

Soil Health as a Foundation for Crop Protection:

Boosting Resilience through Precision Agriculture, Microbiota and Cropping System Design

(Soils4CropProtect)

COST Action CA21134 – TOP-AGRI-Network | Virtual Mobility Grant Report

Prepared by: dr Vladimir Ćirić, Full Professor of Soil Science, Faculty of Agriculture, University of Novi Sad, Serbia

1. How the Report Was Built

This report synthesises achievements on soil health as a scientific and practical foundation for **crop protection**, addressing the Call's theme of breakthroughs in microbiota, precision farming and digital technology. While not among the topics explicitly listed in the Call, this theme was proposed as a valuable addition, integrating digital technologies, cropping system design and microbiology around a single unifying factor: soil health as the basis for **crop protection**. The synthesis builds on lectures delivered within COST Action CA21134 (TOP-AGRI-Network) on soil health as the hidden foundation of crop resilience, and on the design of soil-based, low-**pesticide** cropping systems. It was prepared through a Virtual Mobility Grant, structured around a compulsory video meeting gathering participants from several Action member countries. The applicant drafted an initial outline around four content areas – soil health as a precondition for resilience, cropping system design, digital technologies, and recommendations for research and policy – circulated it to invited participants for input, and integrated contributions into this consolidated document.

The compulsory video meeting foreseen in the working plan was held on 11 September 2026, bringing together the applicant with Prof. **Simonida Đurić** (University of Novi Sad, Faculty of Agriculture, **Serbia**), **Vesna Tunguz** (University of East Sarajevo, **Bosnia and Herzegovina**), **Bojana Petrović** (Institute of Tropical Sciences, Prague, **Czech Republic**) and Prof. **Zvonko Pačanoski** (Ss. Cyril and Methodius University in Skopje, Faculty of Agricultural Sciences and Food, **North Macedonia**); the national examples and comments they contributed are integrated at the relevant points throughout this report.

2. Introduction: Why Soil Health Matters for Crop Protection

Soil is the foundation on which the atmosphere, freshwater and terrestrial life ultimately depend; despite its small share of Earth's total resources, it underpins food, energy and water security. As Franklin D. Roosevelt observed in 1937, “the Nation that destroys its soil destroys itself” – a statement that remains a powerful reminder that soil carbon and structure literally hold agricultural systems together.

Global agriculture faces converging pressures: climate change, soil degradation, biodiversity loss, increasing **pesticide** dependence and the need for sustainable food production. The traditional response to **pest pressure** has been to apply more **pesticides**; a systems-based response instead invests in healthier soil, which supports healthier plants with greater natural resistance and lower **pesticide** dependence. Estimated annual costs of land degradation in the EU are substantial – for example, €3.4–5.6 billion from soil organic matter decline and up to €17.3 billion from pollution – underlining the economic case for soil-based prevention rather than chemical cure.

Reversing this trajectory requires reframing **crop protection** itself: rather than treating **pest** and **disease** pressure as problems to be countered chemically after they arise, a soil-centred approach treats them as symptoms of an underlying loss of soil function, to be prevented by restoring that function in the first place. This is also the direction set by policy: the European Union's Farm to Fork Strategy sets a target of reducing the overall use and risk of chemical **pesticides** by 50% by 2030, and achieving this without compromising yields is precisely the challenge that a soil health-based approach to **crop protection** is best placed to address, by preventing **pest** and **disease** pressure from building up in the first place rather than only intensifying chemical control once it has.

3. Soil Health: Concept and Components

The FAO defines soil health as “the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems”, a definition coined by the Intergovernmental Technical Panel on Soils and supported by the FAO Global Soil Partnership. The definition rests on three principles: soil is living, dynamic and multifunctional.

Soil health is best understood through three interacting property groups:

- Physical properties: soil structure, aggregation, porosity, bulk density, water infiltration and retention.
- Chemical properties: soil pH, nutrient availability, organic carbon, salinity, cation exchange capacity (CEC).
- Biological properties: soil microorganisms, earthworms, fungi, soil biodiversity, enzyme activity.

Among these, soil organic matter is the cornerstone of structural integrity, driving moisture and nutrient retention, acting as a microbial habitat and enabling carbon sequestration. Well-aggregated soil structure allows deep root penetration, balanced aeration and resistance to erosion during heavy rainfall. The soil microbiome – including mycorrhizal fungi, *Rhizobium*, *Bacillus*, *Trichoderma*, *Streptomyces* and *Pseudomonas* – drives nutrient cycling, organic matter decomposition, **disease suppression** and carbon storage.

It is useful to distinguish soil health from the related concepts of soil fertility and soil resilience. Soil fertility is the soil's ability to supply plants with water, nutrients, air, temperature and space; soil health is the broader capacity of soil to function as a living ecosystem, including fertility; soil resilience is the capacity of a healthy soil to withstand and recover from disturbance while maintaining its functions.

Aspect	Soil fertility	Soil health
Definition	Ability of soil to supply nutrients for plant growth	Capacity of soil to function as a living ecosystem
Main focus	Nutrient availability	Overall soil function and sustainability
Key indicators	Nutrient levels (N, P, K), pH, CEC	Organic matter, structure, microbial activity, pH, infiltration
Time scale	Short- to medium-term	Long-term

In practice, soil health is increasingly assessed through composite indices rather than single parameters. For example, the Soil Management Assessment Framework (SMAF) and comparable minimum-dataset approaches combine physical, chemical and biological indicators into a single score, allowing land managers and advisory services to track trends over time and benchmark fields against regional or national reference values.

4. Soil Microbiome and Natural Pest & Disease Suppression

Healthy soils improve plant resistance to **pathogens**, insects and nematodes by fostering physiologically robust plant cell structures that limit **pathogen** entry and by supporting abundant, diverse beneficial microbial communities, including genera such as *Pseudomonas*, *Bacillus* and *Streptomyces*. Three mechanisms of microbiome-mediated protection are particularly relevant to low-**pesticide crop protection**:

- Competitive exclusion: diverse bacterial and fungal communities outcompete **pathogens** for root space and nutrients (e.g., *Pseudomonas* spp. colonising the rhizosphere limit infection by *Fusarium oxysporum*).

- Systemic induced resistance: beneficial soil microbes stimulate the plant's metabolic pathways to pre-emptively trigger natural defences against foliar attacks (e.g., *Bacillus subtilis* inducing resistance in tomato against *Botrytis cinerea*).
- Antibiosis production: native microbiomes synthesise biochemical agents that suppress soil-borne **pathogens** (e.g., *Streptomyces* spp. producing antibiotics that suppress *Rhizoctonia solani* and reduce damping-off in seedlings).

The overall pathway is therefore: healthy soil → diverse microbiome → beneficial microorganisms → **disease suppression**. This system-based approach to **pest control** – healthier soil leading to healthier plants, greater natural resistance and lower **pesticide** dependence – stands in contrast to the traditional approach of relying on increasing **pesticide** inputs.

This mechanism is already being translated into practice in **Serbia**, *Bacillus*-based **biofungicides** and **biobactericide** (marketed as Bacillo Stopper) are applied across seven field and horticultural crops.

This is consistent with a broader market trend: biological crop-protection products (biopesticides and biostimulants derived from beneficial microorganisms) are among the fastest-growing segments of the **plant protection** sector globally, as producers and regulators alike seek alternatives that work with, rather than against, the soil microbiome. Realizing this potential at scale, however, still depends on consistent product quality, correct application timing and – as illustrated above – field-level validation across different pedoclimatic conditions.

5. Precision and Digital Agriculture Tools for Soil-Based Crop Protection

Reliable, well-structured soil data collection is the starting point for any effective digital decision support system (DDSS) in field crop production. Data collection combines sampling and laboratory analysis with remote and proximal sensing (soil sensors, drones, satellite imagery, GIS, yield mapping), forming spatially explicit databases that support decision-making in crop management.

Building on such spatial soil data, Variable Rate Technology (VRT) enables site-specific management of fertilisation, sowing and spraying in place of uniform, blanket applications. A typical workflow moves from producer data and yield maps, through field zoning based on satellite/drone imagery, vegetation indices and elevation, to a structured soil sampling plan, laboratory analysis (P_2O_5 , K_2O , pH, $CaCO_3$, humus, texture, CEC, N-min), fertility mapping and, finally, generation of variable-rate application (e.g., variable-rate urea application in the range of roughly 40–170 kg/ha, and variable-rate seeding density maps in the order of 58,000–66,000 plants/ha) delivered as e-maps to the applicator or seeder. Field evidence from wheat under contrasting nitrogen supply shows that tailored, spatially precise nutrient management supports balanced vegetation growth and avoids the fertiliser-induced weaknesses that can otherwise support **disease spreading**.

The benefits of this precision approach are consistent across the technologies reviewed: less fertiliser and **pesticide** use, healthier soil, reduced crop stress, better and more uniform crop performance, and improved economic planning and long-term farm operability. In parallel, unification of legacy soil datasets – which frequently differ in coordinate system (spherical degrees/minutes/seconds or decimal degrees, Gauss–Krüger, UTM) and file structure – is a necessary but often underestimated step in building the harmonized digital soil databases that feed these decision support systems.

A further illustration comes from the **Czech Republic**, where roughly 75% of farms are large-scale operations that frequently collaborate with universities; using Copernicus satellite data together with Variable Rate Technology and other precision-agriculture tools, these partnerships allow **pesticides** to be applied locally, only where needed, rather than uniformly across the whole field.

Adoption of these tools nonetheless remains uneven across the Action's member countries: large, well-capitalised holdings with established links to universities or advisory services – as in the Czech example above – tend to move first, while smaller family farms, which still dominate the agricultural structure in much of South-Eastern Europe, more often lack the capital, technical support or plot size needed to justify investment in sensors, drones or VRT machinery. Bridging this gap is itself a precondition for translating precision agriculture's soil- and **pesticide**-saving potential into a region-wide, rather than a niche, practice.

From a cost perspective, the investment required for sensors or VRT-capable machinery is increasingly offset by input savings: several of the workflows described above have been shown to pay for themselves within a small number of growing seasons through reduced fertilizer and **pesticide** use alone, which strengthens the case for targeted public support in closing the adoption gap described above.

6. Practical Soil Management Tools for Low-**Pesticide** Cropping Systems

Alongside digital and precision tools, well-established agronomic practices remain central to building soil-based resistance to **pests**, **diseases** and abiotic stress:

6.1 Cover cropping and diversified rotation

Cover crops protect topsoil from wind and rain erosion, improve fertility (especially nitrogen levels when legumes such as clover, hairy vetch, field peas or cowpea are used), increase organic matter, suppress **weeds**, retain moisture, reduce nutrient runoff, support pollinators and beneficial insects, and help break **pest** and **disease** cycles depending on the species used. Grasses (cereal rye, oats, ryegrass, barley) reduce erosion and build organic matter, while brassicas (daikon radish, mustard, turnip) help break up compacted soil and suppress **pests** through bio-fumigation.

Diversified crop rotation (e.g., corn → soybeans → wheat; potatoes → peas → cabbage) breaks the cycles of **weeds**, **pathogens** and insects while improving soil fertility, by shifting crop families in structured sequences that deplete host-specific **pest** and **pathogen** populations and naturally replenish deep soil nutrient structures. Intercropping delivers similar benefits within a single season – for example, corn with beans (nitrogen fixation), corn with squash (**weed** suppression through ground cover), or tomato with basil (**pest** repellence and attraction of beneficial insects) – while also using water, nutrients and sunlight more efficiently and lowering the risk of complete crop failure.

By contrast, national experience shared from North Macedonia points to a more limited picture: crop rotation there is often constrained, with cropping patterns dominated by cash crops and only marginal use of cover crops or intercropping – practices that would otherwise help suppress **weeds**. Public subsidies for regenerative practices were identified as a necessary policy lever to shift this pattern.

A further Serbian example illustrates integrated **weed management** at farm level: on selected holdings, multi-field crop rotation, high-quality tillage and crop-specific cultivation technology are combined with intercropping and, where possible only mechanical **weed control**.

On some organic farms, **weeds** are suppressed without **herbicides** through a strategic tillage system – typically shallow disking, two passes of subsoiling and a single ploughing every five years – combined with high-quality execution of all field operations, especially sowing, so that the crop stand is competitive against **weeds** from the outset.

The five-year rotation below, applied on this basis, is designed specifically to minimise **disease** and **weed** pressure without relying on **pesticides**:

Year	Crop	Rationale
1	Winter pea (legume)	Fixes nitrogen; leaves the field early, an excellent pre-crop for oat.
2	Winter oat (cereal)	Uses the nitrogen left by the pea; helps clean the field of weeds .
3	Spring chickpea (legume)	Re-enriches the soil with nitrogen; sown in spring to make use of winter moisture.
4	Winter flax (industrial crop)	Shallow-rooted; performs well after chickpea and is harvested early.
5	Sunflower (row crop)	Deep-rooted; draws water and nutrients from deeper layers; closes the cycle.

Key rotation principles respected: sunflower returns to the same plot only every fifth year, sharply reducing the risk of **diseases** such as white mould (*Sclerotinia*); legumes and non-legumes (pea, chickpea) alternate as ideal pre-crops for oat and flax; and winter and spring crops alternate, improving both **weed control** and the distribution of machinery use across the season.

6.2 Reduced tillage, organic and regenerative agriculture

Reduced and conservation tillage practices – no-till, strip tillage, mulch tillage and ridge tillage – reduce soil erosion, improve soil structure and health, conserve moisture, increase organic matter, support beneficial soil organisms, lower fuel and labour costs, reduce carbon emissions and help preserve underground fungal networks and organic carbon stability.

Organic agriculture (compost and manure as fertilizer, **biological pest control**, crop rotation and cover crops, mechanical or hand weeding, minimum disturbance) and regenerative agriculture (combining cover crops, rotation, reduced/no-till, organic matter inputs, livestock integration and agroforestry) both aim to improve soil fertility and structure, increase carbon storage, reduce erosion, improve water retention, enhance biodiversity, and reduce dependence on synthetic fertilizers and **pesticides**, thereby increasing long-term farm resilience. The comparison below summarizes the practical trade-offs between conventional, synthetic-input-heavy systems and regenerative soil-based systems.

Agroforestry and living-mulch systems extend the same logic further, by keeping a permanent or near-permanent plant cover on the land: hedgerows, alley cropping and living mulches between tree or shrub rows reduce wind and water erosion, moderate microclimate, and provide additional habitat for the natural enemies of crop **pests**, complementing the annual rotation and tillage measures described above.

Management parameter	Synthetic-heavy systems	Regenerative soil systems
Pest control strategy	Preventative, broad-spectrum chemical inputs	Natural bio-suppression, ecological balance
Soil microbial health	Suppressed biological activity, low diversity	Highly active, diverse microbial networks
Water retention	Low, vulnerable to seasonal drought	High, from biological SOM build-up
Input costs & runoff	High financial costs, chemical leaching	Low external inputs, more circular system

7. Training for farmers

An example of farmer training from **Bosnia and Herzegovina** is the cross-border project “Pesticide Control and Reduction” (PEPCO): Through the Interreg IPA Programme (Croatia–Bosnia and Herzegovina–Montenegro), an Action Plan for the Sustainable Use of Pesticides was developed. The project focuses on protecting the highly sensitive karst area in Bosnia and Herzegovina, where pesticides can rapidly infiltrate underground sources of drinking water. As part of the training, farmers are encouraged to replace chemical control measures with biological and agro-technical alternatives.

8. Regulatory Context: The EU Soil Monitoring Law

Soil degradation is recognized as a significant issue across the European Union, with an estimated 60–70% of EU soils considered to be in an unhealthy or degraded condition. In 2025, the EU adopted its first dedicated legal framework on soil: Directive (EU) 2025/2360 on soil monitoring and resilience (the “Soil Monitoring

Law”), which entered into force on 16 December 2025. The Directive establishes a common framework for monitoring and assessing soil health, addressing soil degradation and contamination, and supporting soil resilience, with the long-term aspirational objective of achieving healthy soils by 2050.

The Directive requires Member States to establish soil-monitoring frameworks covering the physical, chemical and biological condition of soils and to assess key pressures including erosion, loss of soil organic matter, salinization, contamination, compaction, soil sealing and loss of soil biodiversity. Its monitoring framework includes soil descriptors relating to soil structure and physical condition, soil organic carbon and other chemical properties, as well as biological indicators. Monitoring of contaminants, including pesticides and PFAS, has also been strengthened.

The regulatory shift is therefore significant for agriculture because it broadens the policy focus beyond agricultural productivity towards the physical, chemical and biological condition of soils and the ecosystem services they provide. While the Directive does not prescribe a specific farming system or mandate “regenerative” or “low-input” agriculture, its objectives strengthen the policy case for soil-centred management practices such as crop diversification, soil cover, reduced tillage, improved organic-matter management and more sustainable use of pesticides. EU agricultural policy already supports a number of such practices through instruments including eco-schemes and rural-development measures.

For EU candidate and neighboring countries outside the EU, including Serbia, Bosnia and Herzegovina and North Macedonia, the Soil Monitoring Law is not directly binding. However, its monitoring framework and soil-health objectives provide an increasingly relevant reference point for policy development and future approximation with EU environmental and agricultural acquis. Early voluntary alignment with comparable soil-monitoring indicators and management practices could therefore strengthen domestic soil-policy capacity and facilitate future integration with EU environmental and agricultural frameworks. In countries such as Serbia, this is particularly relevant in the context of EU-supported rural-development programming.

9. Recommendations for Research and Policy

9.1 Research

- Validate microbiome-based **pest** and **disease suppression** (competitive exclusion, induced resistance, antibiosis) under field conditions across the diverse pedoclimatic zones represented in the Action, not only in controlled trials, to establish reliable, region-specific recommendations.
- Integrate soil biological indicators (microbial diversity, enzyme activity) into digital decision support systems alongside the physical and chemical parameters currently used for variable rate technology, to move from purely nutrient-based to soil-health-based prescriptions.
- Extend AI-Satellite soil property mapping to other member countries and cross-validate against local ground-truth data, to build interoperable, harmonised digital soil databases across the Action's network.
- Quantify, through long-term trials, the reduction in **pesticide** and fertiliser inputs achievable when crop rotation, cover cropping and variable rate technology are combined, rather than assessed as separate measures.
- Establish a shared, Action-wide field trial protocol so that the **biofungicide**, precision-agriculture and crop-rotation examples reported here can be directly compared across countries, rather than only described side by side.

9.2 Policy

- Align national **crop protection** and agricultural extension policies with the monitoring and restoration targets of the EU Soil Monitoring Law, using its physical, chemical and biological indicators as a common reference framework.

- Support public investment in digital soil infrastructure (satellite-based monitoring, harmonised legacy soil databases, farm-level decision support systems), recognising this as a prerequisite – not an optional add-on – for precision, low-**pesticide crop protection** at scale.
- Use agricultural policy instruments (e.g., within the Common Agricultural Policy) to subsidize diversified crop rotation, cover cropping and reduced tillage, given their demonstrated role in breaking **pest, disease** and **weed** cycles while building soil organic matter.
- Embed soil health indicators into farm advisory and extension services, so that the preventive, systems-based approach to **crop protection** reaches practising farmers rather than remaining primarily at the research level.
- Support non-EU Action member countries in voluntarily aligning national soil monitoring with the EU Soil Monitoring Law's indicator framework ahead of formal accession requirements, using IPA and other pre-accession instruments where available.

10. Conclusions

Three conclusions emerge from this synthesis of achievements on soil health and its links to **crop protection**:

- Soil health is the foundation of sustainable low- and no-**pesticide** crop production: it directly underpins plant nutrition, water availability, biodiversity and resilience, while reducing **pesticide** need.
- Soil physical, chemical and biological properties strongly influence plant resilience and stress tolerance, both biotic (**pest** and **disease suppression** via the soil microbiome) and abiotic (drought, heat and flooding buffering via organic matter and structure).
- Designing resilient, low-**pesticide** cropping systems requires a systems-based understanding that integrates healthy soil, crop diversity, precision and digital agriculture, and climate adaptation – supported by an increasingly demanding EU regulatory framework aiming for healthy soils by 2050.

As emphasized throughout the source material for this synthesis: the soil is a national treasure; its good properties must be maintained and its unfavorable properties improved – a task for every generation.