instrumented, long-duration, system-level evaluation. Its recorded management events and environmental measurements can support model–data fusion and causal comparisons, though it should not be presented as proof that precision pesticide control is already routine at that site (Orr et al., 2016; Takahashi et al., 2018; Hawkins and Harris, 2023; Yang, 2026). The IPM Decisions platform and the LINKDAPA initiative similarly represent different parts of the translation chain—integrated decision access and accessible farm-data services—rather than finished zero-pesticide systems (IPM Decisions, n.d.; Latherow et al., 2024).

The addition proposed here is a biocontrol-readiness layer within digital DSS: alongside weather and pest risk, the system should track biological agent viability, expected performance under local temperature and moisture, compatibility with other treatments, application windows, likely establishment, environmental safety and regulation. This would make the biological alternative visible at the same decision point where a conventional product might previously have been selected. That specific integration is a perspective and research proposal derived from the six reports; it has not been demonstrated as an existing validated platform.

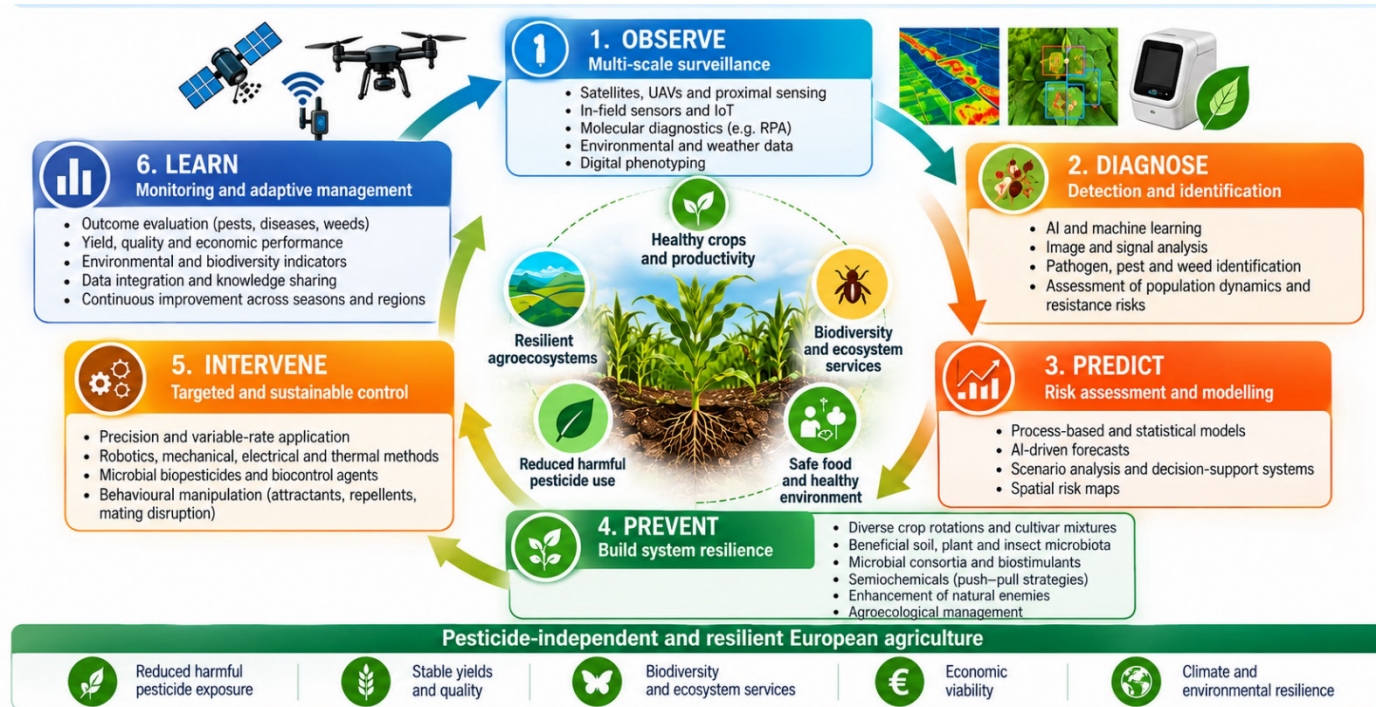


Figure 2. Integrated Digital - Biological Framework: The Observe-Diagnose-Predict-Prevent-Intervene-Learn cycle for pesticide-independent agriculture.

10. New paradigms formulated from the six reports

Paradigm 1 - From eradication to managed ecological risk. Crop protection should seek economically and ecologically tolerable pressure, not indiscriminate elimination of organisms. Thresholds must incorporate crop phenology, host tolerance, natural enemies and the cost of the intervention, recognising that some organisms support biodiversity and agroecosystem functions.

Paradigm 2 - From symptoms to anticipatory biological intelligence. Crop risk should be detected through multi-scale sensing, confirmed through diagnostics and translated into forecast action windows. AI becomes an assistant to phytopathological and ecological reasoning, not a replacement for them.

Paradigm 3 - From plant-centred protection to holobiont-centred resilience. Microbiota are management-relevant partners whose protective functions can be supported, measured or deliberately introduced. The causal role and stability of protective organisms matter more than microbiome diversity as a standalone indicator.

Paradigm 4 - From broad-spectrum treatment to targeted ecological communication. Semiochemicals, trap crops, plant volatiles and host-specific biological agents manipulate pest behaviour and population processes with potentially less collateral damage. Their impacts must nevertheless be checked against natural enemies and non-target communities.

Paradigm 5 - From precision pesticide placement to precision non-chemical action. Digital mapping should increasingly control mechanical, electrical, laser and other physical weed tools, as well as biologically based measures. Pesticide dose reduction is a transition benefit, not the ultimate design objective.

Paradigm 6 - From single-strain replacement to multi-functional biological systems. Biological Control Agents (BCAs), consortia, induced immunity, crop genotype and habitat management should be evaluated

for complementarity, stability and reproducibility. Combining components without evidence of compatibility is not itself an innovation.

Paradigm 7 - From snapshot accuracy to longitudinal decision value. Model performance must be judged by the correctness, timeliness and consequences of agricultural decisions, including the no-treatment decision. Multi-season changes in pathogen inoculum, resistance, pest populations and weed seedbanks are integral outcomes.

Paradigm 8 - From prototype-led innovation to farmer-governed evidence ecosystems. Data ownership, affordability, machine compatibility, operational speed, regulatory clarity and farmer training are co-determinants of success. Co-design, independent field trials and transparent economic analysis should precede scale-up.

These paradigms are deliberately interdependent. For example, an accurate disease map (Paradigm 2) creates system value only if a viable preventive response is available (Paradigms 3, 4 and 6), the intervention is timely (Paradigm 5), its consequences are monitored (Paradigm 7), and farmers can practically use and trust it (Paradigm 8). The shift is therefore from “technology readiness” in isolation to “system readiness” across multiple scientific, environmental and social dimensions.

11. Three illustrative integration pathways

Pathway A - Cereal weeds and herbicide resistance. In a winter cereal landscape, UAV and proximal imagery map black-grass hotspots; spatial and historical information establish the likely seedbank and resistance pressure; the DSS compares delayed sowing, competitive crop establishment, cover crops, rotation and mechanical or electrical control; and follow-up imagery and seed-production surveys measure what was prevented. Cox et al. (2023) provide evidence for weed mapping, whereas the complete integrated programme is a proposed testable workflow synthesised from Božić (2026) and Yang (2026), not a claim of proven implementation.

Pathway B - Soil-borne disease of a vegetable crop. Soil and microclimate monitoring identify conditions favouring root pathogens, UAV or proximal imagery localises unexplained stress, and portable molecular diagnosis confirms the causal agent. Growers then evaluate resistant material, crop and soil management, targeted microbial agents or functionally designed consortia while collecting microbiome and disease data. Repeated sampling determines whether suppression is stable under drought or heat. The molecular, sensing and microbial components each have supporting evidence, but their full integration into a commercially validated protocol is a research priority rather than a demonstrated universal recipe.

Pathway C - Fruit pest, disease and postharvest protection. Digital insect traps monitor population trends in an orchard and help time pheromone-based measures or selective entomopathogens; host resistance and ecological habitat management lower baseline risk. At harvest, fruit health records and handling conditions guide the use and monitoring of antagonistic yeasts against postharvest fungi. The package links field pest management with storage disease outcomes and marketable yield, building on the chemical-ecology and yeast-biocontrol literatures (Cook et al., 2007; Droby et al., 2025; Öztekin and Karbancioglu-Guler, 2023). It is an integration scenario requiring independent economic and biosafety evaluation.

12. Evidence gaps and obstacles to implementation

The dominant technological obstacle is external validity. Imaging or ML models trained on curated images frequently encounter unfamiliar genotypes, weather, lighting, soil backgrounds, lesion stages or pest complexes; high laboratory classification scores may not survive deployment. Similarly, microbe-plant interactions can vary with temperature, soil pH, humidity, drought, resident microbial communities, production method and formulation. Digital and biological validation should use independent sites and seasons with prespecified endpoints; ground-truth diagnostics, balanced error costs and uncertainty reporting are essential (Pereira et al., 2025; Öztekin, 2026; Božić, 2026).

The biological obstacles include consistency of microbial establishment, interactions within consortia, shelf life and delivery, specificity, evolving pest and pathogen populations, and potential consequences for non-target organisms. Entomopathogens and semiochemicals require host-specific efficacy studies and field-scale knowledge of ecology; experimental virus engineering raises additional biosafety and regulatory questions. None of these issues can be resolved with optimisation of AI predictions alone.

Implementation constraints are equally important. Equipment costs, maintenance, farm structure, rural connectivity, skilled labour, interoperability and access to advisers shape the market for precision tools. Microbial-product registration may not translate into local product availability or supply-chain reliability; expert comparisons described in the microbial regulation report highlight that point for several European national settings (Bokszczanin, 2026). Farmer and adviser participation is indispensable when systems recommend departures from familiar routines (Latherow et al., 2024; Yang, 2026).

Finally, sustainability outcomes must be established rather than assumed. Electrical or laser weeding has an energy footprint; mechanical disturbance can change soil properties; microbial amendments can alter community interactions; biological insecticides may still have off-target effects; and biodiversity-enhancing measures can create new agronomic trade-offs. Comparative assessment should account for whole-farm emissions and inputs, effects on soils and water, marketable yields, occupational demands and resistance trajectories. Avoided pesticide kilograms alone is too narrow a success measure.

13. Regulation, safety and the semantics of “biological” protection

The regulatory distinction between microbial plant protection products and plant biostimulants is central. In the EU, a product intended to protect plants from harmful organisms generally falls within the plant protection framework of Regulation (EC) No 1107/2009. The 2022 amendments introduced tailored criteria and evidence requirements for microbial active substances and products, including strain-level identification, potential pathogenicity, infectivity, metabolites of concern and antimicrobial-resistance considerations (Commission Regulations (EU) 2022/1438, 2022/1439 and 2022/1440; Bokszczanin, 2026).

By contrast, Regulation (EU) 2019/1009 concerns EU fertilising products. A plant biostimulant has a defined function related to nutrient-use processes, tolerance to abiotic stress, quality or nutrient availability; the EU-harmonised microbial biostimulant category PFC 6(A) is restricted through component material category CMC 7, which lists specific microbial groups. A *Bacillus* or *Trichoderma* product cannot be classified as an EU-harmonised PFC 6(A) microbial biostimulant merely because it improves plant growth, though separate national routes may be relevant. The intended claim, ingredients, functional mechanism and national rules must be assessed before translation (Regulation (EU) 2019/1009; Bokszczanin, 2026).

This creates a strategic imperative: researchers should design safety, identity, formulation and efficacy assessment into discovery pipelines, rather than deal with regulation only after scientific proof of concept. Consortia may add complexity to product characterisation, while semiochemicals and physical tools face different assessment routes. Harmonising study methods among COST countries could increase evidence portability, but legal harmonisation must not be assumed. A living regulatory map, updated by qualified specialists, is a sensible network output.

14. A testable research and innovation roadmap for TOP-AGRI

Priority A - Common reference landscapes and long-term demonstrations. Develop multi-country experimental platforms spanning cereals, vegetables, orchards and postharvest chains. Include contrasting climates, soils, farm sizes and intensity of pest pressure. Establish a minimum common protocol for site description, diagnostic sampling, sensor calibration, management records, biological agent identity and climate variables. Field and controlled-environment experiments should be linked but analysed separately.

Priority B - Explainable and uncertainty-aware crop-protection models. Combine validated epidemiological or weed demographic models with remotely sensed and IoT data. Distinguish anomaly-detection accuracy from causal diagnostic accuracy and from decision value. Measure false alarms, missed damaging events, intervention lead time, model calibration, geographic transferability and post-deployment drift. Design “no intervention” as a genuine recommendation class.

Priority C - Functional microbiome discovery and consortia design. Move beyond taxonomic association studies to isolate collections, functional genomics, metabolomics, targeted inoculation and withdrawal experiments. Select strains for complementary mechanisms, stress tolerance and genetic stability. Test interaction with native microbiota, host genotype and soil management, paying particular attention to climate resilience and multi-season establishment.

Priority D - New biopesticide delivery and compatibility. Evaluate formulation quality, viability, dosing, shelf life and compatible application equipment for yeasts, bacteria, fungi, entomopathogenic viruses and other

promising candidates. Where semiochemicals or induced resistance are combined with living agents, test synergistic, additive and antagonistic responses rather than assume benefit. Integrate biological-agent performance windows into DSS outputs.

Priority E - Robotics and preventive weed trajectories. Compare machine vision-guided mechanical, electrical, thermal and laser methods across real fields. Record crop injury, target specificity, energy demand and safety. Link interventions to seedbank modelling, crop rotation and resistance management, and test whether preventive management reduces the need for later interventions across several years.

Priority F - Cost, governance and multi-actor adoption. Test tools with farmers, advisers, manufacturers and regulators from the design stage. Include small and medium-sized enterprises, service-sharing schemes and regions with limited connectivity. Provide transparent maintenance costs, farm-data access rules, interoperable interfaces and training curricula. Implementation science should evaluate why technologies are used or abandoned, not only whether they can operate.

A shared outcomes framework should include four indicator families. *Protection*: confirmed disease or pest incidence, weed seed production, damage severity, control stability and marketable yield. *Inputs and externalities*: number and area of pesticide applications, hazard-weighted exposure, soil or water indicators, biodiversity and carbon/energy consequences. *Technology and biology*: model calibration, time to detection, intervention success, strain viability and persistence, reliability under climatic stress. *Socio-economics*: cost per hectare, labour, profit margin, adoption, trust, accessibility and data-governance compliance. Each outcome needs a defined baseline, counterfactual comparator and adequate replication; no single index can substitute for this integrated evaluation.

15. Conclusions: towards a new science of preventive crop protection

The most prominent breakthroughs described in this perspective paper are real and complementary. Portable diagnostics, sensor fusion and AI increase the possibility of earlier and wider detection; robotic precision creates non-chemical options for weed control; entomopathogens and semiochemicals enable selective pest management; microbial communities, antagonistic yeasts and induced immunity extend biological protection; and genetic resistance and cropping diversity reduce intrinsic system vulnerability. What remains less mature is their integration into dependable, affordable and ecologically verified farming systems.

The decisive new paradigm is therefore not a single technology or next-generation product. It is an evidence-based preventive system in which plant health is monitored as a biological and ecological process, digital decisions are explainable and tested, microbial functions are actively managed, physical and selective biological responses are preferred where validated, and feedback across seasons improves resilience. For COST Action CA21134, the lasting contribution can be a shared methodological and conceptual framework that turns promising but dispersed advances into coordinated, measurable progress towards agriculture that does not depend on harmful pesticides.

Source synthesis

This deliverable is a new synthesis of six supplied Virtual Mobility Reports, webinars and discussions held during the COST Action CA21134 physical and online meetings rather than a systematic review of all published research. Illustrative scenarios and proposed paradigms are conceptual integrations, not claims that the full combined systems have been experimentally validated. The bibliography retains the original formal reference lists supplied in the reports. The Bokszczanin and Božić reports do not supply a conventional standalone bibliography; their original regulatory citations and source attribution are therefore identified separately instead of inventing full publication metadata.

Figures were generated using ChatGPT (OpenAI) based on provided prompts and scientific content.

Primary six source Virtual Mobility Reports incorporated in D7

1. Bokszczanin, K. (2026). The Synthesis on Microbial Approaches for Low- and Zero-Pesticide Crop Protection. CA21134 synthesis report.
2. Božić, D. (2026). Digital Technologies for the Transition towards Zero-Pesticide Crop Protection: A Focus on Weed Management.
3. Ince, İ. A. (2026). Microbiota and chemical ecology as biological levers for insecticide- and fungicide-free crop protection: A synthesis of WG3 breakthroughs.
4. Öztekin, S. (2026). Microbiota-based approaches for sustainable crop protection: recent achievements and future perspectives.
5. Tsitsigiannis, D. (2026). Integrating Smart Digital Technologies and Artificial Intelligence in Crop Protection.
6. Yang, L. (2026). Precision Farming in the UK: Technological Advances towards Zero Pesticide Crop Protection.

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