Pesticides and Soil Health

State of the Science and Viable Alternatives

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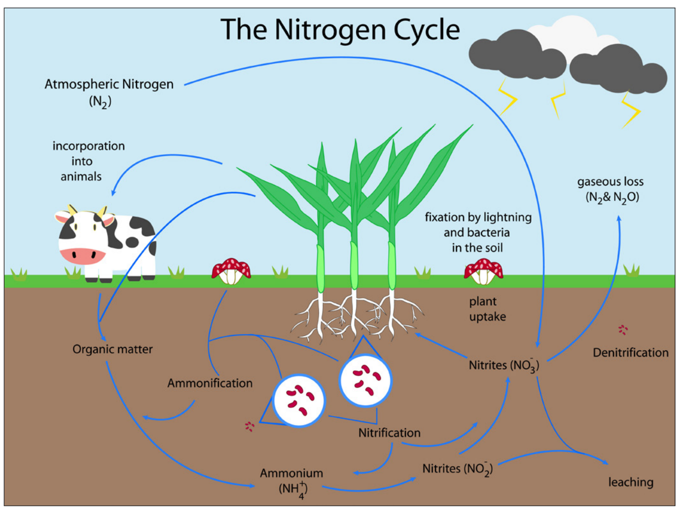
Monoculture cropping systems—unlike more complex and highly diverse cropping systems—are more susceptible to disease, pests and weeds because they are large-scale, homogeneous environments, often with unhealthy soils characterized in part by minimal levels of soil organic matter, inadequate habitat for pests' natural predators, and little natural weed control.[1] As a result, monocultural systems require large agrichemical inputs to manage pests and provide nutrients to the crops. In addition to the deleterious effects of pesticides on beneficial soil organisms, pesticides often kill or harm essential pollinators as well as naturally-occurring predators of crop pests, thus exacerbating pest problems, leading to increasing applications of pesticides.



Key processes of the Nitrogen Cycle

The elements of healthy soil

The beneficial microorganism community associated with healthy soil is extraordinarily diverse, both in terms of its species and their functions. A single teaspoon of healthy soil may contain from 100 million to 1 billion bacteria; they are just one group of soil microorganisms.[2] Agrichemical applications have many negative effects on the structure and function of the microbial community and on soil health generally.

At the center of soil health is the role of microorganisms in nutrient acquisition and cycling, suppression of phytopathogens, building resistance to biotic and/or abiotic stressors, and the foundational element of building **soil organic matter (SOM)**. SOM results from a complex interplay of beneficial soil microorganisms, larger organisms such as earthworms, and biologically active root systems. Most stabilized SOM—required for long-lasting soil health—appears to derive from **microbial processing** of root exudates and other organic residues, and are not of direct plant origin.[3]

Conventional farming practices typically are depleted in SOM and rely heavily on petroleum-based pesticides and fertilizers. A growing body of research addresses both short-term and extended impacts of pesticides on nutrient availability and soil health *per se*, as well as impacts on future food security, greenhouse gas emissions, and farmers' financial survival.

Nitrogen (N), essential to plant production and protein synthesis, must be provided to crops either from natural sources or from synthetic fertilizers applied to the soil. In nature, it is only specialized nitrogen-fixing organisms in plants and soil, that can take abundant but unusable nitrogen gas from the atmosphere and transform it into a plant-available form. Synthetic chemicals including pesticides have been shown to inhibit nitrogen-fixing rhizobia bacteria, increase dependence on synthetic fertilizers, and reduce overall plant yield.[4] Nitrogenase activity, the key enzyme involved in nitrogen fixation, has been shown to be less prevalent in soils exposed to pesticides.

Nematodes are very small (often microscopic) worm-like insects often known best as plant parasites. Most soil-inhabiting nematodes are actually beneficial, playing key roles in organic matter decomposition, nitrogen cycling and biological control. Pesticide applications have contributed to a shift to greater proportions of plant-parasitic nematodes and reductions in beneficial bacteria and fungi-feeding nematodes.[5]

Earthworms, vital for healthy soil structure and fertility, are key bioindicators of chemical contamination. Multiple studies have demonstrated that pesticides (including glyphosate and parathion) decrease reproductive success, juvenile survival, and overall development in earthworms.[6]

N-fixing nodules on plant roots

Photo: photographyfirm

As soil organic matter decreases, it becomes increasingly difficult to grow plants, because problems with fertility, water availability, compaction, erosion, parasites, diseases, and insects become more common. Ever higher levels of inputs—fertilizers, irrigation, pesticides, and machinery—are required to maintain yields in the face of soil organic matter depletion. (Sustainable Agriculture Research and Education — SARE)*

* Sustainable Agriculture Research and Education (SARE). 2020. Building Soils for Better Crops, Third Edition: Why Soil Organic Matter Is So Important. https://www.sare.org/publications/building-soils-for-better-crops/organic-matter-what-it-is-and-why-its-so-important/why-soil-organic-matter-is-so-important/

Synthetic pesticides degrade soil health and function

Fungicide use generally destabilizes soil ecosystems by reducing the abundance and diversity of soil microorganisms responsible for such key functions as nutrient cycling, soil formation, enhancing plant growth and protection of plants against pathogens. While soil organic matter can help protect the soil and water environment against contamination (by tightly binding chemicals, allowing time for detoxification by microbes)[7], that contamination can inhibit the very formation of organic matter.[8]

Applications of the common fungicide captan has been associated with decreases in populations of nitrogen-fixing bacteria and archaea (single-celled microorganisms, similar to bacteria), and increased populations of denitrifiers (microorganisms that convert plant-available N back into N_2 gas).[9] Inhibition of N-fixation requires increased applications of synthetic N in the form of fertilizers, increasing the likelihood of greater nitrous oxide (N_2O) emissions—a greenhouse gas between 265 and 298 times more potent than carbon dioxide.[10] A review of several pesticide application practices documented severe suppression of nitrification (a key step in making plant-available N) for about one month following application of the fungicides Vortex and dazomet, and inhibition of both free-living and symbiotic N-fixing bacteria—the latter even at very low levels of fungicide applications.

Fungicide applications are also linked to decreases in both the number and type of soil fungi, especially arbuscular mycorrhizal fungi (AMF), and the associated reduction in formation of macroaggregates essential to good soil structure.[11] In a laboratory study, applications of the fungicides benomyl, PCNB and captan were shown to inhibit spore germination and reduce total root length colonized by beneficial fungi, as well as decrease fungal propagule viability.[12, 13] Other studies have shown the effects of fungicides and other pesticides to include shifts in populations of bacterial and fungal genera, inhibition of several enzymes including dehydrogenases and phosphatases, and toxic effects on seed germination and root elongation.[14]

The controversial herbicide **glyphosate** is a powerful, non-selective pesticide that kills most plants. The intensive use of glyphosate is largely attributed to use on "Roundup Ready" crops (e.g., corn and soybeans), which are genetically engineered to tolerate the herbicide. Several studies in recent years have reported numerous deleterious effects of glyphosate on soil health, especially adverse effects on beneficial soil microorganisms. Glyphosate use affects populations of mycorrhizal fungi, and is correlated with reductions in viable spores for beneficial AMF reaching up to 56% in certain cases,[15] and decreases in root colonization by up to 40%.[16,] Widespread use of glyphosate has been associated with disruptions of nutrient cycling processes, reduced bioavailability of essential nutrients leading to lower content in associated crops, and greater reliance on synthetic fertilizers.[17]

Soil fumigants are a group of broad spectrum pesticides applied in large quantities directly to the soil, usually as gases (or products that quickly convert to gases) to ensure penetration throughout the soil profile. A seven day incubation with the fumigant metam-sodium showed negative, but temporary, effects on several N cycling processes. However, the fumigation led to long-term (more than 2 months) changes in bacterial diversity, community structure and a shift in predominant species.[18] Results published in the journal *Agronomy* demonstrated that sites fumigated for 15, 26, 33 and 39 years experienced lower proportions of mycorrhizal fungi, reduced microbial biomass, completely

Photo: Susan Kostic

altered community structures, and lower levels of macronutrients and soil organic carbon (SOC)—all of which contribute to impaired soil health and crop viability.[19]

Crop resilience to both biological and physical disturbance is similarly diminished by use of soil fumigants. Non-fumigated soils, with higher biodiversity and intact community structures, withstand transient heat stress and persistent chemical stress, while fumigated soils with impaired biodiversity are strongly affected.[20] In addition to negative impacts on soil biology, application of the fumigant chloropicrin is associated with 7-8-fold increases in the production of the highly potent greenhouse gas nitrous oxide (N_2O), and fumigation with MITC alone or in combination with chloropicrin shows similar results.[21, 22]

Insecticide use has been shown to lead to destabilization of the soil microbial community by triggering shifts in predominant species—increases in bacterial biomass and decreases in fungal biomass—and the different soil ecosystem functions they provide. Lower ratios of fungal to bacterial biomass have been associated with higher sensitivity to disturbance and lower rates of carbon sequestration, contributing to higher rates of crop damage and a lost opportunity for climate change mitigation.[23]

Carbamate pesticides have been shown to have a toxic effect similar to that of organochlorine pesticides on Nitrosomonas, Nitrobacter and Thiobacillus, all gram-negative bacteria which contribute to nitrification and denitrification processes critical to crop nutrient uptake and strongly associated with high productivity, soil fertility and yield.

The damage inflicted by **organophosphate** (OP) pesticides, however, is even more severe, drastically altering the relative abundance of predominant microbial species.[24] More concerning still is the presence of OP oxon breakdown forms, the presence of which increases with increased temperature. Chlorpyrifos-oxon, for example, has a toxic effect 26 times higher than its parent. This form has been associated with sharp reductions in urease activity, signalling a rapid destruction of soil microorganisms essential to key nitrogen cycling processes.[25]

Farmer Benefits of Agroecological Practices

Sales of cover crops	Reduced soil and nutrient loss to erosion
Savings on fertilizer & pesticide costs	Reduced seeding rates
Improved yield	Improved weed control
Reduced machinery costs	Improved water quality

These benefits are greatest in highly diverse cropping systems that include perennial plants that continuously feed a healthy, diverse soil biological community and provide habitat for pollinators and natural enemies of pests (American Farmland Trust, 2020).

Photo: sodawhiskey

Neonicotinoid insecticides can cause significant adverse effects on key soil organisms and persist in soils for several years. One study reported that residues of the neonicotinoid imidacloprid on leaves resulted in a significant reduction in leaf litter breakdown, negatively impacting earthworms and soil microbes. Imidacloprid has also been shown to be associated with decreased fungal abundance and significant changes in levels of nitrate-N, ammonium, nitrite-N, and nitrate reductase enzyme activity, among other repercussions.[26] Such reductions in soil nutrient content increases the need for costly additional fertilizers and mineral supplements.

Agroecological practices build healthy soil

Agroecological practices that include elimination of synthetic pesticide use and implementation of diverse cropping systems (often integrated with livestock production) stimulate soil biological activity and build and stabilize soil organic matter, critical to long-term cropping system health and productivity. Agroecological practices maintain SOM by preserving the microbial community structure and function, ultimately promoting resilience to physical stresses and immunity to biological stresses that threaten crop health.[27]

As a result, cropping systems that integrate cover crops, diversified crop rotations, organic amendments, and utilize low or no-till cultivation practices, are profitable by significantly reducing costs and—through increasing SOM content and improving soil health generally—increasing crop yields and sales. Increases in SOM also translate directly to significant carbon sequestration potential, estimated at 600–1,000 lb soil organic carbon (SOC)/acre per year in cold-temperate semi arid regions like the northern Great Plains to tropical regions in Africa.[28, 29] Farmers in California, Illinois, New York and Ohio who received federal grants for cover cropping and no-till operations have reported consistent and significant net income gains resulting from sales of cover crops, savings on fertilizer costs, positive yield benefits, reduced machinery costs, reduced soil and nutrient loss to erosion, improved water quality, improved weed control, reduced seeding rates, as well as savings from pesticide elimination.[30]

Notes

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