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Soil Management for Disease Prevention

Soils are made up of four basic components: minerals, air, water, and organic matter. In most soils, minerals represent around 45% of the total volume, water and air about 25% each, and organic matter from 2% to 5%. The mineral portion consists of three distinct particle sizes classified as sand, silt, or clay. Sand is the largest particle that can be considered soil. Sand is largely the mineral quartz, though other minerals are also present. Quartz contains no plant nutrients, and sand cannot hold nutrients—they leach out easily with rainfall. Silt particles are much smaller than sand, but like sand, silt is mostly quartz.

The smallest of all the soil particles is clay. Clays are quite different from sand or silt, and most types of clay contain appreciable amounts of plant nutrients. Clay has a large surface area resulting from the plate-like shape of the individual particles. Sandy soils are less productive than silts, while soils containing clay are the most productive and use fertilisers most effectively. Soil texture refers to the relative proportions of sand, silt, and clay. A loam soil contains these three types of soil particles in roughly equal proportions. A sandy loam is a mixture containing a larger amount of sand and a smaller amount of clay, while a clay loam contains a larger amount of clay and a smaller amount of sand.

Another soil characteristic—soil structure—is distinct from soil texture. Structure refers to the clumping together or "aggregation" of sand, silt, and clay particles into larger secondary clusters. If you grab a handful of soil, good structure is apparent when the soil crumbles easily in your hand. This is an indication that the sand, silt, and clay particles are aggregated into granules or crumbs. Both texture and structure determine pore space for air and water circulation, erosion resistance, looseness, ease of tillage, and root penetration. While texture is related to the minerals in the soil and does not change with agricultural activities, structure can be improved or destroyed readily by choice and timing of farm practices.

IMPORTANCE OF SOIL ORGANISMS

An acre of living topsoil contains approximately 900 pounds of earthworms, 2,400 pounds of fungi, 1,500 pounds of bacteria, 133 pounds of protozoa, 890 pounds of arthropods and algae, and even small mammals in some cases. Therefore, the soil can be viewed as a living community rather than an inert body.

Soil organic matter also contains dead organisms, plant matter, and other organic materials in various phases of decomposition. Humus, the dark-colored organic material in the final stages of decomposition, is relatively stable. Both organic matter and humus serve as reservoirs of plant nutrients; they also help to build soil structure and provide other benefits. The type of healthy living soil required to support humans now and far into the future will be balanced in nutrients and high in humus, with a broad diversity of soil organisms. It will produce healthy plants with minimal weed, disease, and insect pressure. To accomplish this, we need to work with the natural processes and optimise their functions to sustain our farms.

Considering the natural landscape, you might wonder how native prairies and forests function in the absence of tillage and fertilisers. These soils are tilled by soil organisms, not by machinery. They are fertilised too, but the fertility is used again and again and never leaves the site. Native soils are covered with a layer of plant litter and/or growing plants throughout the year. Beneath the surface litter, a rich complexity of soil organisms decompose plant residue and dead roots, then release their stored nutrients slowly over time. In fact, topsoil is the most biologically diverse part of the earth. Soil-dwelling organisms release bound-up minerals, converting them into plant-available forms that are then taken up by the plants growing on the site. The organisms recycle nutrients again and again with the death and decay of each new generation of plants. There are many different types of creatures that live on or in the topsoil. Each has a role to play. These organisms will work for the farmer's benefit if we simply manage for their survival. Consequently, we may refer to them as soil livestock. While a great variety of organisms contribute to soil fertility, earthworms, arthropods, and the various microorganisms merit particular attention.

Earthworms

Earthworm burrows enhance water infiltration and soil aeration. Fields that are "tilled" by earthworm tunneling can absorb water at a rate 4 to 10 times that of fields lacking worm tunnels. This reduces water runoff, recharges groundwater, and helps store more soil water for dry spells. Vertical earthworm burrows pipe air deeper into the soil, stimulating microbial nutrient cycling at those deeper levels. When earthworms are present in high numbers, the tillage provided by their burrows can replace some expensive tillage work done by machinery.

Worms eat dead plant material left on top of the soil and redistribute the organic matter and nutrients throughout the topsoil layer. Nutrient-rich organic compounds line their tunnels, which may remain in place for years if not disturbed. During droughts these tunnels allow for deep plant root penetration into subsoil regions of higher moisture content. In addition to organic matter, worms also consume soil and soil microbes. The soil clusters they expel from their digestive tracts are known as *worm casts* or *castings*. These range from the size of a mustard seed to that of a sorghum seed, depending on the size of the worm.

Table 1. Selected nutrient analyses of worm casts compared to those of the surrounding soil.

Nutrient	*Worm casts (Lbs/ac)*	*Soil (Lbs/ac)*
Carbon	171,000	78,500
Nitrogen	10,720	7,000
Phosphorus	280	40
Potassium	900	140

The soluble nutrient content of worm casts is considerably higher than that of the original soil. A good population of earthworms can process 20,000 pounds of topsoil per year—with turnover rates as high as 200 tons per acre having been reported in some exceptional cases. Earthworms also secrete a plant growth stimulant. Reported increases in plant growth following earthworm activity may be partially attributed to this substance, not just to improved soil quality. Earthworms thrive where there is no tillage. Generally, the less tillage the better, and the shallower the tillage the better. Worm numbers can be reduced by as much as 90% by deep and frequent tillage. Tillage reduces earthworm populations by drying the soil, burying the plant residue they feed on, and making the soil more likely to freeze. Tillage also destroys vertical worm burrows and can kill and cut up the worms themselves. Worms are dormant in the hot part of the summer and in the cold of winter. Table 2 shows the effect of tillage and cropping practices on earthworm numbers.

Table 2. Effect of crop management on earthworm populations.

Crop	*Management*	*Worms/foot^2*
Corn	Plow	1
Corn	No-till	2
Soybean	Plow	6
Soybean	No-till	14
Bluegrass/clover	—	39
Dairy pasture	—	33

As a rule, earthworm numbers can be increased by reducing or eliminating tillage (especially fall tillage), not using a moldboard plow, reducing residue particle size (using a straw chopper on the combine), adding animal manure, and growing green manure crops. It is beneficial to leave as much surface residue as possible year-round. Cropping systems that typically have the most earthworms are perennial cool-season grass grazed rotationally, warm-season perennial grass grazed rotationally, and annual croplands using no-till. Ridge-till and strip tillage will generally have more earthworms than clean tillage involving plowing and disking. Cool season grass rotationally grazed is highest because it provides an undisturbed environment plus abundant organic matter from the grass roots and fallen grass litter. Generally speaking, worms want their food on top, and they want to be left alone.

Earthworms prefer a near-neutral soil pH, moist soil conditions, and plenty of plant residue on the soil surface. They are sensitive to certain pesticides and some incorporated fertilisers. Carbamate insecticides, including Furadan, Sevin, and Temik, are harmful to earthworms, notes worm biologist Clive Edwards of Ohio State University. Some insecticides in the organophosphate family are mildly toxic to earthworms, while synthetic pyrethroids are harmless to them. Most herbicides have little effect on worms except for the triazines, such as Atrazine, which are moderately toxic. Also, anhydrous ammonia kills earthworms in the injection zone because it dries the soil and temporarily increases the pH there. High rates of ammonium-based fertilisers are also harmful.

Arthropods

In addition to earthworms, there are many other species of soil organisms that can be seen by the naked eye. Among them are sowbugs, millipedes, centipedes, slugs, snails, and springtails. These are the primary decomposers. Their role is to eat and shred the large particles of plant and animal residues. Some bury residue, bringing it into contact with other soil organisms that further decompose it. Some members of this group prey on smaller soil organisms. The springtails are small insects that eat mostly fungi. Their waste is rich in plant nutrients released after other fungi and bacteria decompose it. Also of interest are dung beetles, which play a valuable role in recycling manure and reducing livestock intestinal parasites and flies.

Bacteria

Bacteria are the most numerous type of soil organism: every gram of soil contains at least a million of these tiny one-celled organisms. There are many different species of bacteria, each with its own role in the soil environment. One of the major benefits bacteria provide for plants is in making nutrients available to them. Some species release nitrogen, sulfur, phosphorus, and trace elements from organic matter. Others break down soil minerals, releasing potassium, phosphorus, magnesium, calcium, and iron. Still other species make and release plant growth hormones, which stimulate root growth. Several species of bacteria transform nitrogen from a gas in the air to forms available for plant use, and from these forms back to a gas again. A few species of bacteria fix nitrogen in the roots of legumes, while others fix nitrogen independently of plant association. Bacteria are responsible for converting nitrogen from ammonium to nitrate and back again, depending on certain soil conditions. Other benefits to plants provided by various species of bacteria include increasing the solubility of nutrients, improving soil structure, fighting root diseases, and detoxifying soil.

Fungi

Fungi come in many different species, sizes, and shapes in soil. Some species appear as thread-like colonies, while others are one-celled yeasts. Slime molds and mushrooms are also fungi. Many fungi aid plants by breaking down organic matter or by releasing nutrients from soil minerals. Fungi are generally quick to colonise larger pieces of organic matter and begin the decomposition process. Some fungi produce plant hormones, while others produce antibiotics including penicillin. There are even species of fungi that trap harmful plant-parasitic nematodes. The mycorrhizae are fungi that live either on or in plant roots and act to extend the reach of root hairs into the soil. Mycorrhizae increase the uptake of water and nutrients, especially phosphorus. They are particularly important in degraded or less fertile soils. Roots colonised by mycorrhizae are less likely to be penetrated by root-feeding nematodes, since the pest cannot pierce the thick fungal network. Mycorrhizae also produce hormones and antibiotics that enhance root growth and provide disease suppression. The fungi benefit by taking nutrients and carbohydrates from the plant roots they live in.

Actinomycetes

Actinomycetes are thread-like bacteria that look like fungi. While not as numerous as bacteria, they too perform vital roles in the soil. Like the bacteria, they help decompose organic matter into humus, releasing nutrients. They also produce antibiotics to fight diseases of roots. Many of these same antibiotics are used to treat human diseases. Actinomycetes are responsible for the sweet, earthy smell noticed whenever a biologically active soil is tilled.

Algae

Many different species of algae live in the upper half-inch of the soil. Unlike most other soil organisms, algae produce their own food through photosynthesis. They appear as a greenish film on the soil surface following a saturating rain. Algae improve soil structure by producing slimy substances that glue soil together into water-stable aggregates. Some species of algae (the blue-greens) can fix their own nitrogen, some of which is later released to plant roots.

Protozoa

Protozoa are free-living microorganisms that crawl or swim in the water between soil particles. Many soil protozoa are predatory, eating other microbes. One of the most common is an amoeba that eats bacteria. By eating and digesting bacteria, protozoa speed up the cycling of nitrogen from the bacteria, making it more available to plants.

Nematodes

Nematodes are abundant in most soils, and only a few species are harmful to plants. The harmless species eat decaying plant litter, bacteria, fungi, algae, protozoa, and other nematodes. Like other soil predators, nematodes speed the rate of nutrient cycling.

SOIL QUALITY

All these organisms—from the tiny bacteria up to the large earthworms and insects—interact with one another in a multitude of ways in the soil ecosystem. Organisms not directly involved in decomposing plant wastes may feed on each other or each other's waste products or the other substances they release. Among the substances released by the various microbes are vitamins, amino acids, sugars, antibiotics, gums, and waxes.

Roots can also release into the soil various substances that stimulate soil microbes. These substances serve as food for select organisms. Some scientists and practitioners theorize that plants use this means to stimulate the specific population of microorganisms capable of releasing or otherwise producing the kind of nutrition needed by the plants.

Research on life in the soil has determined that there are ideal ratios for certain key organisms in highly productive soils. The Soil Foodweb Lab, located in Oregon, tests soils and makes fertility recommendations that are based on this understanding. Their goal is to alter the makeup of the soil microbial community so it resembles that of a highly fertile and productive soil.

Because we cannot see most of the creatures living in the soil and may not take time to observe the ones we can see, it is easy to forget about them. Table 3 for estimates of typical amounts of various organisms found in fertile soil.

Table 3. Weights of soil organisms in the top 7 inches of fertile soil.

Organism	*Pounds of liveweight/acre*
Bacteria	1000
Actinomycetes	1000
Molds	2000
Algae	100
Protozoa	200
Nematodes	50
Insects	100
Worms	1000
Plant roots	2000

ORGANIC MATTER

Understanding the role that soil organisms play is critical to sustainable soil management. Based on that understanding, focus can be directed toward strategies that build both the numbers and the diversity of soil organisms. Like cattle and other farm animals, soil livestock require proper feed. That feed comes in the form of organic matter.

Organic matter and humus are terms that describe somewhat different but related things. Organic matter refers to the fraction of the soil that is composed of both living organisms and once-living residues in various stages of decomposition. Humus is only a small portion of the organic matter. It is the end product of organic matter decomposition and is relatively stable. Further decomposition of humus occurs very slowly in both agricultural and natural settings. In natural systems, a balance is reached between the amount of humus formation and the amount of humus decay. This balance also occurs in most agricultural soils, but often at a much lower level of soil humus. Humus contributes to well-structured soil that, in turn, produces high-quality plants. It is clear that management of organic matter and humus is essential to sustaining the whole soil ecosystem.

The benefits of a topsoil rich in organic matter and humus are many. They include rapid decomposition of crop residues, granulation of soil into water-stable aggregates, decreased crusting and clodding, improved internal drainage, better water infiltration, and increased water and nutrient holding capacity. Improvements in the soil's physical structure facilitate easier tillage, increased water storage capacity, reduced erosion, better formation and harvesting of root crops, and deeper, more prolific plant root systems.

Soil organic matter can be compared to a bank account for plant nutrients. Soil containing 4% organic matter in the top seven inches has 80,000 pounds of organic matter per acre. That 80,000 pounds of organic matter will contain about 5.25% nitrogen, amounting to 4,200 pounds of nitrogen per acre. Assuming a 5% release rate during the growing season, the organic matter could supply 210 pounds of nitrogen to a crop. However, if the organic matter is allowed to degrade and lose nitrogen, purchased fertiliser will be necessary to prop up crop yields.

All the soil organisms mentioned previously, except algae, depend on organic matter as their food source. Therefore, to maintain their populations, organic matter must be renewed from plants growing on the soil, or from animal manure, compost, or other materials imported from off site. When soil livestock are fed, fertility is built up in the soil, and the soil will feed the plants.

Ultimately, building organic matter and humus levels in the soil is a matter of managing the soil's living organisms—something akin to wildlife management or animal husbandry. This entails working to maintain favorable conditions of moisture, temperature, nutrients, pH, and aeration. It also involves providing a steady food source of raw organic material.

Soil Tilth

A soil that drains well, does not crust, takes in water rapidly, and does not make clods is said to have good tilth. Tilth is the physical condition of the soil as it relates to tillage ease, seedbed quality, easy seedling emergence, and deep root penetration. Good tilth is dependent on aggregation—the process whereby individual soil particles are joined into clusters or "aggregates."

Aggregates form in soils when individual soil particles are oriented and brought together through the physical forces of wetting and drying or freezing and thawing. Weak electrical forces from calcium and magnesium hold soil particles together when the soil dries. When these aggregates become wet again, however, their stability is challenged, and they may break apart. Aggregates can also be held together by plant roots, earthworm activity, and by glue-like products produced by soil microorganisms. Earthworm-created aggregates are stable once they come out of the worm. An aggregate formed by physical forces can be bound together by fine root hairs or threads produced by fungi.

Crusting is a common problem on soils that are poorly aggregated. Crusting results chiefly from the impact of falling raindrops. Rainfall causes clay particles on the soil surface to disperse and clog the pores immediately beneath the surface. Following drying, a sealed soil surface results in which most of the pore space has been drastically reduced due to clogging from dispersed clay particles. Subsequent rainfall is much more likely to run off than to flow into the soil.

Since raindrops start crusting, any management practices that protect the soil from their impact will decrease crusting and increase water flow into the soil. Mulches and cover crops serve this purpose well, as do no-till practices, which allow the accumulation of surface residue. Also, a well-aggregated soil will resist crusting because the water-stable aggregates are less likely to break apart when a raindrop hits them.

Long-term grass production produces the best-aggregated soils. A grass sod extends a mass of fine roots throughout the topsoil, contributing to the physical processes that help form aggregates. Roots continually remove water from soil microsites, providing local wetting and drying effects that promote aggregation. Fine root hairs also bind soil aggregates together.

Roots also produce food for soil microorganisms and earthworms, which in turn generate compounds that bind soil particles into water-stable aggregates. In addition, perennial grass sods provide protection from raindrops and erosion. Thus, a perennial cover creates a combination of conditions optimal for the creation and maintenance of well-aggregated soil.

Conversely, cropping sequences that involve annual plants and extensive cultivation provide less vegetative cover and organic matter, and usually result in a rapid decline in soil aggregation.

Farming practices can be geared to conserve and promote soil aggregation. Because the binding substances are themselves susceptible to microbial degradation, organic matter needs to be replenished to maintain microbial populations and overall aggregated soil status. Practices should conserve aggregates once they are formed, by minimising factors that degrade and destroy aggregation. Some factors that destroy or degrade soil aggregates are:

- bare soil surface exposed to the impact of raindrops
- removal of organic matter through crop production and harvest without return of organic matter to the soil
- excessive tillage
- working the soil when it is too wet or too dry
- use of anhydrous ammonia, which speeds up decomposition of organic matter
- excess nitrogen fertilisation
- allowing the build-up of excess sodium from irrigation or sodium-containing fertilisers

Tillage

Several factors affect the level of organic matter that can be maintained in a soil. Among these are organic matter additions, moisture, temperature, tillage, nitrogen levels, cropping, and fertilisation. The level of organic matter present in the soil is a direct function of how much organic material is being produced or added to the soil versus the rate of decomposition. Achieving this balance entails slowing the speed of organic matter decomposition, while increasing the supply of organic materials produced on site and/or added from off site.

Moisture and temperature also profoundly affect soil organic matter levels. High rainfall and temperature promote rapid plant growth, but these conditions are also favorable to rapid organic matter decomposition and loss. Low rainfall or low temperatures slow both plant growth and organic matter decomposition. The native Midwest prairie soils originally had a high amount of organic matter from the continuous growth and decomposition of perennial grasses, combined with a moderate temperature that did not allow for rapid decomposition of organic matter. Moist and hot tropical areas may appear lush because of rapid plant growth, but soils in these areas are low in nutrients. Rapid decomposition of organic matter returns nutrients back to the soil, where they are almost immediately taken up by rapidly growing plants.

Tillage can be beneficial or harmful to a biologically active soil, depending on what type of tillage is used and when it is done. Tillage affects both erosion rates and soil organic matter decomposition rates. Tillage can reduce the organic matter level in croplands below 1%, rendering them biologically dead. Clean tillage involving moldboard plowing and disking breaks down soil aggregates and leaves the soil prone to erosion from wind and water. The moldboard plow can bury crop residue and topsoil to a depth of 14 inches.

At this depth, the oxygen level in the soil is so low that decomposition cannot proceed adequately. Surface-dwelling decomposer organisms suddenly find themselves suffocated and soon die. Crop residues that were originally on the surface but now have been turned under will putrefy in the oxygen-deprived zone. This rotting activity may give a putrid smell to the soil. Furthermore, the top few inches of the field are now often covered with subsoil having very little organic matter content and, therefore, limited ability to support productive crop growth.

The topsoil is where the biological activity happens—it's where the oxygen is. That's why a fence post rots off at the surface. In terms of organic matter, tillage is similar to opening the air vents on a wood-burning stove; adding organic matter is like adding wood to the stove. Ideally, organic matter decomposition should proceed as an efficient burn of the "wood" to release nutrients and carbohydrates to the soil organisms and create stable humus. Shallow tillage incorporates residue and speeds the decomposition of organic matter by adding oxygen that microbes need to become more active.

In cold climates with a long dormant season, light tillage of a heavy residue may be beneficial; in warmer climates it is hard enough to maintain organic matter levels without any tillage.

Tillage also reduces the rate of water entry into the soil by removal of ground cover and destruction of aggregates, resulting in compaction and crusting. Table 4 shows three different tillage methods and how they affect water entry into the soil. Notice the direct relationship between tillage type, ground cover, and water infiltration. No-till has more than three times the water infiltration of the moldboard-plowed soil. Additionally, no-till fields will have higher aggregation from the organic matter decomposition on site. The surface mulch typical of no-till fields acts as a protective skin for the soil. This soil skin reduces the impact of raindrops and buffers the soil from temperature extremes as well as reducing water evaporation.

Table 4. Tillage effects on water infiltration and ground cover.

	Water Infiltration mm/minute	*Ground Cover Percent*
No-till	2.7	48
Chisel Plow	1.3	27
Moldboard Plow	0.8	12

Both no-till and reduced-tillage systems provide benefits to the soil. The advantages of a no-till system include superior soil conservation, moisture conservation, reduced water runoff, long-term buildup of organic matter, and increased water infiltration. A soil managed without tillage relies on soil organisms to take over the job of plant residue incorporation formerly done by tillage. On the down side, no-till can foster a reliance on herbicides to control weeds and can lead to soil compaction from the traffic of heavy equipment.

Pioneering development work on chemical-free no-till farming is proceeding at several research stations and farms in the eastern U.S. Pennsylvania farmer Steve Groff has been farming no-till with minimal or no herbicides for several years. Groff grows cover crops extensively in his fields, rolling them down in the spring using a 10-foot rolling stalk chopper. This rolling chopper kills the rye or vetch cover crop and creates a nice no-till mulch into which he plants a variety of vegetable and grain crops. After several years of no-till production, his soils are mellow and easy to plant into.

Other conservation tillage systems include ridge tillage, minimum tillage, zone tillage, and reduced tillage, each possessing some of the advantages of both conventional till and no-till. These systems represent intermediate tillage systems, allowing more flexibility than either a no-till or conventional till system might. They are more beneficial to soil organisms than a conventional clean-tillage system of moldboard plowing and disking.

Adding manure and compost is a recognised means for improving soil organic matter and humus levels. In their absence, perennial grass is the only crop that can regenerate and increase soil humus. Cool-season grasses build soil organic matter faster than warm-season grasses because they are growing much longer during a given year. When the soil is warm enough for soil organisms to decompose organic matter, cool-season grass is growing. While growing, it is producing organic matter and cycling minerals from the decomposing organic matter in the soil. In other words, there is a net gain of organic matter because the cool-season grass is producing organic matter faster than it is being used up. With warm-season grasses, organic matter production during the growing season can be slowed during the long dormant season from fall through early spring. During the beginning and end of this dormant period, the soil is still biologically active, yet no grass growth is proceeding. Some net accumulation of organic matter can occur under warm-season grasses, however. In a Texas study, switchgrass grown for four years increased soil carbon content from 1.1% to 1.5% in the top 12 inches of soil. In hot and moist regions, a cropping rotation that includes several years of pasture will be most beneficial.

Effect of Nitrogen

Excessive nitrogen applications stimulate increased microbial activity, which in turn speeds organic matter decomposition. The extra nitrogen narrows the ratio of carbon to nitrogen in the soil. Native or uncultivated soils have approximately 12 parts of carbon to each part of nitrogen, or a C:N ratio of 12:1. At this ratio, populations of decay bacteria are kept at a stable level, since additional growth in their population is limited by a lack of nitrogen. When large amounts of inorganic nitrogen are added, the C:N ratio is reduced, which allows the populations of decay organisms to explode as they decompose more organic matter with the now abundant nitrogen.

While soil bacteria can efficiently use moderate applications of inorganic nitrogen accompanied by organic amendments (carbon), excess nitrogen results in decomposition of existing organic matter at a rapid rate. Eventually, soil carbon content may be reduced to a level where the bacterial populations are on a starvation diet. With little carbon available, bacterial populations shrink, and less of the free soil nitrogen is absorbed. Thereafter, applied nitrogen, rather than being cycled through microbial organisms and re-released to plants slowly over time, becomes subject to leaching. This can greatly reduce the efficiency of fertilisation and lead to environmental problems.

To minimise the fast decomposition of soil organic matter, carbon should be added with nitrogen. Typical carbon sources—such as green manures, animal manure, and compost—serve this purpose well. Amendments containing too high a carbon to nitrogen ratio (25:1 or more) can tip the balance the other way, resulting in nitrogen being tied up in an unavailable form. Soil organisms consume all the nitrogen in an effort to decompose the abundant carbon; tied up in the soil organisms, nitrogen remains unavailable for plant uptake. As soon as a soil microorganism dies and decomposes, its nitrogen is consumed by another soil organism, until the balance between carbon and nitrogen is achieved again.

Conventional Fertilisers

Commercial fertiliser can be a valuable resource to farmers in transition to a more sustainable system and can help meet nutrient needs during times of high crop nutrient demand or when weather conditions result in slow nutrient release from organic resources. Commercial fertilisers have the advantage of supplying plants with immediately available forms of nutrients. They are often less expensive and less bulky to apply than many natural fertilisers.

Not all conventional fertilisers are alike. Many appear harmless to soil livestock, but some are not. Anhydrous ammonia contains approximately 82% nitrogen and is applied subsurface as a gas. Anhydrous speeds the decomposition of organic matter in the soil, leaving the soil more compact as a result. The addition of anhydrous causes increased acidity in the soil, requiring 148 pounds of lime to neutralise 100 pounds of anhydrous ammonia, or 1.8 pounds of lime for every pound of nitrogen contained in the anhydrous. Anhydrous ammonia initially kills many soil microorganisms in the application zone. Bacteria and actinomycetes recover within one to two weeks to levels higher than those prior to treatment. Soil fungi, however, may take seven weeks to recover. During the recovery time, bacteria are stimulated to grow more, and decompose more organic matter, by the high soil nitrogen content. As a result, their numbers increase after anhydrous applications, then decline as available soil organic matter is depleted. Farmers commonly report that the long-term use of synthetic fertilisers, especially anhydrous ammonia, leads to soil compaction and poor tilth. When bacterial populations and soil organic matter decrease, aggregation declines, because existing glues that stick soil particles together are degraded, and no other glues are being produced.

Potassium chloride (KCl) (0-0-60 and 0-0-50), also known as muriate of potash, contains approximately 50 to 60% potassium and 47.5% chloride. Muriate of potash is made by refining potassium chloride ore, which is a mixture of potassium and sodium salts and clay from the brines of dying lakes and seas. The potential harmful effects from KCl can be surmised from the salt concentration of the material. Table 5 shows that, pound for pound, KCl is surpassed only by table salt on the salt index. Additionally, some plants such as tobacco, potatoes, peaches, and some legumes are especially sensitive to chloride. High rates of KCl must be avoided on such crops. Potassium sulfate, potassium nitrate, sul-po-mag, or organic sources of potassium may be considered as alternatives to KCl for fertilisation.

Sodium nitrate, also known as Chilean nitrate or nitrate of soda, is another high-salt fertiliser. Because of the relatively low nitrogen content of sodium nitrate, a high amount of sodium is added to the soil when normal applications of nitrogen are made with this material. The concern is that excessive sodium acts as a dispersant of soil particles, degrading aggregation. The salt index for KCl and sodium nitrate can be seen in Table 5.

Table 5. Salt index for various fertilisers.

Material	*Salt Index*	*Salt index per unit of plant food*
Sodium chloride	153	2.90
Potassium chloride	116	1.90
Ammonium nitrate	105	3.00
Sodium nitrate	100	6.10
Urea	75	1.60
Potassium nitrate	74	1.60
Ammonium sulfate	69	3.30
Calcium nitrate	53	4.40
Anhydrous ammonia	47	0.06
Sulfate-potash-magnesia	43	2.00
Di-ammonium phosphate	34	1.60
Monammonium phosphate	30	2.50
Gypsum	8	0.03
Calcium carbonate	5	0.01

Topsoil

Topsoil is the capital reserve of every farm. Ever since mankind started agriculture, erosion of topsoil has been the single largest threat to a soil's productivity—and, consequently, to farm profitability. This is still true today. In the U.S., the average acre of cropland is eroding at a rate of 7 tons per year. To sustain agriculture means to sustain soil resources, because that's the source of a farmer's livelihood. The major productivity costs to the farm associated with soil erosion come from the replacement of lost nutrients and reduced water holding ability, accounting for 50 to 75% of productivity loss. Soil that is removed by erosion typically contains about three times more nutrients than the soil left behind and is 1.5 to 5 times richer in organic matter. This organic matter loss not only results in reduced water holding capacity and degraded soil aggregation, but also loss of plant nutrients, which must then be replaced with nutrient amendments.Five tons of topsoil (the so-called tolerance level) can easily contain 100 pounds of nitrogen, 60 pounds of phosphate, 45 pounds of potash, 2 pounds of calcium, 10 pounds of magnesium, and 8 pounds of sulfur.

Water erosion gets started when falling rainwater collides with bare ground and detaches soil particles from the parent soil body. After enough water builds up on the soil surface, following detachment, overland water flow transports suspended soil downslope. Suspended soil in the runoff water abrades and detaches additional soil particles as the water travels overland. Preventing detachment is the most effective point of erosion control because it keeps the soil in place. Other erosion control practices seek to slow soil particle transport and cause soil to be deposited before it reaches streams. These methods are less effective at protecting the quality of soil within the field.

Commonly implemented practices to slow soil transport include terraces and diversions. Terraces, diversions, and many other erosion "control" practices are largely unnecessary if the ground stays covered year-round. For erosion prevention, a high percentage of ground cover is a good indicator of success, while bare ground is an "early warning" indicator for a high risk of erosion. Muddy runoff water and gullies are "too-late" indicators. The soil has already eroded by the time it shows up as muddy water, and it's too late to save soil already suspended in the water. Protecting the soil from erosion is *the* first step toward a sustainable agriculture. Since water erosion is initiated by raindrop impact on bare soil, any management practice that protects the soil from raindrop impact will decrease erosion and increase water entry into the soil. Mulches, cover crops, and crop residues serve this purpose well.

Additionally, well-aggregated soils resist crusting because water-stable aggregates are less likely to break apart when the raindrop hits them. Adequate organic matter with high soil biological activity leads to high soil aggregation.

Many studies have shown that cropping systems that maintain a soil-protecting plant canopy or residue cover have the least soil erosion. This is universally true. Long-term cropping studies begun in 1888 at the University of Missouri provide dramatic evidence of this. Gantser and colleagues examined the effects of a century of cropping on soil erosion. They compared depth of topsoil remaining after 100 years of cropping. As the table shows, the cropping system that maintained the highest amount of permanent ground cover had the greatest amount of topsoil left.

Table 6. Topsoil depth remaining after 100 years of different cropping practices.

Crop Sequence	*Inches of topsoil remaining*
Continuous Corn	*7.7*
6-year rotation	12.2
Continuous timothy grass	17.4

The researchers commented that subsoil had been mixed with topsoil in the continuous corn plots from plowing, making the real topsoil depth less than was apparent. In reality, all the topsoil was lost from the continuous corn plots in only 100 years. The rotation lost about half the topsoil over 100 years. How can we feed future generations with this type of farming practice? Some soils naturally have very thick topsoil, while other soils have thin topsoil over rock or gravel. Roughly 8 tons/acre/year of soil-erosion loss amounts to the thickness of a dime spread over an acre. Twenty dimes stack up to 1-inch high. So a landscape with an 8-ton erosion rate would lose an inch of topsoil about every 20 years. On a soil with a thick topsoil, this amount is barely detectable within a person's lifetime and may not be noticed. Soils with naturally thin topsoils or topsoils that have been previously eroded can be transformed from productive to degraded land within a generation.

Tillage for the production of annual crops is the major problem in agriculture, causing soil erosion and the loss of soil quality. Any agricultural practice that creates and maintains bare ground is inherently less sustainable than practices that keep the ground covered throughout the year. Wes Jackson has spent much of his career developing perennial grain crops and cropping systems that mimic the natural prairie. Perennial grain crops do not require tillage to establish year after year, and the ground is left covered. Ultimately, this is the future of grain production and truly represents a new vision for how we produce food.

INTEGRATED SOIL MANAGEMENT

Food security is the most important factor that determines the survival of human kind. Without food security, a nation cannot expect better life for its people. Famines in India are "a nightmare of the past". The green revolution witnessed in late 1960s has contributed immensely over the years to cereal production in India and hence a substantial increase in the net per capita availability of food grains was registered (Table 7). This has led to a nationwide sense of complacency that, in a way, slowed down the growth rate in agricultural production during 1990s, while the population continued to grow at a high rate. The net result was a decline in the per capita food grain availability in the terminal decade of 20th Century. Even with present level of production, there is enough food in the country to meet energy and protein requirements of the current population, if the food were distributed equitably according to needs. But as we see, surplus production and widespread hunger coexist at the national level. At present, India alone accounts for one fourth of all world hunger. It is particularly ironic that there are 200 million food-insecure people in a country that currently bas buffer stocks of food grains in excess of 60 million metric tonnes.

Table 7. Per capita net availability of food grains in India (g/day)

Year	*Cereals*	*Pulses*	*Total food grains*
1951	334.2	60.7	394.9
1961	399.7	69.0	468.7
1971	417.6	51.2	468.8
1981	417.3	37.5	454.8
1991	468.5	41.6	510.1
2001	385.1	29.1	414.1

Inadequate or lack of purchasing power among the poor is the main cause of food insecurity in rural India. As reported by Rajendra Prasad, the per capita consumption of most food items in rural India is far below the recommended dietary allowances. Though the per capita intake of cereals in all regions, and sugar and milk consumption in North and Western regions is closer to or above the standard requirements, the consumption of all other food items throughout the country is woefully lower than their respective dietary requirements as per ICMR (Indian Council of Medical Research) norms.

A general low intake of pulses, vegetables, fruits, fats and oils, eggs, meat and fish is responsible for widespread occurrence of protein energy malnutrition (PEM) and chronic energy deficiency (CED). It was reported that 23 to 70 percent of the rural population in different parts of the country is suffering from protein energy malnutrition, while the chronic energy deficiency affected 17 to 54 percent of people (Table 8). Prevalence of poverty and low and fluctuating income levels also limit the access to diversified diet and thus adversely affect balanced diet. The vegetable products account for a lion share in the intake of all dietary constituents. A comparison of share of vegetable products and animal products in meeting total dietary energy, protein and fat in India, USA and the World as a whole makes this point clear. In India, vegetable products provide 93 percent dietary energy, 84 percent protein and 73 percent fat, while animal products supply the remaining small portion, i.e., 7 percent, 16 percent and 27 percent of energy, protein and fat, respectively. On the contrary, in a developed country like USA, the animal products account for 30 percent, 64 percent and 511 percent share in meeting dietary energy, protein and fat supply, respectively. Child malnutrition rates in India are still very high. According to the UNDP, 53 percent of children under five in India were under-weight during the period 1990-97, the highest rate from any of the 174 developing countries listed.

Table 8. Extent of PEM and CED in rural India

Region	*Percent of population with*	
	Protein energy malnutrition (PEM)	*Chronic energy deficiency (CED)*
Northern	34.9-36.9	23.0-44.0
Eastern and Central	23.5-58.2	17.1-57.3
Western	30.2-39.8	36.2-53.1
South	31.4-70.3	33.2-53.8

In India, unabated growth in population has been and will continue to be the single most factors that have the potential to negate all the progress made in agricultural production. India's population grew at an annual growth rate of around 2 percent in 1970s, 1980s and 1990s to reach 1 027 million in 2001 and is estimated to increase further to 1 262 and 1 542 million by the year 2011 and 2021, respectively. Growing population means mounting more pressure on natural resources to meet increased food demand. According to a conservative estimate, the food grain demand in India for the years 2010 and 2020 is projected to be 246 and 294 mt, respectively (Table 9). This means that India's food grain production has to increase from 212 mt to 246 mt in 2010 and then to 294 mt in 2020. It is by all means a daunting task and the ability to accomplish this task determines the future food security of the country.

Table 9. Current production and future demands of food grains in India

Food item	*Current (2001-02) production (mt)*	*Estimated demand (mt)*	
		2010	*2020*
Rice	93.1	3.6	122.1
Wheat	71.8	85.8	102.8
Total cereals	198.8	224.4	265.8
Pulses	13.2	21.4	27.8
Total food grains	212.0	245.8	293.6

With continued rise in population, the arable land to man ratio has decreased from 0.5 ha to 0.14 ha at present and is expected to decline further to 0.08 ha by year 2020. The average number of land holdings has also increased simultaneously from 77 million to over 115 million at present due to population growth and the law of inheritance of land property. The average size of operational farm holding is only 1.57 ha. Further, about 78 percent of the 115 million farm holders in the country come under small and marginal category with the size of farm being less than 2 ha. The small size and scattered nature of the holdings will adversely affect the farm efficiency and will result in high cost of production. This in turn will result in low productivity and thus reduced agricultural sustainability and food security.

The total factor productivity (TFP) is used as an important measure to evaluate the performance of a production system and sustainability of its growth pattern. As stated earlier, adoption of green revolution technology led to a phenomenal growth in agricultural production during 1970s and 1980s. But of late, there are signs of fatigue in the agricultural growth process. In spite of continued growth of inputs, there has been no matching growth in agricultural production during 1990s, indicating a decrease in TEP. The declining trends of annual growth rate of productivity in respect of all major crops (Table 10) are also suggestive of decreasing TFP in Indian agriculture.

Table 10. Productivity growth rate of important crops in India

Crop	*Annual growth rate in productivity (%)*		
	1980-81 to 1989-90	*1990-91 to1999-2000*	*2000-01 to2002-03*
Rice	3.19	1.27	-0.72
Wheat	3.10	2.11	0.73
Pulses	1.61	0.96	-1.84
Total food grains	2.74	1.52	-0.69
Oilseeds	2.43	1.25	-3.83
Non-food grains	2.31	1.04	-1.02
All principal crops	2.56	1.31	-0.87

In fact, all the crops except wheat registered a negative annual growth rate in their productivity during the recent past. If this alarming trend is allowed to continue, it will spell doom on the country's future food security prospects. Reasons for decreasing the total factor productivity are:

(1) High nutrient turn over in soil-plant system coupled with low and imbalanced fertiliser use,

(2) Emerging deficiencies of micro and secondary nutrients (S, Zn, B, Fe, Mn, etc.),

(3) Soil degradation due to acidification, aluminum toxicity, soil salinisation and alkalisation, soil erosion,

(4) Wide nutrient gap between nutrient demand and supply, and

(5) Consequent deterioration in soil physical, biological and chemical quality and low fertiliser use efficiency.

The growth in fertiliser consumption slowed down during 1990's and there is stagnation in consumption during the last 4-5 years. After achieving a record consumption level of 18.1 mt of NPK in 1999-2000, the total NPK consumption is hovering around 16-17 mt during the last 3 years. At the present level of crop production, there exists a negative balance of 10 mt between nutrient (NPK) demand by crops and supply of nutrient through application of fertiliser annually.

The stagnant situation in fertiliser consumption and higher negative nutrient balance are posing a threat to soil quality and sustainable agriculture. It is now imperative to review the reasons for the stagnant trend in fertiliser consumption and take remedial action to alter this trend. The stagnant trend in fertiliser consumption despite slow increase in maximum retail price of fertilisers reveals that besides pricing, there are various other reasons which affect the fertiliser consumption. Weather cannot be solely blamed for the stagnant situation as the performance of southwest monsoon had been normal in the last few years. The total NPK consumption did not exceed 17 mt during the year-2003-04, in spite of having good southwest monsoon rainfall. Deteriorating soil quality and the emerging deficiencies in secondary and micronutrients aside from major nutrients appear to be one of the major factors in the stagnation of fertiliser consumption. A cereal production of 5-10 t/ha/year in rice-wheat rotation, which is the backbone of India's food security removes 380-760 kg N-P_2O_5-K_2O per hectare per year. Farmers generally apply 50 percent to 80 percent of this amount. Thus there is a gradual depletion of the inherent soil fertility.

Soil Nutrient Balances

There are hardly any farm-level exercises which have been or are being conducted to monitor nutrient balances in intensively cropped areas. It is generally accepted that soils are being mined and that their nutrient capitals being continuously depleted throughout intensively cultivated areas. No quantitative or semi-quantitative estimates, however, are available on nutrient recycling or balances based on various input-output components at the farm level. This is an area where some insights from a few well-defined benchmark farms (not research stations) will be extremely valuable in developing sustainable systems, not only for site-specific adoption, but also for adoption to similar environments.

The fate of soil nutrient capital and balance in the two most important cropping systems of Uttar Pradesh is illustrated below (Table 11). These computations are primarily illustrative and based on several assumptions, due to the present inadequate database. The initial soil nutrient capital is taken to reflect the soil's low status in nitrogen, medium in phosphorus, and high in potassium for the plow layer. Fertiliser inputs for the sugarcane-wheat system are typical of the practice.

Table 11. Nutrient balance after a sugarcane-wheat system in western Uttar Pradesh (productivity 120 mt cane/ha/2 crops + 3 tonnes wheat grain/ha)

Item	*N*	P_2O_5	K_2O
Initial available soil nutrient capital (kilograms per hectare)	280	40	336
For sugarcane plant crop			
Fertiliser input (kg/ha)125	58	10	
10 t/ha FYM (0.75-0.175-0.55) of N-P_2O_5-K_2O	75	18	55
1 t/ha press mud (0.026-1.70-0.24% available N-P_2O_5-K_2O)	1	17	2
Green manure (not practiced)	0	0	0
Crop residues (not recycled)	0	0	0
Total nutrient capital	481	133	403
Nutrient uptake by 60 t/ha sugarcane crop (kg/ha)	135	30	144
Losses from soil (25% of fertiliser N)	31	0	0
Nutrient balance after cane harvest (kg/ha)	315	103	215
For sugarcane ratoon crop			
Starting soil nutrient capital	315	103	215
Fertiliser input (kg/ha)	62	29	5
3 t/ha cane residues recycled (0.4-0.18-1.28)	12	5	38
FYM not used	0	0	0
Total nutrient capital	389	137	258
Nutrient uptake by 60 t/ha ratoon crop (kg/ha)	135	30	188
Losses from soil (25% of fertiliser N)	16	0	0
Nutrient balance after ratoon	238	107	70
For wheat crop			
Starting soil nutrient capital (kg/ha)	238	107	70
Fertiliser input	100	50	10
FYM not used	0	0	0
Crop residues burnt	0	0	38
Total nutrient capital	338	157	118
Nutrient uptake by 4 t/ha wheat crop (kg/ha)	96	36	132
Losses from soil (25% of fertiliser N)	25	0	0

Nutrient balance after wheat (kg/ha)	217	121	-14
Change in initial soil capital	-63	81	-350
Percentage change	-23	102	-104
Initial soil nutrient capital	280	40	336
Capital after sugarcane plant crop	315	103	215
Capital after sugarcane ratoon			
Capital after wheat	217	121	-14
Capital after the system	217	121	-14
Change after 2 years (one crop cycle) in percent	-63(-23%)	81(102%)	-350 (-104%)

The analysis shows that after one cycle of the sugarcane-wheat system, the initial soil nutrient capital decreased by 23 percent in the case of N, increased by 1.2 percent in the case of P but decreased by 104 percent in the case of K. The improvement in P status was attributed to its application to both the main crops and input of FYM and press mud, that less was removed from the crop than was added and the ability of P (unlike N) to accumulate in the soil. The large depletion in K was due to its very weak position in the fertiliser use pattern and crop removal exceeding the K input.

The apparent K balance of long-term fertiliser experiment under maize-wheat-cowpea during 27 years of cropping showed that mining of soil K occurred even under NPK and NPK + FYM treatments, i.e. application of 15 t FYM/ha along with recommended rates of NPK. This shows that the selection of suitable components of INM should vary with cropping systems and nutrient requirement. Integration of crop residues, along with farmyard manure and fertilisers, may arrest the mining of K from soils where the production systems have higher K demand.

High Nutrient Turnover in Soil-plant System

Fertiliser consumption in India is grossly imbalanced since the beginning. It is tilted more towards N followed by P. Further the decontrol of the phosphatic and potassic fertilisers resulted in more than doubling the prices of phosphatic and potassic fertilisers. Thus, the already unbalanced consumption ratio of 6:2.4:1 ($N:P_2O_5:K_2O$) in 1990-91 has widened to 7:2.7:1 in 2000-01 as against favourable ratio of 4:2:1 implying there from that farmers started adding more nitrogen and proportionately less phosphatic and potassic fertilisers. Even today, the situation is grim as far as fertiliser application by farmers is concerned. In many areas the imbalanced fertilisation is the root cause of poor crop yields and poor soil fertility status.

Accordingly, agro-ecological regions 4, 9 14, 15 and 18 and cropping systems like rice-wheat, maize-wheat, rice-pulse, potato-wheat and sugarcane demands immediate attention to correct the imbalances in nutrient consumptions to prevent further deterioration of soil quality and to break the yield barriers. There is wide variation in the consumption ratios of fertilisers from region to region but in the absence of information on the extent of cultivated area and details of cropping patterns in each agro-ecological region, it is difficult to estimate the crop removal of each region.

Deficiencies of Secondary and Micronutrient in Soils

Intensive cropping systems are heavy feeders and are bound to heavily extract nutrients from the soil. Hence, nutrient deficiencies are inevitable unless steps are taken to restore fertility levels. Deficiencies of essential elements in Indian soils and crops started emerging during the 1950s after the initiation of the government of Independent India, a five-year plan to give a fillip to food production through intensification. As food production increased with time, the number of elements becoming deficient in soils and crops also increased.

Unless corrective measures are taken immediately, the list of essential elements becoming deficient is bound to increase further. A classical example of the effect of imbalanced fertiliser use is the fertility decline in an intensive cropping for over 25 years that has been reported by Swarup and Ganeshamurthy. When only N was applied the P and K status in soils at all the centers have gone down. When N & P were applied the soil K status declined more conspicuously in alluvial soils (Ludhiana), Terai soils (Pantnagar) and laterite soils (Bhubaneshwar). All secondary and micronutrients generally declined in all the soils.

Although not universal, deficiency of S has cropped up as serious obstacle in the sustainability of yields in cropping systems particularly if a sulphur responsive crop like rice, oil seed or pulse crop is involved. The extent of S problems depends more on input of S through irrigation and atmosphere, the information from which is completely lacking. The results of long-term experiments (Table 12) show that response was very little in certain crops like wheat and jute and very conspicuous in certain other crops like rice and soybean.

Micronutrient deficiencies in soils are also emerging as yield limiting factors. Analysis of 1.5 lakh soil samples from different regions of the country indicated that about 47 percent of soils were deficient in available Zn, 20 percent of samples were deficient in available B, 18 percent of samples were deficient in Mo, 12 percent of samples were deficient in available Fe and 5 percent of soil samples were found deficient in available Cu. Among the micronutrients, zinc deficiency is widely encountered followed by B, Mo and Fe, in that order.

Table 12. Mean grain yield response (kg/ha) of rice and wheat at Pantnagar

Nutrient or FYM	*Mean response over 5 years (1987-92)*		*Mean response over 20 years (1972-92)*	
	Rice	*Wheat*	*Rice*	*Wheat*
N	1 864	2 372	1 512	2 140
P	124	213	-16	47
K	211	109	430	71
S	183	184	261	150
Zn	520	543	285	307
FYM	587	645	745	623

Field scale deficiency of Zn in crops is being increasingly reported. But suggestions that B and Mo as yield limiting factors are not convincing as trials that include these elements rarely generate conclusive evidence to support this hypothesis. Field scale Mo deficiencies and Mn as a factor of yield decline is not common. However, exception to this is in the rice-wheat system on sandy soils and reclaimed sodic soil. Continuous cropping of rice-wheat on these soils led to deficiency of Mn in wheat crop following leaching of reduced Mn from surface soils under rice culture. The productivity of wheat could be restored by soil and foliar applications of Mn.

SOIL DEGRADATION

It has been stated that of the total 328.73 m ha geographical area, nearly 188 m ha of land in the country is potentially exposed to various degradation processes. The land area subjected to degradation by way of soil displacement through erosion by water and wind is estimated at 148.9 and 13.5 m ha, respectively (nearly half of the area). About 13.8 m ha is under chemical deterioration due to loss of nutrients and organic matter, salinisation and sodification. Soil acidification also rendered about 49 m ha of land degraded.

Adequate plant nutrient supply holds the key to improving the food grain production and sustaining livelihood. Nutrient management practices have been developed, but in most of the cases farmers are not applying fertilisers at recommended rates. They feel fertilisers are very costly and not affordable and due there is a risk particularly under dry land conditions. Therefore, INM plays an important role which involves integrated use of organic manures, crop residues, green manures, biofertilisers etc. with inorganic fertilisers to supplement part of plant nutrients required by various cropping systems and thereby fulfilling the nutrient gap.