CHAPTER 5

Soil Ecology

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The community of organisms that lives in soil plays many important roles in the successful functioning of agricultural ecosystems. This community consists of bacteria, fungi, protozoa, nematodes (predators of microorganisms and pathogens of plants), earthworms, arthropods, and other organisms. Although certain species are harmful to crops, most are beneficial and even essential for the well-being of plants. There are striking similarities between the roles of microorganisms in the human body and in the soil. In spite of the substantial attention paid to soilborne pests, the beneficial species far outnumber harmful ones in the soil.

The importance of soil organisms is often ignored and may be masked and diminished in tilled farming systems that rely on synthetic fertilizers, high levels of pesticides, and minimal inputs of carbon. Farming systems that include organic amendments as nutrient sources, on the other hand, are particularly dependent on biological activity to decompose the amendments. Consequently, growers, advisers, and researchers interested in cover crops may benefit by becoming more aware of the belowground community. This chapter describes how cover crops affect soil organisms and provides an overview of other management practices that favor beneficial soil organisms.

Overview of Soil Organisms

Microorganisms

Although invisible to the naked eye, soil microorganisms are an important part of the belowground community in farm soils, and they are a potentially valuable asset to the grower. Their value lies in the roles they play in the decomposition of organic matter, improvement of soil structure, cycling of nutrients, and as a living reservoir of nutrients. The microbial community is most beneficial to the grower when it is diverse, abundant, and active. Microbial populations play active and passive roles in soil fertility.

Microorganisms as agents of change. The major groups of soil microorganisms are bacteria (including actinomycetes), fungi, and protozoa (fig. 5-1). Because these microorganisms are best characterized by the roles they play rather than by their individual species, they are often categorized in functional groups. One important example is the bacteria and fungi that are responsible for the conversion of organic compounds to their mineral components, a process called mineralization. The mineralizers include microbes that split complex and large plant molecules (e.g., cellulose, hemicellulose, lignin) into smaller molecules, as well as microbes that convert the smaller molecules (e.g., sugars, amino acids, aromatics, aliphatics) into simpler mineral forms (e.g., ammonium- and nitrate-nitrogen, carbon dioxide, water, sulfate).

Many other agriculturally important functions are carried out by soil microorganisms (table 5-1). Excellent overviews of soil organisms and their functions are provided in Killham (1994) and Paul and Clark (1989). Important groups include the nitrifying bacteria (*Nitrosolobus, Nitrobacter*, *Nitrosomonas*) that are involved in the conversion of ammonium to nitrate. This conversion makes the nitrogen not only more available for some plants but also directly susceptible to leaching and denitrification. Another group of organisms is most active under poorly aerated conditions, such as when soils are flooded or poorly drained or when the demand for oxygen is greater than what can be supplied by diffusion through air-filled pores. Denitrifying bacteria convert nitrate to forms of nitrogen that are lost to the atmosphere as nitrogen gas or nitrous oxide. Fermenters such as yeasts and certain bacteria decompose organic materials under anaerobic conditions, often forming foul-smelling substances. There are groups of bacteria that oxidize (often when oxygen is present) or reduce (usually when oxygen is not present) many elements that are plant nutrients. These microbial reactions can result in, depending on the element, the conversion of iron, sulfur, manganese, and some trace elements into forms that are more or less available to crops. Other groups of organisms, such as mycorrhizal fungi, make phosphorus more accessible to plants, either by dissolving complex phosphorus-bearing substances or by effectively expanding the surface area of plant roots.

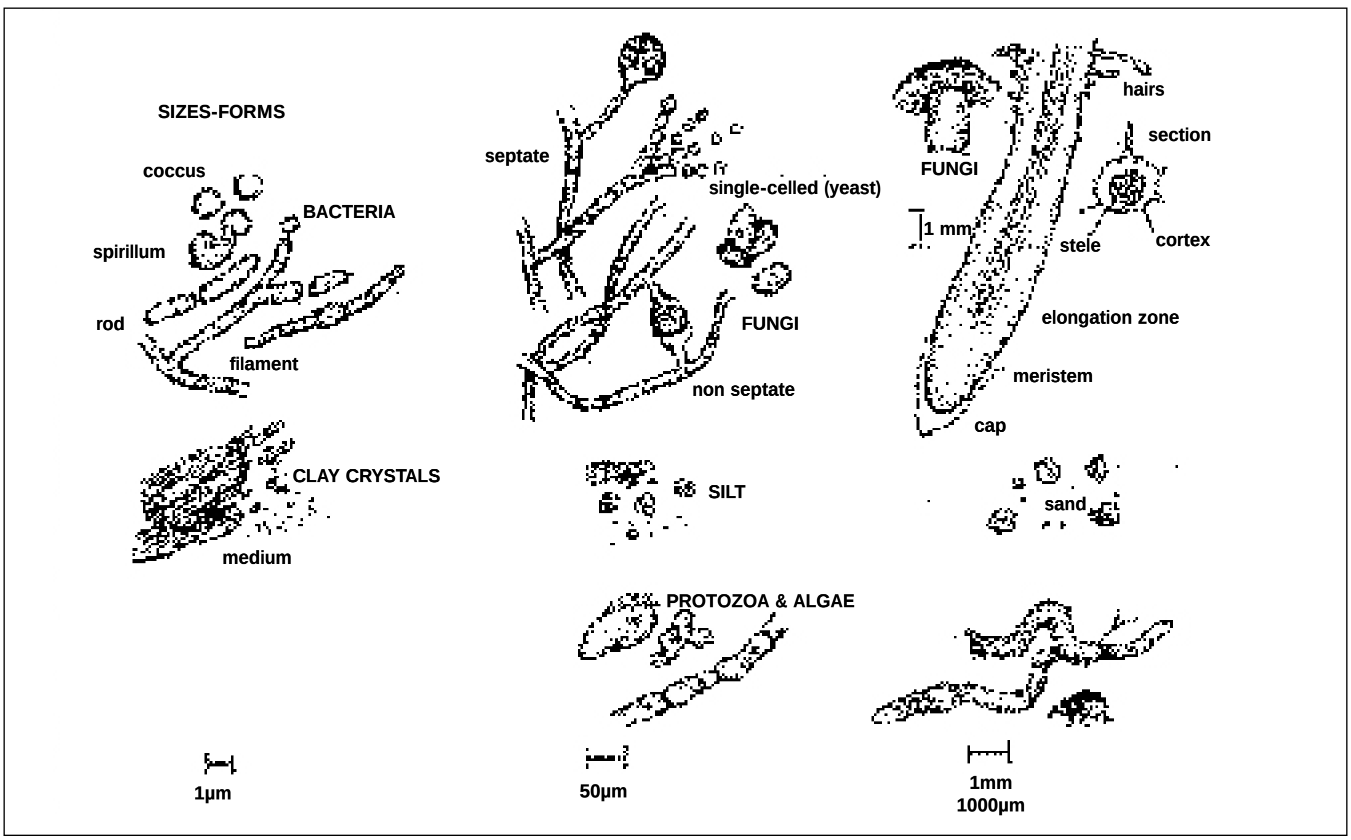

Figure 5-1. Sizes and forms of soil biota in relation to particle sizes. ***Source*****: Singer and Munns 1991, p. 145.**

Table 5-1. Beneficial activities of microorganisms in soil

Function	Type of Organism
Decomposition of plant residues	Decomposers (bacteria, fungi, micro- and macrofauna).
Control of nitrogen availability to plants	
Conversion of organic to mineral forms	Mineralizers (most microorganisms)
Conversion of ammonium to nitrate	Nitrifying bacteria
Denitrification of nitrate to nitrogen gas	Denitrifying bacteria (facultative and obligate anaerobes)
Conversion of atmospheric nitrogen gas to organic nitrogen	Nitrogen-fixing bacteria (symbiotic and free-living)
Increase availability of phosphorus, iron, sulfur, and other elements	Many organisms, mycorrhizal fungi
Formation of soil humus	Fungi
Soil aggregate formation and stability	Polysaccharide-producing fungi and bacteria
Production of plant growth-promoting substances	Primarily bacteria
Suppression of plant pathogens	General microbial community, producers of toxins, producers of iron chelators
Breakdown of pesticides and other toxic chemicals	Biodegrading bacteria and fungi

Nitrogen-fixing bacteria, such as symbionts in the genus *Rhizobium* and the free-living *Azotobacter* and *Azospirillum*, convert elemental nitrogen gas (N_2) in the atmosphere to ammonia (NH_3) that can be readily used by crops. Rhizobia living in symbiosis with legumes provide nitrogen for growth of these crops, reducing or eliminating the need for nitrogen fertilizer. If the cover crop is incorporated into soil as a green manure, a large portion of the nitrogen fixed by the symbiotic relationship can fertilize the subsequent crops. Because of the large amount of energy required for nitrogen fixation, the amount of nitrogen fixed by free-living bacteria is vastly lower than that fixed by symbiotic bacteria. This is because free-living organisms must compete with many other soil microorganisms for the organic compounds that provide energy, whereas the symbiotic organisms obtain the compounds directly from the plant.

Other functions of soil microorganisms affect soil physical properties. Their transformation of plant material into the more stable forms of organic compounds that make up the humus is important to the maintenance of the organic fraction of soil. Many organisms promote soil aggregate formation and stability through production of extracellular polysaccharides (e.g., bacteria and fungi) and physical binding of organic matter and clay with hyphae (e.g., fungi and actinomycetes). Another important function is the ability of certain microorganisms to decompose organic pesticides into harmless products. If microorganisms did not degrade these substances, pesticide concentrations would eventually build up to hazardous levels in agricultural soils.

One group of microorganisms deserving special attention because of their importance in vineyards is the mycorrhizal fungi. Mycorrhizal fungi form beneficial symbiotic relationships with plant roots. The association of fungus and root is called a mycorrhiza, which literally means "fungus root." Mycorrhizae are found on almost every type of plant; one exception is brassicas such as mustards and radishes (Bethlenfalvey and Lindermann 1992). The particular type of mycorrhiza formed on grapes and nonbrassica cover crops is called a vesicular-arbuscular mycorrhiza (VAM) (Lindermann 1988). VAM fungi enter the plant root cells and grow hyphae that extend out into the surrounding soil. Hyphae are long, thin strands that form the main body of fungi. The VAM hyphae effectively increase the surface area of the plant root system and help the plant to mine nutrients from areas that the plant roots cannot reach or to obtain nutrients that diffuse very slowly through the soil solution (e.g., phosphorus). In exchange, VAM fungi receive carbohydrates that the plant has produced through photosynthesis. The plant benefits from improved nutrient uptake and because roots colonized by VAM are often more resistant to attack by fungal pathogens and parasitic nematodes (Perrin 1990; Hussey and Roncadori 1982). Separate plant individuals and species may actually be connected below ground by a bridge of VAM hyphae, with phosphorus being transferred from one plant to another through this underground network (Chiariello, Hickman, and Mooney 1982).

Microorganisms as a pool of nutrients. Nutrient cycling and energy flow in soil ecosystems is tied to the decomposition of organic matter. Soil organic matter consists of broad groups of substances, often called pools, that vary in their rates of decomposition and functions. At one extreme, organic matter includes readily decomposable materials that have not yet been transformed or still closely resemble their plant and animal origins. At the other extreme, organic matter consists of humic substances that are virtually resistant to further decomposition. One of the most important pools of organic matter is the microbial biomass (the mass of microorganisms). The microbial biomass is a relatively available reservoir of plant nutrients such as nitrogen and phosphorus (Marumoto, Anderson, and Domsch 1982). Although the size of the microbial biomass is relatively small (e.g., its nitrogen content constitutes only 1 to 5 percent of the total organic nitrogen in soil), the nutrients within this pool are recycled rapidly within the soil profile, perhaps 8 to 10 times per year (Coleman, Reid, and Cole 1983). The amount of nitrogen in microbial biomass in agricultural soils ranges from 36 to 344 pounds per acre (40 to 385 kg/ha) (Paul and Voroney 1984).

Earthworms and Other Soil Fauna

Earthworms, when present, stimulate the decomposition of cover crop residues. Their feeding and burrowing activities incorporate residues and other amendments into the soil, enhancing organic matter decomposition, humus formation, nutrient cycling, and the development of soil structure (Werner 1993, 1994). Earthworm burrows can persist even after the worms responsible for building them are gone, providing pathways for rapid root growth, water infiltration, and gas exchange. Deep-burrowing species can burrow through compacted soil and penetrate plow pans. Earthworm numbers generally decrease when soils are tilled, left bare in the winter, fumigated, or treated with fungicide or insecticides (Lee 1985). Also, there may be localized, short-term negative effects of ammonia-based fertilizers on earthworms. Cover-cropped, minimum-tilled vineyards with limited or no chemical inputs can provide ideal habitats for earthworms.

Because there are many different earthworms, it is not useful for a grower to learn to recognize the individual species. However, there are three main types of earthworms that are defined by where the earthworms live, what they eat, and what they look like, and knowing the three types can be very useful (table 5-2). Most agroecosystems in California contain only endogeic earthworms. This type of earthworm lives and feeds below ground, where it is somewhat protected from chemical and physical disturbances.

Epigeic earthworms live in surface accumulations of organic matter, and they usually disappear in soils that are regularly cultivated or plowed because the surface layer of organic matter is buried. Epigeic species such as the redworm (*Eisenia foetida*) are used in vermicompost. Anecic earthworms can play a very important role by incorporating organic matter from the soil surface into the deeper horizons and creating deep, continuous, stable channels for aeration and infiltration. In deciduous forests, this type of earthworm is capable of burying the entire autumn leaf-fall within a couple of months (Knollenberg, Merritt, and Lawson 1985). Werner (forthcoming) introduced anecic earthworms in an apple orchard in coastal California and saw apple litter incorporation rates during the winter increase from 20 to 80 percent. In California, anecic earthworms are not widespread, perhaps due to the relatively arid climate. In the Pacific Northwest, in contrast, anecic earthworms are especially abundant in perennial crops and are commonly harvested for the bait-worm market, where they are known as nightcrawlers. Anecic earthworms could potentially be introduced into California vineyards, though their longevity is uncertain and would partly depend on soil management practices.

There are many other types of invertebrate animals that live in the soil, but because of their small size and cryptic habits they are seldom seen. They are thought to play important roles in the decomposition of cover crops and in the functioning of ecosystems in general. Soil mites and Collembola (springtails) number up to a million per square meter of soil. Another important group of organ-

Table 5-2. Three types of earthworms and their characteristics

Type	Appearance	Habitat	Food	Examples
Endogeic	Variable size; light or no pigmentation; slow moving	Continuous burrows in soil; generally feed and defecate belowground	Mixture of buried organic matter and mineral soil, decaying roots	*Allolobophora chlorotica*; *Aporrectodea trapezoides*; *Aporrectodea caliginosa*
Epigeic	Small; dark red or brown color; fast growing; move quickly	Areas of high organic matter; litter layer, manure piles, cool compost piles	Large proportion of diet is organic matter	*Lumbricus rubellus*; *Eisenia foetida* (red worm, manure worm)
Anecic	Large and very muscular; wedge-shaped tail; color on front end, less on tail end; fast moving but slow growing	Build permanent, very deep vertical burrows; raised midden of castings and residue marks burrow entrance	Feed by pulling organic matter from surface down into burrow before ingesting	*Aporrectodea longa*; *Lumbricus terrestris* (nightcrawler)

isms are the nematodes (see chapter 10). Although the plant parasitic species receive more attention for their destructive activities on crops, nematodes that prey on bacteria, fungi, and each other make up the majority of the nematodes present in soil.

Many mites, springtails, and nematodes feed on the microbes that decompose organic matter. Because many of them carry microbial spores on their body, they inoculate organic matter with the very microbes that they feed on. Springtails feed on fungi and have profound effects on fungi population dynamics. Some mites are predators, as are pseudoscorpions, spiders, rove beetles, and centipedes. These creatures help to maintain balance by preying on the springtails and other decomposers that would quickly become overabundant without regulation.

Effect of Cover Crops on the Soil Community

The Living Cover Crop

Cover crops directly influence the soil community by their root growth and plant cover over the winter. The majority of organisms found in soil are associated with the plant roots that provide them with carbon and other nutrients. Long periods of bare fallow may disrupt the community structure and reduce the numbers and activity of soil organisms, particularly mycorrhizal fungi. The physical cover on the soil surface also moderates soil temperature and moisture changes, creating a generally more hospitable habitat for soil organisms.

As a general rule, soil with vegetation supports higher microbial populations than does fallow soil. Plant roots exude compounds such as amino acids, simple sugars, and organic acids, and they slough off cells containing polysaccharides. These compounds provide a continuous energy supply to microorganisms living in the root zone (the rhizosphere). Studies have shown that the size of the microbial biomass fluctuates seasonally in response to the growth of crops such as wheat due to the rhizosphere effect (Lynch and Panting 1980).

Cover Crop Residues

Changes in soil habitat with crop incorporation. One of the major effects of a cover crop on the soil community is the increased input of organic matter contributed by cover crop residues. The large sources of carbon and energy for microbial communities that could be provided by cash crop residues are often removed from agricultural systems by current management practices. Vineyards yield relatively little biomass that is returned to the field. Vines will typically produce 1,500 to 2,500 pounds per acre (1,700 to 2,800 kg/ha) of prunings (fresh weight) and 800 to 1,500 pounds per acre (900 to 1,700 kg/ha) of leaves (dry weight). This is in contrast to a typical corn crop biomass residue of 8,000 to 12,000 pounds per acre (8,900 to 13,500 kg/ha). In vineyards, leaves and early prunings usually stay on-site. Much of the residue associated with vines is somewhat woody and not as easily decomposed as cover crop residues. Even with minimal removal of vine residues, a dryland cover crop producing 1,800 to 3,600 pounds per acre (2,000 to 4,000 kg/ha) of dry matter could contribute a significant amount of biomass to vineyards.

Growers often consider only mineral forms of essential plant nutrients (nitrogen, phosphorus, sulfur). However, soil organic matter and plant residues are other important sources of these nutrients. Therefore, a pool of potentially available nitrogen and other nutrients in organic forms is associated with the cover crop biomass. The amount of nitrogen contributed by cover crops is much greater if the cover crop is a legume and fixes nitrogen than if it is a grass crop. Organic forms of phosphorus and sulfur are also associated with cover crops. Although little research has been conducted on the availability of organic phosphorus and sulfur, it is likely that the organic forms are an important source of nutrients under certain soil chemical conditions (e.g., at low and high pH).

Changes in microbial populations. Studies have shown that fields receiving organic amendments regularly for many years (e.g., in the form of green or animal manure) generally have larger and more active microbial populations than fields receiving synthetic fertilizers (Scow et al. 1994). Because microbes are often limited by available carbon in agricultural soils, fresh organic material added to soil stimulates microbial activity. Increases in activity and biomass cease when the input is used up and microbes die off. These boom and bust cycles of microbial activity may be quite rapid. Buchanan and King (1992) observed weekly fluctuations in microbial activity in both no-till and reduced chemical input systems of continuous maize and maize-wheat-soybean rotations.

A long-term study at the Sustainable Agriculture Farming Systems (SAFS) Project in Davis, California, has provided information on the effect of cover crops, as well as other sustainable agricultural practices, on soil communities in row crops in a Mediterranean climate. Although the study is of row crops, some of the findings are indicative of what would occur with use of cover crops in vineyards. The SAFS study compares the effect of four farming systems (conventional 2-year rotation, conventional 4-year rotation, organic, and low-input) on microbial and nematode populations in tomato plots (Temple et al. 1994; Scow et al. 1994). Sources of plant nutrients to the organic system are cover crops (oat-vetch) and manure, whereas the low-input system receives cover crops and mineral fertilizer. At the beginning of the study, there was little difference in the size of the microbial biomass among the different farming systems. Only immediately after cover crop incorporation was the biomass higher in organic and low-input than in conventional tomatoes. Since the third year of the study, however, the microbial biomass and its activity has almost always been higher in the organic and low-input than conventional tomatoes. This 3-year period corresponds to the transition period often observed by growers converting from conventional to organic farming practices. Soil fertility can be problematic during this period. Suprisingly, there is little difference between the microbial populations in the organic and low-input systems, even though the organic system receives poultry manure in addition to cover crops. Microbial populations in all farming systems appear to be sensitive to soil moisture and temperature and often decline sharply in midsummer after irrigation has been reduced and when temperatures are quite high.

Measurement of the microbial biomass or population density is a complicated and imperfect science even for soil microbiologists. A common method for biomass determination involves fumigation of a soil sample with chloroform, extraction with potassium sulfate solution, and quantification of carbon in the extract. Population density is also determined by fluorescent microscopy after staining a soil suspension. Both methods require specialized equipment; however, there are institutions that provide these measurements as a service. The anaerobic incubation method for potentially mineralizable nitrogen (PMN) is a simple method that does not require complex equipment and provides an estimate of the amount of organic nitrogen contained in microbial biomass (Doran 1987). The PMN is calculated by measuring ammonium before and after incubation of soil that has been submerged in water for one week at a high temperature. Ammonium analyses can be performed by many soil analytical laboratories. The SAFS project has found that PMN is strongly correlated with microbial biomass carbon measured by fumigation extraction and that PMN is significantly higher in organic than conventional soils. During the 1993 growing season, values of PMN ranged from 10 to 30 µg NH_4–N per gram soil in the conventional tomatoes and from 20 to 50 µg NH_4–N per gram soil in organic tomatoes (Gunapala and Scow 1997).

Measuring the diversity of microbial communities is much more complicated than the measurement of microbial biomass. Diversity analysis, a relatively new activity, has been made possible by recent advances in biotechnology. Techniques used previously for identifying species, such as dilution plate counts, are not capable of detecting from 90 to 98 percent of the microorganisms actually present in soil and are therefore poor methods for representing the soil community. Methods such as microscopic counts can at best quantify cells and hyphae of bacteria and fungi but do not provide taxonomic information. Newer methods include molecular biological approaches similar to those used in criminological or paternity investigations that analyze the DNA and RNA extracted from the soil microbial community. Another method analyzes the phospholipid fatty acid (PLFA) profile that can be extracted directly from the membranes of bacterial and fungal cells present in soil (Bossio and Scow 1998). In the near future, as these new methods are increasingly applied in different studies, we will know far more about the diversity of soil microbial communities and how farming practices affect this diversity.

Changes in soil fauna. Although earthworms are not particularly picky about what they eat, they do show preference for food that is high in nitrogen. This is partly because earthworms are very inefficient at assimilating the nitrogen contained in their food into their body tissues; however, their loss is our gain. Because earthworms are made up of 60 to 70 percent protein (dry weight), they need to ingest large quantities of organic matter to meet their nitrogen requirements. Therefore, leguminous cover crops that are cut before they set seed (thus high in nitrogen) provide one of the best food materials for earthworms. Cover crop residues ingested by earthworm's are ground up in the earthworm's gut, inoculated with bacteria (some of which are nitrogen-fixers), bathed in enzymes, and excreted as biologically active and nutrient-rich casts. Castings may contain 75 percent of the nitrogen found in the ingested organic matter. The high levels of residual nutrients are largely available to plants. Earthworms also release the nitrogen that is assimilated into their body tissue as ammonium-N and amino-N in urine, mucoproteins, other secretions, and through mortality (Lee 1985).

Impact of cover crops on the soil community. Cover crops provide food for soil organisms throughout the growing cycle of the crop. Figure 5-2 is a simple model of the complex food webs that are based on inputs of organic matter to the soil. While the cover crop is alive and growing, the roots release sugars, dead cells, mucilage, and other materials into the soil as root exudates that fuel the decomposition process. If the cover crop is mowed, the cut portions of the plant provide habitat, shade, and food at the soil surface. If the cover crop is incorporated into the soil, all parts of the plant enter the organic matter pool and become a food source. The model contains several feedback loops of nutrient flow. For example, feces form a nutrient reservoir that continues to decompose after defecation through enzymatic and microbial activity. Soil animals commonly reingest feces, a behavior known as coprophagy (McBrayer 1973).

Ecological succession describes the changes and developments that occur in ecosystems over time. Successional changes in the biological community that spring up after cover crop incorporation are a response to the availability of a new, energy-rich food resource. The microcommunity that quickly develops in and around this resource is distinct from the fauna of the surrounding soil (Dindal 1973). With decomposing straw, three phases are discernible; an initial bacterial phase, a phase characterized by mites that eat bacteria, and a final phase including springtails, other mites, and other microarthropods (Naglitsch 1966). Successional changes in the microarthropod community are probably caused by changes in the food source brought about by microbial activity (Harding and Stuttard 1974). There is a peak in species diversity when decomposition is most active. However, if not renewed regularly, substrates such as cover crop residues become exhausted. As this occurs, the opportunistic decomposer community is gradually replaced by the species indigenous to the soils of that area. The decomposer community is in essence self-annihilating and nonreplenishing without periodic organic matter additions. Decomposer organisms have evolved many unique adaptations to allow them to locate and exploit short-lived food sources. For example, in the absence of fresh organic matter, low numbers of fungi may persist in dormant forms (e.g., as spores). With the input of organic matter, these fungi quickly grow to high densities and contribute to the decomposition of the plant residue.

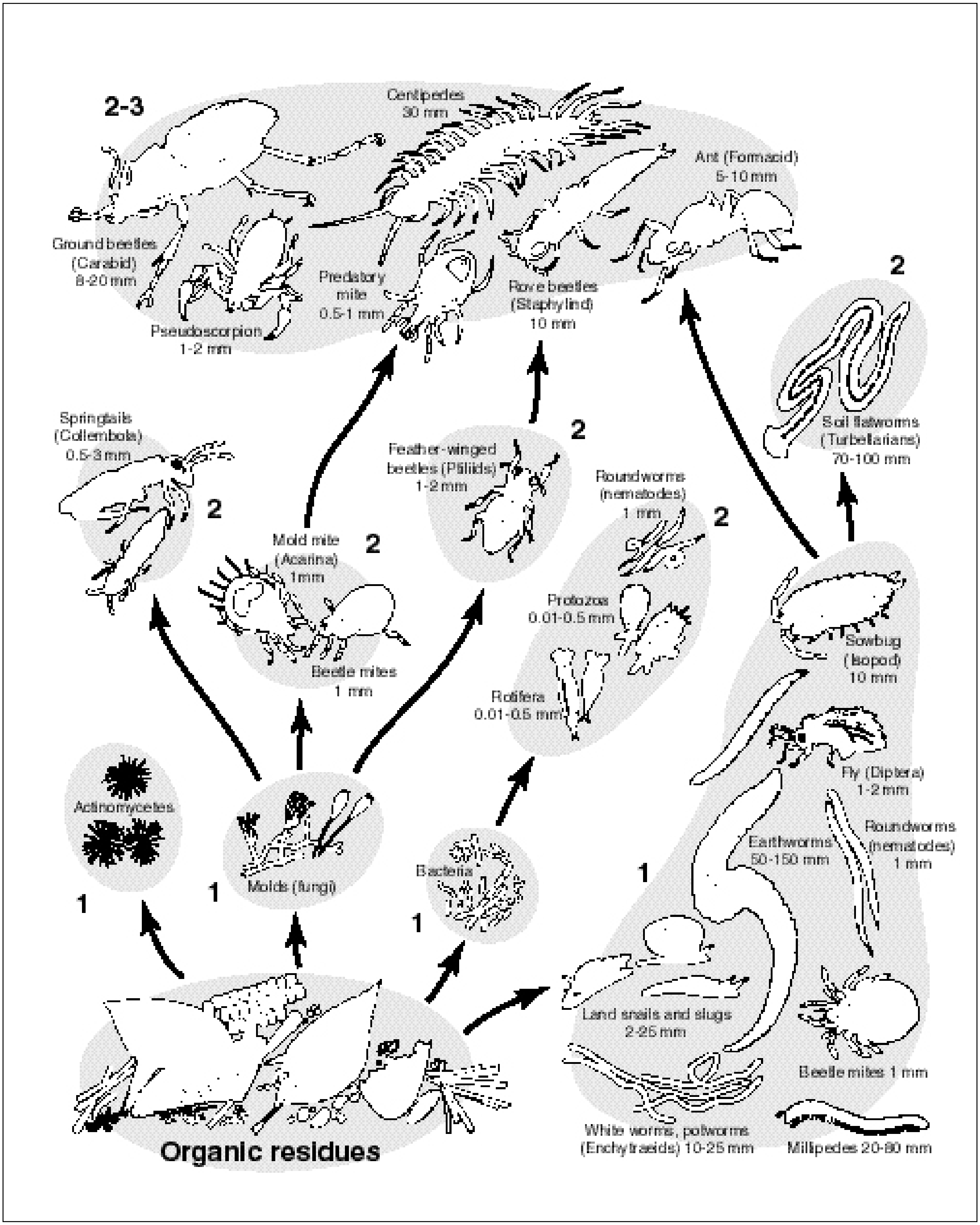

Figure 5-2. Food web of the compost pile. Energy flows in the direction of the arrows. 1 = First-level consumers; 2 = Second-level consumers; 3 = Third-level consumers. *Source*: Redrawn from Dindal n.d., pp. 6–7.

Practical Implications of Interactions between Soil Biota and Cover Crops for Vineyards

There are several questions growers might raise about the use of cover crops in vineyards. In converting from conventional production to the use of organic inputs, how long will it take for the decomposer organisms to effectively break down cover crop residues and cycle nutrients? Are microbial inoculants necessary or worth the money? Are decomposer communities more diverse in cover-cropped systems? Does this diversity improve nutrient cycling or suppress pathogens? Does the enhancement of decomposer organisms affect grape yield or quality? Although it is not possible to answer all these questions at this time, we can discuss some of the known benefits resulting from the influence of cover crops on the soil community.

Soil Structure

Soil structure and stability are particularly important in vineyards, which are often located on hillsides. Various forces cause the arrangement of primary soil particles (sand, silt, clay, and organic matter) into soil aggregates. The arrangement and stability of particles, aggregates, and voids is soil structure. The void or pore size distribution of soils is determined by the shape, size, and stability of aggregates. From an agricultural point of view, a well-structured soil has low bulk density, is well aerated, absorbs rainfall and irrigation rapidly, and is easily penetrated by plant roots and soil animals. The growth of fine plant roots and fungal hyphae knits soil particles and small aggregates together into larger units called macroaggregates. Grasses have a greater effect than do other plants on stable aggregate production because a large proportion of plant biomass is maintained underground in the root system. Production of polysaccharide gums by rhizosphere microorganisms and plant roots enhances the formation and stabilization of macroaggregates because the materials act as glues to bind particles together. Roberson, Sarig, and Firestone (1991) found improved aggregate stability in cover-cropped soils compared with conventional soils. Cover crops with a higher C/N ratio (e.g., mixtures containing grasses) may promote greater polysaccharide production and thus greater aggregate stability than do cover crops with lower C/N ratios (e.g., legumes).

Earthworms also influence soil structure. As earthworms burrow they ingest soil. The ingested soil aggregates are broken apart into a liquid slurry that mixes mineral soil with organic material and binding agents in the earthworm's gut. The excreted casts become stable after drying and contribute to soil structure. Dindal, Theoret, and Moreau (1978) observed that the size of soil aggregates (casts) is related to the size of the earthworm species producing them. *Lumbricus terrestris* (nightcrawler) populations are positively correlated with the presence of 1/6-inch (4 mm) water-stable aggregates. Their vertical burrows form large channels that allow rapid infiltration of water, exchange of gases deep into the soil, and penetration into soil by plant roots.

Nutrient Management and Microbial Communities

Nitrogen-rich cover crops (e.g., legumes) are a potential source of nutrients if they are incorporated into the soil during periods of crop demand. A potential negative effect of using cover crops in grapes, however, is the possibility of nitrogen immobilization after incorporation of a cover crop containing a high C/N ratio (e.g., grasses). Such effects are usually temporary and do not result in long-term influences on plant yields. Also, the effects can be minimized by proper timing of incorporation. An advantage of cover crops with high C/N ratios is their ability to reduce nitrate leaching by direct uptake of nitrogen or by promoting immobilization of soil nitrate by microorganisms during periods when there is a high potential for leaching. This characteristic can be especially important in sandy soils.

The development of the large and active microbial community that results from organic inputs is desirable because of the multiple roles it plays in soil fertility. Large microbial populations may also support a greater diversity in higher trophic levels (e.g., soil fauna) and thus increase the potential for the soil to sustain crop growth in the face of perturbations such as drought stress. Inoculation with biological additives containing microorganisms may result in short-term, but probably minor and not cost-effective, stimulation of processes regulating soil fertility. Any benefit of inoculation, however, will almost always be short-lived because of the inability of the foreign organisms to compete with the locals. The foundation of a healthy and thriving microbial community is good nutrition and protection from major stresses. If the conditions in soil are good, there will be plenty of microorganisms. If conditions are poor, microorganisms will not survive or be active, no matter how many organisms are added to soil.

Mycorrhizal Fungi

Vesicular-arbuscular mycorrhizal fungi (VAM) populations in vineyards are reduced by clean cultivation of the vineyard floor, as well as by preplant fumigants and fungicides. Methyl bromide is very toxic to VAM, and this toxicity can result in stunting of grapevines (Menge 1982, 1983). The recovery time of fungi is slower than that of bacteria, and it can be on the order of years for VAM (Liebman and Daar 1995). VAM inoculants are available commercially in the form of fungal spores that are applied to the soil in an aqueous suspension. Another way to increase VAM is to grow a cover crop. The dense root growth of cover crops boosts VAM growth and increases the likelihood of grape roots being colonized because of the close proximity between the root systems of cover crops and grapevines. This was shown in an apple orchard, where VAM colonization and leaf phosphorus content was greater in plots with a grass cover than in plots that had been treated with a herbicide (Atkinson 1983).

Disease Suppression

In some cases, cover crops may reduce plant disease through the enhancement of beneficial microorganisms. Large and diverse microbial communities, especially in the plant rhizosphere, may actually suppress pathogens. Although the evidence for this suppression is not strong, it is highly suggestive. Both cover crops and manure have been observed to be associated with suppressiveness. Mechanisms reported to be responsible for disease control with the use of cover crop residues include an increased resistance of crop plants through supplementation of nutrients or other factors; altered virulence or growth of the pathogen directly (such as by allelopathic effects of the cover crop); an increase in activity of beneficial soil organisms resulting in their shutting out pathogens through antagonism or competition for niches or nutrients; and a combination of all three (Patrick and Toussoun 1965). Although suppressive soils have been found in association with grapes, the positive benefits of suppressiveness may not be evident until a vineyard is well established (Liebman and Daar 1995).

Enhancing Earthworm Communities in Vineyards

While it is common to find only endogeic earthworms on California farms, it would be useful to encourage diversification of earthworm communities by managing systems to include anecic or epigeic species or both. Managing the habitat to encourage the increase of earthworm populations would include minimizing physical disturbance of the soil (especially in the winter when earthworms are most active); limiting chemical use (especially fumigants, certain fungicides, and ammonium-based fertilizers); providing a near-neutral pH; and providing a food source. A perennial or winter annual cover crop that is periodically mowed, with the residue left on the surface, is an excellent way to provide these conditions.

In some cases it may be desirable to inoculate a soil with anecic earthworms, either through direct inoculation with nightcrawlers purchased from a bait dealer or by transferring blocks of soil (1 cubic foot [28 cm^3] each) from an area with an established anecic earthworm population. Another method is to set aside a small portion of a vineyard to be managed intensively as an earthworm reservoir. This method is especially useful in perennial crops like grapes. If needed, the soil could be limed to bring it near pH 7, fertilized, and a cover crop established and cut periodically to provide an organic mulch as food and physical cover. In this area of the vineyard, a population of the desired species could be introduced and built up. From this reservoir blocks could periodically be taken and introduced into the field. This might be done each year in the fall when earthworm activity is increasing. Remember to provide an organic mulch. The rate of spread would vary with species and conditions in the field. An individual nightcrawler is capable of traveling at least 63 feet (19.2 m) on the soil surface in the course of one evening foray. However, the spread and establishment of an entire earthworm colony will take longer.

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