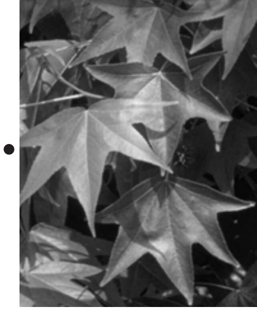


1 THE SCIENCE OF COMPOSTING

If moist food scraps are placed in a container and left to sit for a week or two, the end product is likely to be a smelly "slop" that attracts flies. Given the proper conditions, these same food scraps can be composted to produce a material that looks and smells like rich soil and can be used to enhance soil texture and productivity. So, what are these conditions that promote composting?

The physical and chemical conditions that should be maintained in a compost heap seem logical if you think about what compost really is—a big pile of food for billions of minute organisms. These microorganisms have certain chemical requirements, primarily carbon for energy, nitrogen to build proteins, and oxygen for respiration. Interacting with these are physical requirements, such as aeration to maintain optimal oxygen levels while not depleting the moisture necessary for microbial growth.

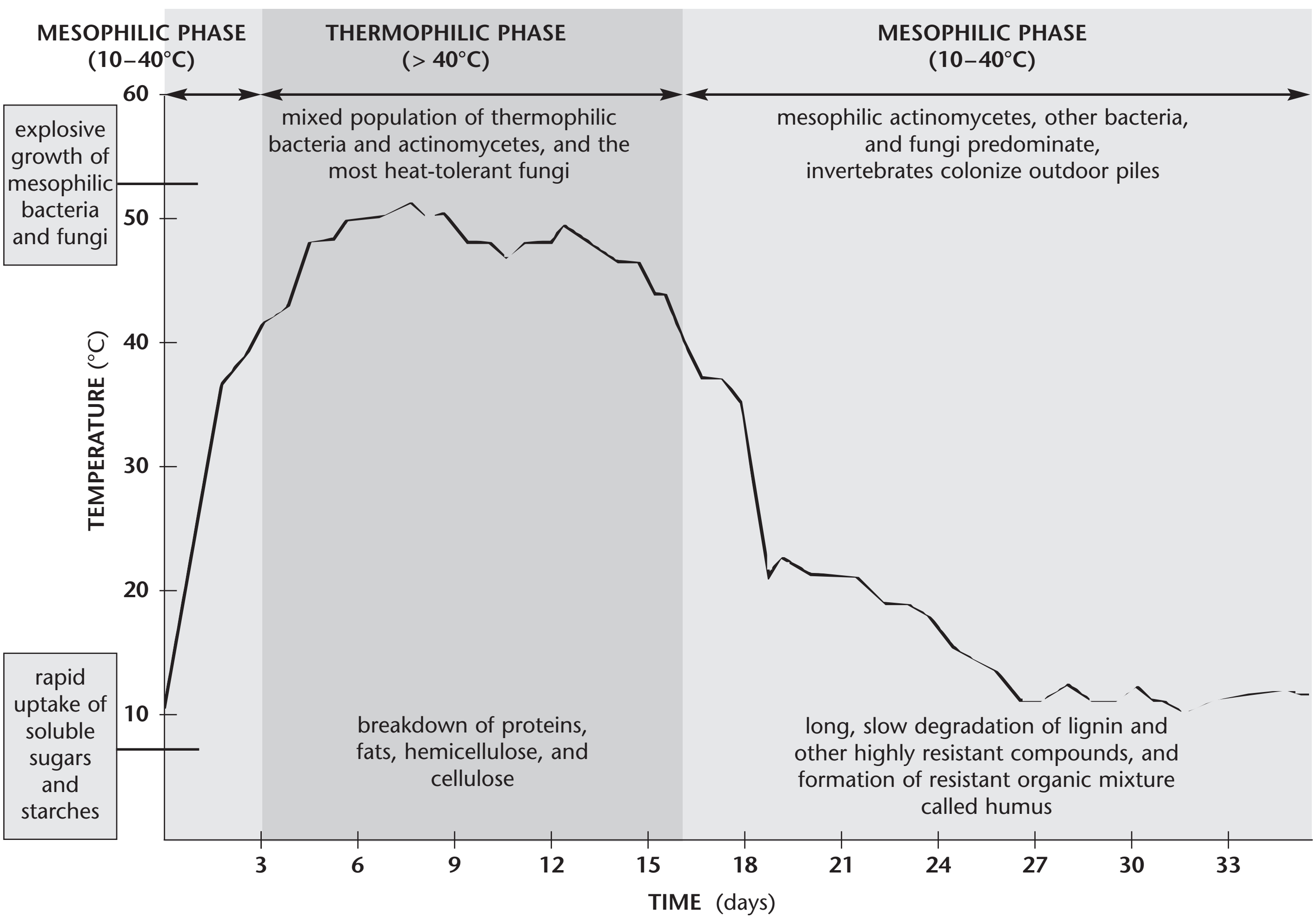
This chapter begins with an overview of the chemical, physical, and biological changes that occur during thermophilic composting, thereby providing an example of how several sciences can be integrated in the study of composting. This overview is followed by more detailed, separate sections on compost chemistry, physics, and biology. Much of the information in the chemistry and physics sections focuses on thermophilic composting. The biology section includes a discussion of the microbes that are present in all types of composting, and of the diversity of invertebrates that live in outdoor and some worm composting systems.

The information presented here reflects the current body of scientific knowledge regarding composting. Much remains unknown, leaving a variety of intriguing questions for future research. Some of these questions are identified as ***Research Possibilities***, sprinkled in italics throughout the text. We hope they will provide the inspiration for students to ask a much wider range of questions, and to design their own original research.

THERMOPHILIC COMPOSTING

Many composting systems are based on providing the optimal conditions for thermophilic composting because its high temperatures promote rapid decomposition and kill weed seeds and disease-causing organisms. These high temperatures are a by-product of the intense microbial activity that occurs in thermophilic composting. Thermophilic composting can be divided into three phases, based on the temperature of the pile: (1) a mesophilic, or moderate-temperature phase (up to 40°C), which typically lasts for a couple of days; (2) a thermophilic, or high-temperature phase (over 40°C), which can last from a few days to several months depending on the size of the system and the composition of the ingredients; and (3) a several-month mesophilic curing or maturation phase. Periodic temperature measurements can be used to chart the progress of thermophilic composting, producing a "temperature profile" showing these three phases (Figure 1–1).

Figure 1–1. The Three Phases of Thermophilic Composting.

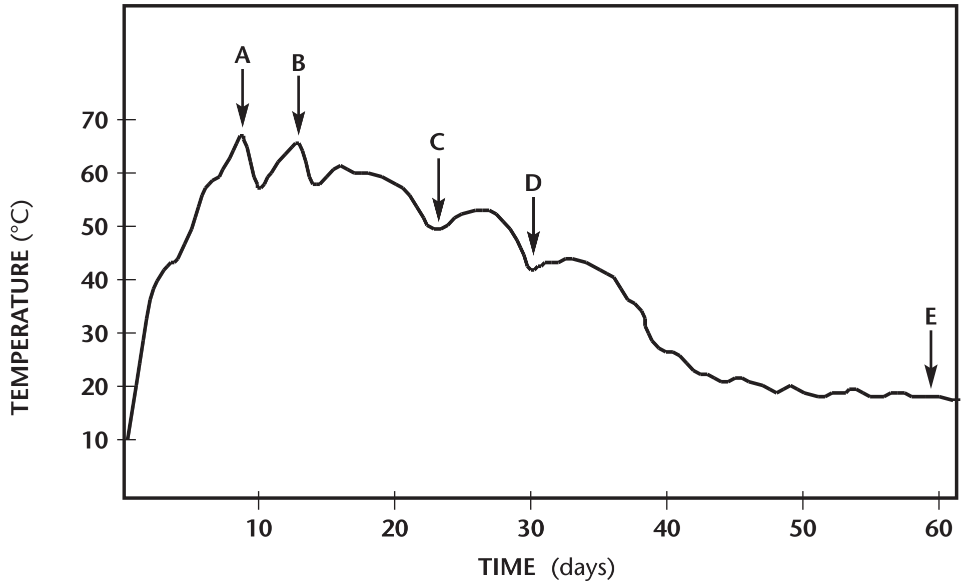


Different communities of microorganisms predominate during the various temperature phases. Initial decomposition is carried out by mesophilic microorganisms, those that thrive at moderate temperatures. These microbes rapidly break down the soluble, readily degradable compounds, and the heat they produce causes the compost temperature to rapidly rise. Once temperatures exceed 40°C, the mesophilic microorganisms become less competitive and are replaced by thermophilic, or heat-loving microbes. During the thermophilic stage, high temperatures accelerate the breakdown of proteins, fats, and complex carbohydrates like cellulose and hemicellulose, the major structural molecules in plants. As the supply of these compounds becomes exhausted, the compost temperature gradually decreases and mesophilic microorganisms once again take over for the final phase of "curing," or maturation of the remaining organic matter. Although the compost temperature is close to ambient during the curing phase, chemical reactions continue to occur that make the remaining organic matter more stable and suitable for plant use.

The smaller systems used for indoor composting are not likely to get as hot as compost in large piles or windrows. A well-designed indoor compost system, ≥10 gallons in volume, will heat up to 40–50°C in the first two or three days. Soda bottle bioreactors, because they are so small, are more likely to peak at temperatures of 40–45°C. At the other end of the scale, commercial or municipal-scale compost systems may reach temperatures above 60°C. Because temperatures above 55°C are lethal to many microorganisms that cause human or plant diseases, this is the target temperature that compost managers use for suppression of pathogens. However, if the compost temperature goes above 60–65°C, the beneficial microbial populations are also killed.

Humans can control the temperatures during composting by mixing or turning the organic materials (Figure 1–2). If the pile or windrow is getting too hot, turning a pile can release heat from the inner core, which temporarily cools it down (points A and B in Figure 1–2). As the food available to thermophilic organisms becomes depleted, their rate of growth slows and the temperature begins to drop. Turning the pile at this point may produce a new temperature peak (points C and D in Figure 1–2). This is because relatively undecomposed organic matter gets mixed into the center of the pile, where temperature and moisture conditions are optimal for rapid decomposition. In addition, mixing loosens up the compost ingredients, which increases the infiltration of oxygen that is needed by aerobic microorganisms. After the thermophilic phase is completed, the compost temperature drops, and it is not restored by turning or mixing (point E).

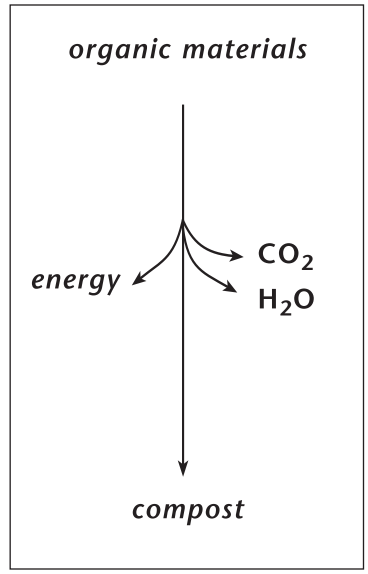
Figure 1–2. The Effects of Turning on Compost Temperature.
(See p.3 for explanation.)



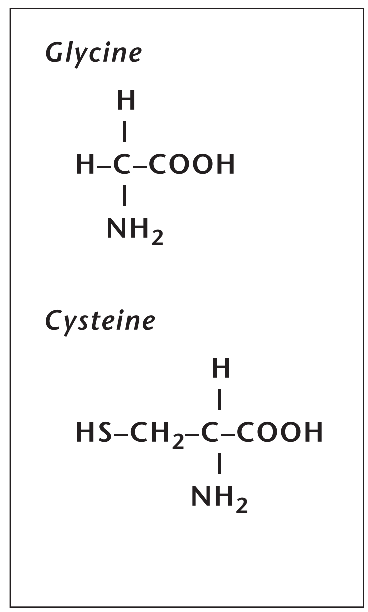
Research Possibility: *Garden supply stores and catalogs often sell compost "starters," which they claim speed up the composting process. Develop a recipe for a compost starter and design a research project to test its effect on the compost temperature profile. (Hint: You might want to include finished compost or soil as an inoculant, or nitrogen fertilizer or sugar to trigger fast microbial growth.)*

COMPOST CHEMISTRY

Many chemical changes occur during composting, either relatively rapidly in thermophilic systems or more slowly in worm bins or other systems that do not heat up (Figure 1–3). In all of these compost systems, chemical breakdown is triggered by the action of enzymes produced by microorganisms. Bacteria and fungi secrete enzymes that break down complex organic compounds, and then they absorb the simpler compounds into their cells. The enzymes catalyze reactions in which sugars, starches, proteins, and other organic compounds are oxidized, ultimately producing carbon dioxide, water, energy, and compounds resistant to further decomposition. The enzymes are specialized, such as cellulase to break down cellulose, amylase for starches, and protease for proteins. The more complex the original molecule, the more extensive the enzyme system required to break it down. Lignins, large polymers that cement cellulose fibers together in wood, are among the slowest compounds to decompose because their complex structure is highly resistant to enzyme attack.



As organic matter decomposes, nutrients such as nitrogen, phosphorus, and potassium are released and recycled in various chemical forms through the microorganisms and invertebrates that make up the compost food web. Proteins decompose into amino acids such as glycine or cysteine. These nitrogen- and sulfur-containing compounds then further decompose, yielding simple inorganic ions such as ammonium (NH_4^+), nitrate (NO_3^-), and sulfate (SO_4^{2-}) that become available for uptake by plants or microorganisms.

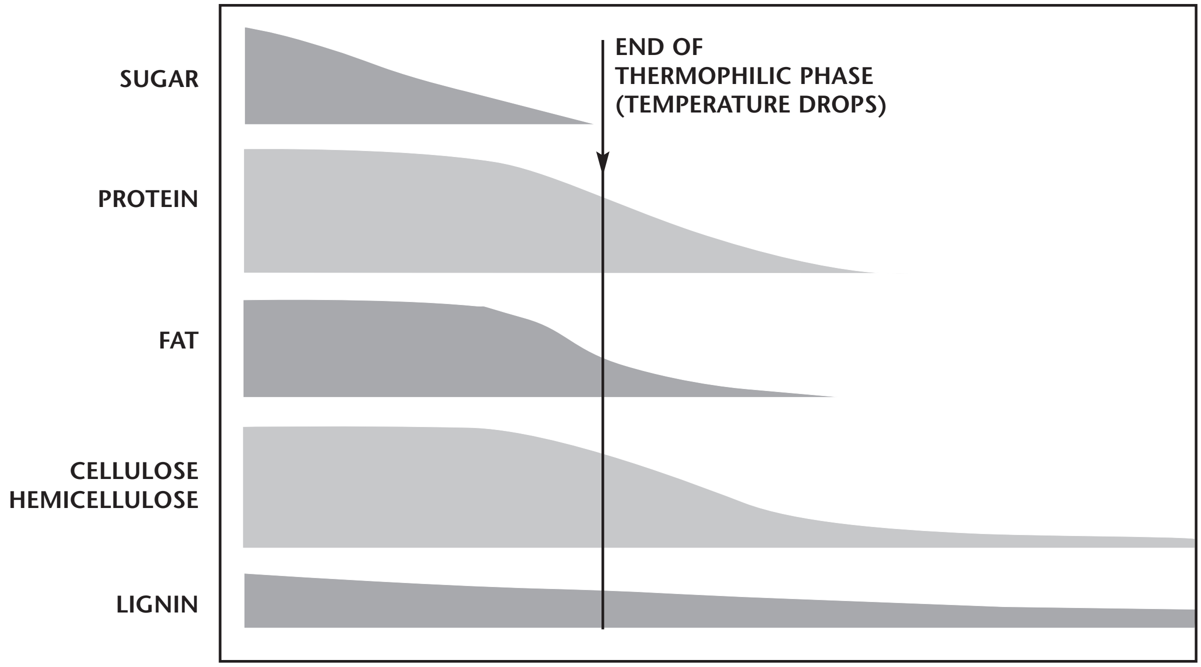


Not all compounds get fully broken down into simple ions. Microbes also link some of the chemical breakdown products together into long, intricate chains called polymers. These resist further decomposition and become part of the complex organic mixture called humus, the end product of composting.

In thermophilic composting, any soluble sugars in the original mixture are almost immediately taken up by bacteria and other microorganisms. The resulting explosive microbial growth causes the temperature to rise. During the thermophilic phase, more complex compounds such as proteins, fats, and cellulose get broken down by heat-tolerant microbes. Eventually, these compounds become depleted, the temperature drops, and the long process of maturation begins. During this final phase, complex polymers continue slowly to break down. Those most resistant to decay become incorporated into humus.

Research Possibility: *How well do human nutrition concepts apply to compost microorganisms? For example, will the microbes get a "sugar high," demonstrated by a quick, high temperature peak when fed sugary foods, compared with a longer but lower peak for more complex carbohydrates?*

Figure 1–3. Chemical Decomposition during Thermophilic Composting.



CHEMICAL REQUIREMENTS FOR THERMOPHILIC COMPOSTING

In order for successful thermophilic composting to occur, the proper conditions need to be created for optimal microbial growth. The key factors are the relative amounts of carbon and nitrogen, the balance between oxygen and moisture content, and pH.

CARBON-TO-NITROGEN RATIO

Of the many elements required for microbial decomposition, carbon and nitrogen are the most important and the most commonly limiting. Carbon is both an energy source (note the root in our word for high-energy food: *carbo*hydrate), and the basic building block making up about 50% of the mass of microbial cells. Nitrogen is a crucial component of the proteins, amino acids, enzymes, and DNA necessary for cell growth and function. Bacteria, whose biomass is over 50% protein, need plenty of nitrogen for rapid growth.

The ideal carbon-to-nitrogen (C:N) ratio for composting is generally considered to be around 30:1, or 30 parts carbon for each part nitrogen by weight. Why 30:1? Although the typical microbial cell is made up of carbon and nitrogen in ratios as low as 6:1, additional carbon is needed to provide the energy for metabolism and synthesis of new cells. C:N ratios lower than 30:1 allow rapid microbial growth and speedy decomposition, but excess nitrogen will be lost as ammonia gas, causing undesirable odors as well as loss of the nutrient. C:N ratios higher than 30:1 do not provide sufficient nitrogen for optimal growth of the microbial populations. This causes the compost to remain relatively cool and to degrade slowly, at a rate determined by the availability of nitrogen.

As composting proceeds, the C:N ratio gradually decreases from 30:1 to 10–15:1 for the finished product. This occurs because each time that organic compounds are consumed by microorganisms, two-thirds of the carbon is lost to the atmosphere as CO_2 gas, while most of the nitrogen is recycled into new microorganisms. Although finished compost has a low C:N ratio, this does not result in the odor problems mentioned above because the organic matter is in a stable form, having already undergone extensive decomposition.

Attaining a C:N ratio of roughly 30:1 in the mix of compost ingredients is a useful goal; however, this ratio may need to be adjusted according to the bioavailability of the materials in question. Most of the nitrogen in compostable materials is readily available. Some of the carbon, however, may be bound up in compounds that are highly resistant to biological degradation. Newspaper, for example, decays less readily than other types of paper because it has not been chemically treated to remove lignin. Lignin, a highly resistant compound found in wood, forms sheaths around cellulose fibers, retarding their decomposition. The result is that it takes almost four times as much newsprint as office paper to provide the same amount of bioavailable carbon in composting.[1] Corn stalks and straw are similarly slow to break down because they are made up of a resistant form of cellulose. All of these materials can still be composted, but it is best to mix them with other sources containing more readily biodegradable carbon.

Research Possibility: *Newspaper has a higher lignin content than office paper and therefore should take longer to decompose. Is this true in thermophilic composting? What about in worm bins?*

Particle size can also affect the availability of carbon. Whereas the same amount of carbon is contained in comparable masses of wood chips and sawdust, the larger surface area in the sawdust makes its carbon more readily available for microbial use. A larger volume of wood chips than sawdust would therefore be needed to achieve the same amount of available carbon.

In addition to carbon and nitrogen, adequate phosphorus, sulfur, calcium, and potassium are essential to microbial metabolism, as are trace elements such as magnesium, iron, and copper. Normally, these nutrients are not limiting because the compost ingredients provide sufficient quantities for microbial growth.

OXYGEN

Oxygen is essential for the metabolism and respiration of aerobic microorganisms and for oxidizing the various organic molecules present in the waste material. As microorganisms oxidize organic matter for energy and nutrition, oxygen is used and carbon dioxide is produced. If oxygen supplies are depleted, the composting process will become anaerobic and produce undesirable odors, including the rotten-egg smell of hydrogen sulfide gas. Therefore, compost systems need to be designed to provide adequate air flow using either passive or forced aeration systems.

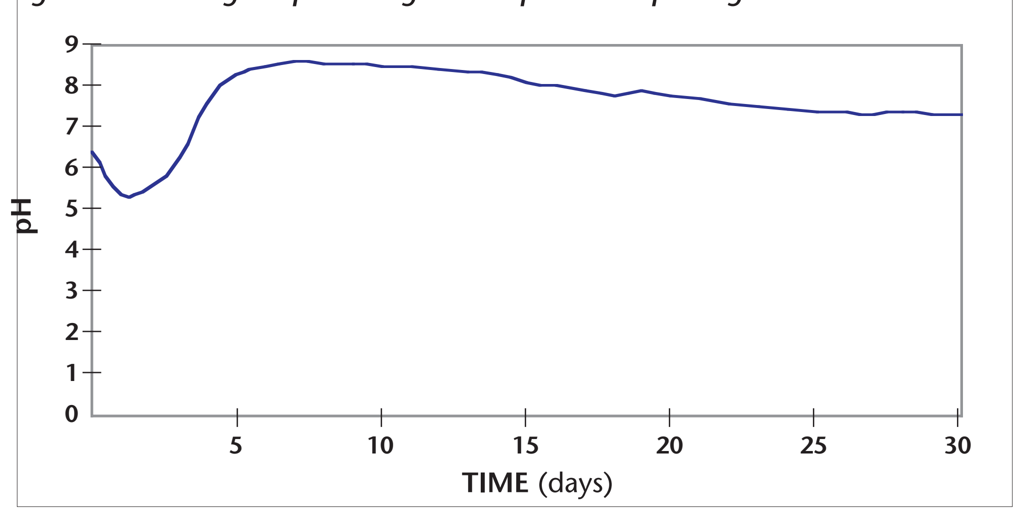
(For information on the balance between aeration and moisture, see pp. 10–11).

pH

During the course of composting, the pH generally varies between 5.5 and 8.5 (Figure 1–4). The initial pH depends on the composition of the ingredients. In the early stages of composting, organic acids may accumulate as a by-product of the digestion of organic matter by bacteria and fungi. The resulting drop in pH encourages the growth of fungi, which are active in the decomposition of lignin and cellulose. Usually, the organic acids break down further during the composting process, and the pH rises. This is caused by two processes that occur during the thermophilic phase: decomposition and volatilization of organic acids, and release of ammonia by microbes as they break down proteins and other organic nitrogen sources. Later in the composting process, the pH tends to become neutral as the ammonia is either lost to the atmosphere or incorporated into new microbial growth. Finished compost generally has a pH between 6 and 8.

If the system becomes anaerobic, it will not follow this trend. Instead, acid accumulation may lower the pH to 4.5, severely limiting microbial activity. In such cases, aeration usually is sufficient to return the compost pH to acceptable ranges.

Figure 1–4. Change in pH during Thermophilic Composting.



Research Possibility: *Measure the pH of a number of different compost mixes. How does the pH of initial ingredients affect the pH of finished compost?*

Research Possibility: *Some instructions call for adding lime to increase the pH when compost ingredients are mixed. Other instructions caution to avoid this because it causes a loss of nitrogen. How does adding various amounts of lime to the initial ingredients affect the pH of finished compost?*

Research Possibility: *Does the pH of the initial compost ingredients affect the populations of microorganisms during composting?*

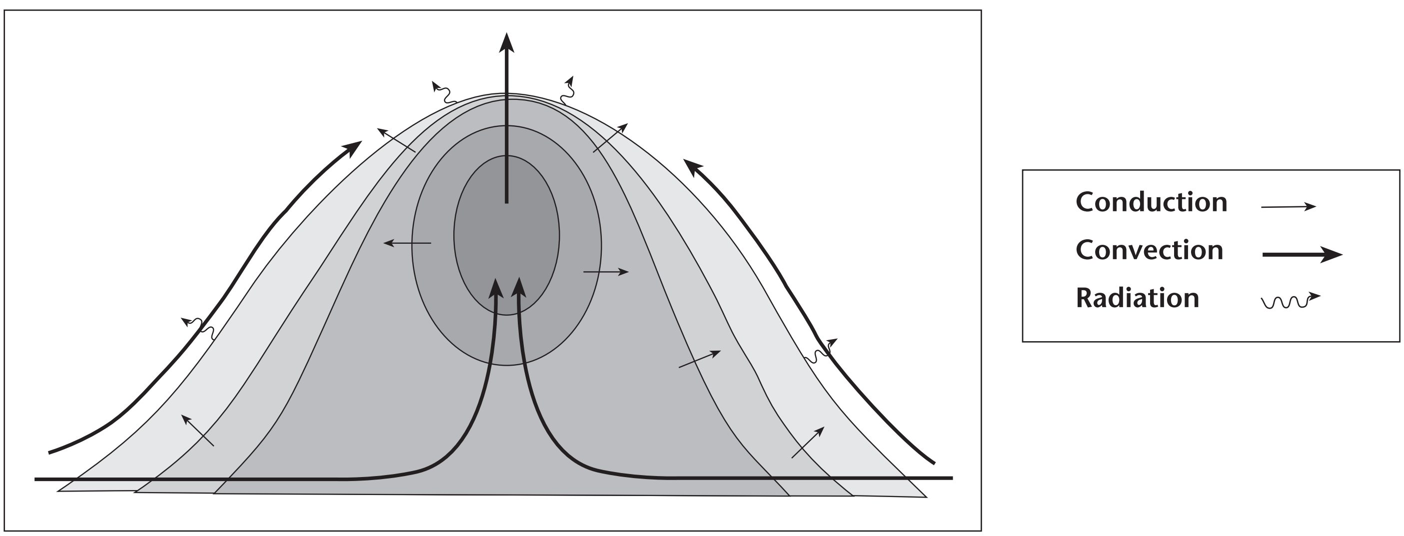
COMPOST PHYSICS

Providing the right conditions for thermophilic organisms involves a series of balancing acts between various physical properties of the compost system and its ingredients. The pile or vessel must be large enough to retain heat and moisture, yet small enough to allow good air circulation. The compost must be sufficiently moist to support microbial growth but not so wet that it becomes anaerobic. Also, the particle size of organic materials must be large enough to maintain a porous mix but not so large that decomposition is inhibited.

MECHANISMS OF HEAT LOSS

The temperature at any point during composting depends on how much heat is being produced by microorganisms, balanced by how much is being lost through conduction, convection, and radiation (Figure 1–5). *Conduction* refers to energy that is transferred from atom to atom by direct contact. At the edges of a compost pile, conduction causes heat loss to the surrounding air molecules. The smaller the bioreactor or compost pile, the greater the surface area-to-volume ratio, and therefore, the larger the degree of heat loss to conduction. Insulation helps to reduce this loss in small compost bioreactors.

Figure 1–5. Three Mechanisms of Heat Loss from a Thermophilic Compost Pile.



Research Possibility: *Design a thermophilic composting system to provide a heat exchange system for heating water. Compare the effectiveness of several different systems.*

Convection refers to the transfer of heat by movement of a substance such as air or water. When compost gets hot, warm air rises within the system, and the resulting convective currents cause a slow but steady movement of heated air upward through the compost and out the top. In addition to this natural convection, some composting systems use "forced convection" driven by blowers or fans. This forced air, in some cases triggered by thermostats that indicate when the piles are getting too hot, increases the rates of both conductive and convective heat losses. Much of the energy transfer is in the form of latent heat—the energy required to evaporate water. You can sometimes see steamy water vapor rising from hot compost piles or windrows.

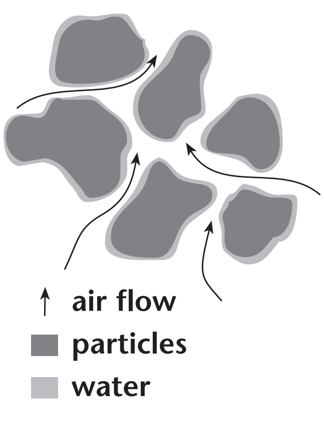
The third mechanism for heat loss, *radiation*, refers to electromagnetic waves like those that you feel when standing in the sunlight or near a warm fire. Similarly, the warmth generated in a compost pile radiates out into the cooler surrounding air. However, radiation is a negligible loss of heat from compost because of the relatively small difference in temperature between the outer edges of the compost and the surrounding air.

Research Possibility: *What type of insulation works best for soda bottle bioreactors? Does it help to have a reflective layer? Do different insulative materials or different thicknesses affect the temperature profile?*

Because water has a higher specific heat than most other materials, drier compost mixtures tend to heat up and cool off more quickly than wetter mixtures, providing that adequate moisture levels for microbial growth are maintained. The water acts as a thermal stabilizer, damping out the changes in temperature as microbial activity ebbs and flows.

AERATION

Maintaining the proper balance between moisture and oxygen is one of the keys to successful composting. Because oxygen diffuses thousands of times faster through air than through water, oxygen transfer is impeded if water fills the pores between compost particles. If the thin films of water surrounding individual particles dry out, however, the microorganisms that decompose inorganic matter will become inactive. Therefore, the key to successful composting is to provide enough water to maintain the thin films around compost particles, but not so much that it replaces air in the larger pores.



At the start of the composting process, the oxygen concentration in the pore spaces is about 15–20% (similar to the normal composition of air), and the CO_2 concentration varies from 0.5–5%. As biological activity progresses, the O_2 concentration decreases and CO_2 concentration increases. If the average O_2 concentration in the pile falls below 5%, regions of anaerobic conditions develop. Providing that the anaerobic activity is kept to a minimum, the compost pile acts as a biofilter to trap and degrade the odorous compounds produced as a by-product of anaerobic decomposition. However, should the anaerobic activity increase above a certain threshold, undesirable odors may result.

Oxygen concentrations greater than 10% are considered optimal for aerobic composting. Some systems are able to maintain adequate oxygen passively, using air holes or aeration tubes. Others require forced aeration provided by blowers or agitators.

A common misconception in composting is that piles should be turned or mixed every couple of weeks in order to maintain adequate oxygen levels. In fact, calculations show that the oxygen introduced by turning a rapidly degrading compost pile becomes depleted within the first several hours, indicating that diffusion and convection rather than turning are the primary mechanisms that keep the compost aerobic.[2] Mixing does help to keep the pile aerated, however, by loosening it up and increasing the pore spaces through which air flow occurs. Another reason for turning compost is to mix the drier and cooler materials from the edges into the center of the pile, where the more constant heat and moisture promote optimal decomposition.

Research Possibility: *When constructing compost bins or piles, some people incorporate perforated pipe, wire mesh, or other systems to increase passive air flow. What is the effect of different methods of aeration on the temperature profile of any one compost system?*

Research Possibility: *How do various means and schedules for turning a pile affect the temperature profile and the time needed for production of finished compost?*

Research Possibility: *What is the effect of forced aeration (with an aquarium pump or similar apparatus) on the temperature profile in a soda bottle or a two-can bioreactor?*

MOISTURE

An initial moisture content of 50–60% by weight is generally considered optimum for composting because it provides sufficient water to maintain microbial growth but not so much that air flow is blocked. Decomposition by microorganisms occurs most rapidly in the thin films of water surrounding compost particles. When conditions become drier than 35–40%, bacterial activity is inhibited because these films begin to dry up. At the other end of the range, moisture levels above 65% result in slow decomposition, odor production in anaerobic pockets, and nutrient leaching.

PARTICLE SIZE

Most microbial activity occurs on the surface of the organic particles. Therefore, decreasing particle size, through its effect of increasing surface area, will encourage microbial activity and increase the rate of decomposition. Decreasing particle size also increases the availability of carbon and nitrogen. Thus, the carbon in wood shavings or sawdust is more available than the carbon in large wood chips. However, when particles are too small and compact, air circulation through the pile is inhibited. This decreases the oxygen available to microorganisms, and it ultimately decreases the rate of microbial activity and decomposition. “Bulking agents” consisting of large particles such as wood chips, chopped branches, pine cones, or corn cobs are often added to piles to enhance aeration. At the end of the composting process, bulking agents that have not decomposed can be sieved out from the compost and reused.

Research Possibility: *Try several bulking agents with different particle sizes. Is there a difference in the temperature profile and length of time it takes to produce compost?*

SIZE OF COMPOST SYSTEM

A compost pile must be large enough to prevent rapid dissipation of heat and moisture, yet small enough to allow good air circulation. Conventional wisdom for thermophilic composting is that piles should be at least 1 m^3 in size to ensure sufficient heat and moisture retention. Smaller systems such as soda bottle bioreactors require insulation for heat retention. Compost in bioreactors made of nested garbage cans will heat up without insulation if the inner can is at least 10 gallons in size and the surrounding air temperatures are not too low.

Research Possibility: *Try mixing the same ingredients in a large outdoor pile, a two-can bioreactor, and a soda bottle bioreactor. Which system reaches the hottest temperatures? Which remains hot the longest? How does this affect the compost produced?*

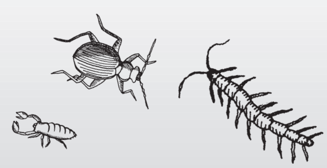
COMPOST BIOLOGY

No matter what system is used for composting, biological organisms play a central role in the decomposition process. The most vital of these are microorganisms, but worms and other invertebrates are also key players in some types of composting.

Food webs provide one way of portraying interactions among organisms. When you think of a food web, you may think of the sun's energy being converted into food by green plants, which are eaten by herbivores, who in turn are eaten by an array of predators. The leaves, feathers, and excrement produced by each of these organisms, as well as the plants and animals themselves when they die, provide the energy source for another type of food web—the decomposition food web. Among leaves and logs on the forest floor, in a steaming pile of hay or manure, or in a compost pile, many of the same organisms are at work. These microorganisms convert organic debris into a source of energy and nutrients for other organisms, as well as serve as prey for higher level microbes, invertebrates, and vertebrates (Figure 1–6).

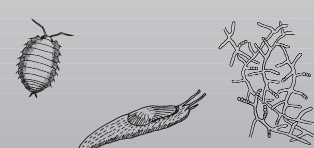
Figure 1–6. Functional Groups of Organisms in a Compost Food Web.

Tertiary Consumers
organisms that eat secondary consumers
centipedes, predatory mites,
rove beetles, pseudoscorpions



Secondary Consumers
organisms that eat primary consumers
springtails, feather-winged beetles,
and some types of mites,
nematodes, and protozoa

Primary Consumers
organisms that feed on organic residues
actinomycetes and other bacteria, fungi,
snails, slugs, millipedes, sowbugs, some types
of mites, nematodes, and protozoa

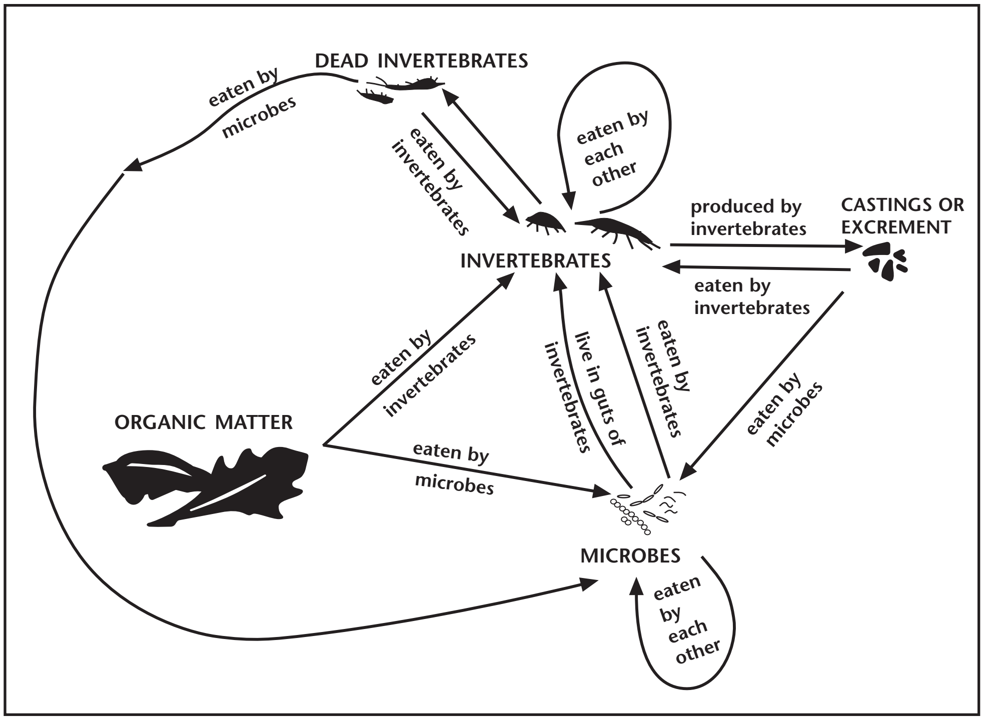


Organic Residues
leaves, grass clippings, other plant debris,
food scraps, fecal matter and animal bodies including
those of soil invertebrates

The organic residues forming the base of the compost food web are consumed by fungi, actinomycetes and other bacteria, and invertebrates including millipedes, sowbugs, nematodes, snails, slugs, and earthworms. These primary consumers serve as food for secondary consumers including springtails and some predatory species of nematodes, mites, and beetles. Finally, there are higher-level predators such as centipedes, rove beetles, and pseudoscorpions that prey on each other and the secondary-level compost invertebrates.

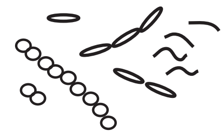
The interactions between organic matter, microbes, and invertebrates in compost are sometimes difficult to portray in a food web (Figure 1–7). For example, some invertebrates digest only feces, or organic matter that has already passed through the guts of other organisms. Others feed on fresh organic matter but require microorganisms inhabiting their gut to break it down into a form they can digest. Worms and some other invertebrates derive nutrition by digesting the microorganisms growing on organic detritus, as well as the detritus itself.

Figure 1–7. Feeding Interactions among Organisms in Compost.



MICROORGANISMS

All types of composting depend on the work of bacteria and fungi. These microbes digest organic matter and convert it into chemical forms that are usable by other microbes, invertebrates, and plants. During thermophilic composting, the populations of various types of microorganisms rise and fall in succession, with each group thriving while environmental conditions and food sources are favorable, then dying off and leaving a new set of conditions that favor another group of organisms. Even in vermicomposting and outdoor composting, microorganisms play an active role, within the invertebrates' digestive systems, on their excrement, and in layers coating the particles of organic material.

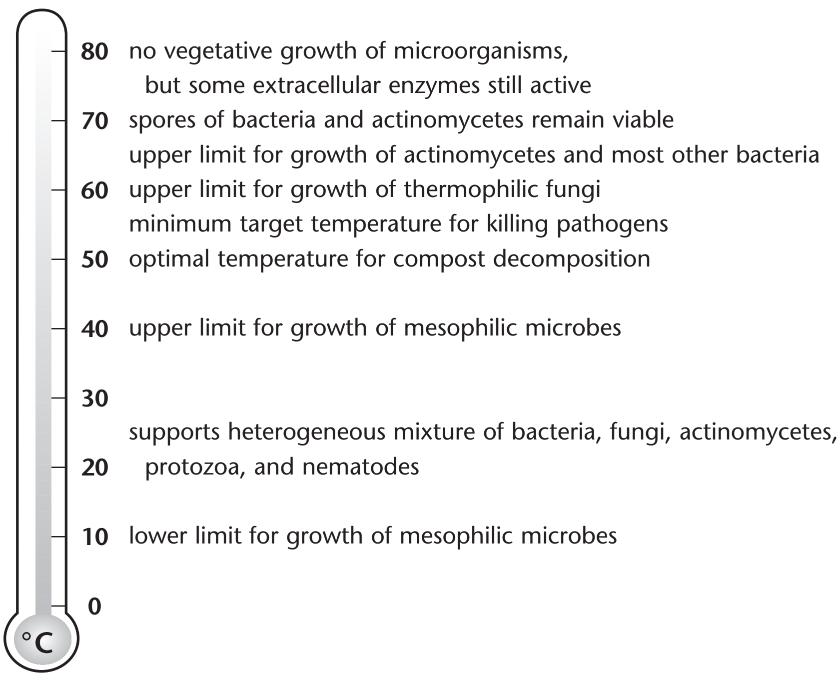


BACTERIA

Bacteria are responsible for most of the decomposition and heat generation in compost. They are the most nutritionally diverse group of compost organisms, using a broad range of enzymes to chemically break down a variety of organic materials. Bacteria are single-celled and are structured as rod-shaped bacilli, sphere-shaped cocci, or spiral-shaped spirilli. Many are motile, meaning they have the ability to move under their own power.

At the beginning of the composting process (up to 40°C), mesophilic bacteria predominate (Figure 1–8). They include hydrogen-oxidizing, sulfur-oxidizing, nitrifying, and nitrogen-fixing bacteria. Most of these can also be found in topsoil. Their populations increase exponentially during the initial stages of composting as they take advantage of the readily available simple compounds such as sugars and starches. Heat is produced by their metabolic activity, and if conditions are right, the compost begins to get hot.

Figure 1–8. Temperature Ranges for Compost Microorganisms.

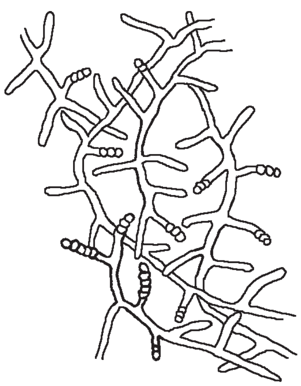


As temperatures rise above 40°C, mesophilic bacteria no longer thrive and thermophilic species take over. The microbial populations during this phase are dominated by members of the genus *Bacillus*. The diversity of bacilli species is fairly high at temperatures from 50–55°C but decreases dramatically above 60°C. When conditions become unfavorable, bacilli form thick-walled endospores that are highly resistant to heat, cold, and dryness. These spores are ubiquitous in nature and become active whenever environmental conditions are favorable.

At the highest compost temperatures, bacteria of the genus *Thermus* have been isolated. Composters sometimes wonder how microorganisms evolved in nature that can withstand the high temperatures found in active compost. *Thermus* bacteria were first found in hot springs in Yellowstone National Park, and they may have evolved there.[3] Other places where thermophilic conditions exist in nature include deep-sea thermal vents, manure droppings, and accumulations of decomposing vegetation.

Eventually, the compounds that are usable by thermophilic bacteria become depleted. As the activity of the thermophilic bacteria declines, the temperature falls and mesophilic bacteria again predominate. The numbers and types of mesophilic microbes that recolonize compost as it matures depend on what spores and organisms are present in the compost and the immediate environment. As the curing or maturation phase progresses, the diversity of the microbial community gradually increases. Eventually, the available carbon in the compost becomes depleted, and microbial populations once again drop.

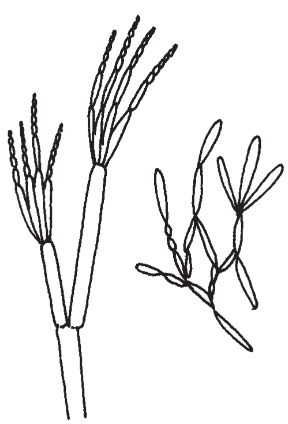
ACTINOMYCETES



The characteristic earthy smell of soil is caused by actinomycetes, a type of bacteria that forms chains or filaments. In composting, actinomycetes play an important role in degrading complex organic molecules such as cellulose, lignin, chitin, and proteins. Although they do not compete well for the simple carbohydrates that are plentiful in the initial stages of composting, their enzymes enable them to chemically break down resistant debris, such as woody stems, bark, and newspaper, that are relatively unavailable to most other forms of bacteria and fungi. Some species of actinomycetes appear during the thermophilic phase, and others become important during the cooler curing phase, when only the most resistant compounds remain. Actinomycetes thrive under warm, well-aerated conditions and neutral or slightly alkaline pH.

Actinomycetes form long, threadlike branched filaments that look like gray spider webs stretching through compost. These filaments are most commonly seen toward the end of the composting process, in the outer 10 to 15 cm of the pile. Sometimes they appear as circular colonies that gradually expand in diameter.

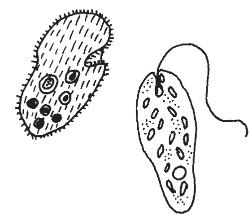
FUNGI



Fungi include molds and yeasts, and they are responsible for the decomposition of many complex plant polymers in soil and compost. In compost, fungi are important because they break down tough debris including cellulose. They can attack organic residues that are too dry, acidic, or low in nitrogen for bacterial decomposition. Most fungi secrete digestive enzymes onto the food, and then they absorb the products of extracellular digestion.

Fungal species are predominantly mesophilic. When temperatures are high, most are confined to the outer layers of compost. Compost molds are strict aerobes. They can be microscopic or appear as gray or white fuzzy colonies that are visible on the compost surface. Some fungi form chains of cells called hyphae that look like threads weaving through the organic matter. The mushrooms that you may find growing on compost are the fruiting bodies of some types of fungi. Each is connected to an extensive network of hyphae that reaches through the compost and aids in decomposition.

Research Possibility: *Composting recipes sometimes call for inoculating the pile by mixing in a few handfuls of finished compost. Is there any observable difference in appearance of microbes between systems that have and have not been so inoculated?*



PROTOZOA

Protozoa are one-celled microscopic organisms. In compost piles, they feed on bacteria and fungi. Protozoa make up only a small proportion of microbial biomass in compost.

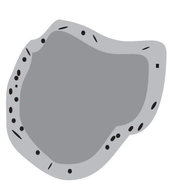
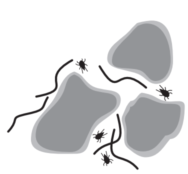
INVERTEBRATES

Composting can occur either with or without the aid of invertebrates. In indoor commercial or industrial composting, invertebrates are often purposely excluded, and the systems are managed to promote thermophilic composting by microorganisms. Invertebrates are not active at the high temperatures that occur in thermophilic composting.

In contrast, compost in outdoor piles or bins provides an ideal habitat for a vast array of invertebrates commonly found in soil and decaying vegetation. Although most of the decomposition still is carried out by microorganisms, invertebrates aid in the process by shredding organic matter and changing its chemical form through digestion. If the compost heats up, the invertebrates may go into a dormant stage or move to the periphery of the pile where the temperatures are cooler.

Scientists use a number of systems for categorizing organisms that live in soil and compost. Different classification schemes provide different "filters" through which we view complex biological communities. The food web is one classification system, based on groups of organisms occupying the same trophic level (see Figure 1–6). Another way to classify compost invertebrates is by size (Figure 1–9). Body length sometimes is used to divide organisms into microfauna (<0.2 mm), mesofauna

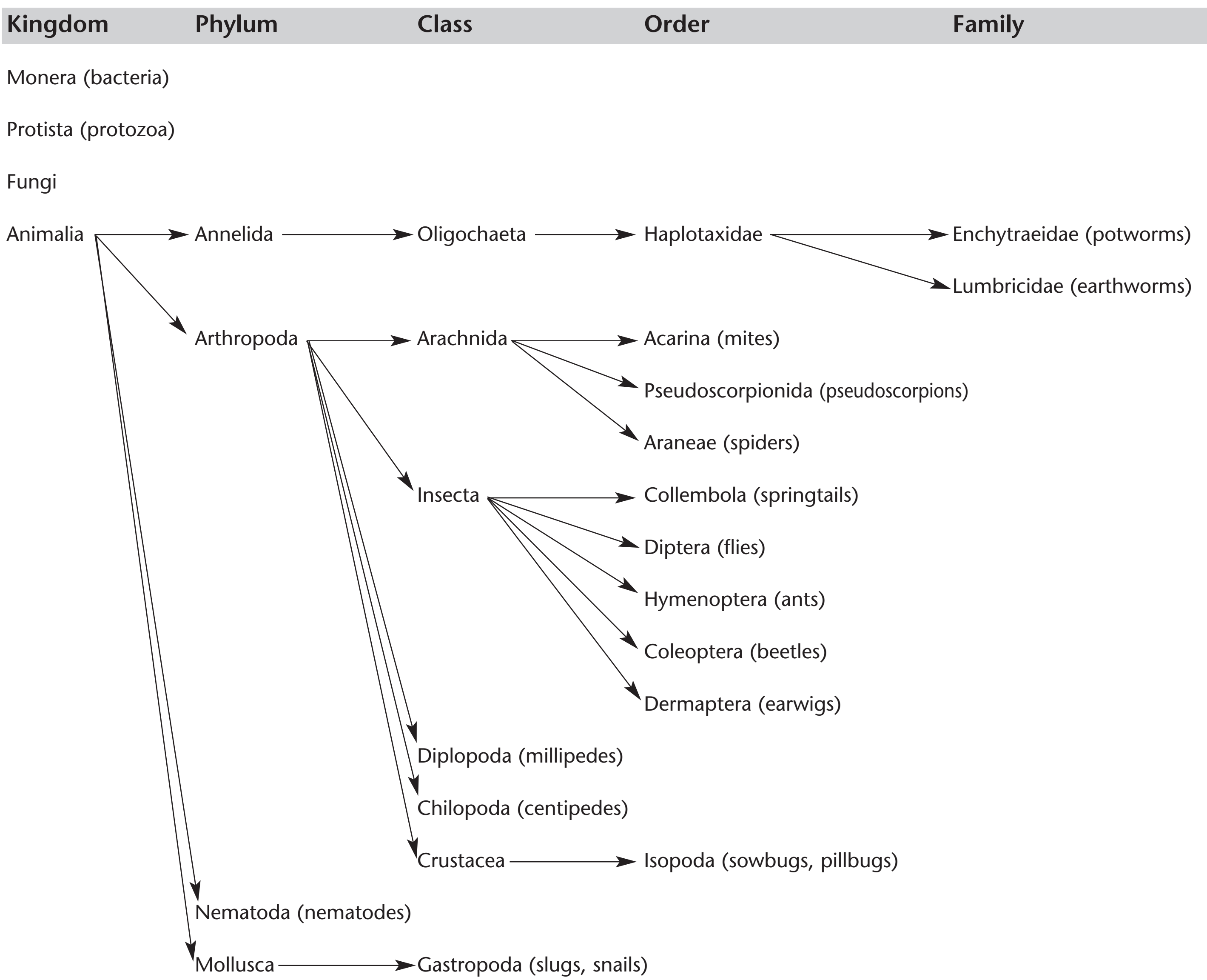
Figure 1–9. Classification of Compost Organisms According to Body Width.

MICROFAUNA live in water films	**MESOFAUNA** live in air spaces	**MACROFAUNA** create space by burrowing
← < 0.1 mm →	← 0.1–2 mm →	← 2–60 mm →
Nematodes Protozoa 	Mites Pseudoscorpions Springtails Potworms Flies 	Earwigs Sowbugs Centipedes Millipedes Earthworms Slugs & Snails 

(0.2–10 mm), and macrofauna (>10 mm). A similar classification scheme is based on body width. Body width is important because it specifies which organisms are small enough to live in the film of water surrounding compost particles, which live in the air-filled pore spaces, and which are large enough to create their own spaces by burrowing.

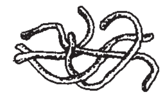
The commonly used taxonomic classification system that divides organisms into kingdom, phylum, class, order, family, genus, and species is based on phylogenic (evolutionary history) relationships among organisms. The following descriptions of common invertebrates found in compost are organized roughly in order of increasing size within the broad phylogenic classifications (Figure 1–10).

Figure 1–10. Phylogenic Classifications of Common Compost Organisms.

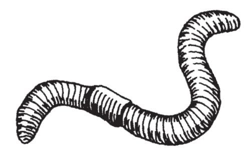


ANNELIDS

OLIGOCHAETES



Potworms (Phylum Annelida, Class Oligochaeta, Order Haplotoxidae, Family Enchytraeidae): Enchytraeids are small (10–25 mm long) segmented worms also known as white worms or potworms. Because they lack hemoglobin, they are white and can thus be distinguished from newly hatched, pink earthworms. Potworms often are found in worm bins and damp compost piles. They feed on mycelia, the thread-like strands produced by fungi. They also eat decomposing vegetation along with its accompanying bacterial populations.

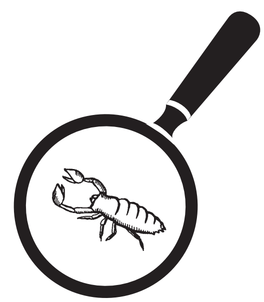


Earthworms (Phylum Annelida, Class Oligochaeta): Because earthworms are key players in vermicomposting, they are described in greater detail later in this chapter (pp. 22–26).

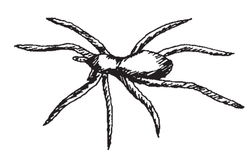
ARTHROPODS

ARACHNIDS

Mites (Phylum Arthropoda, Class Arachnida, Order Acarina): There are over 30,000 species of mites worldwide, living in every conceivable habitat. Some are so specialized that they live only on one other species of organism. Like spiders, they have eight legs. They range in size from microscopic to the size of a pin head. Sometimes mites can be seen holding onto larger invertebrates such as sowbugs, millipedes, or beetles. Mites are extremely numerous in compost, and they are found at all levels of the compost food web (see Figure 1–6). Some are primary consumers that eat organic debris such as leaves and rotten wood. Others are at the secondary level, eating fungi or bacteria that break down organic matter. Still others are predators, preying on nematodes, eggs, insect larvae, springtails, and other mites.



Pseudoscorpions (Phylum Arthropoda, Class Arachnida, Order Pseudoscorpionida): Pseudoscorpions look like tiny scorpions with large claws relative to their body size, but lacking tails and stingers. They range from one to several millimeters in size. Their prey includes nematodes, mites, springtails, and small larvae and worms. Lacking eyes and ears, pseudoscorpions locate their prey by sensing odors or vibrations. They seize victims with their front claws, then inject poison from glands located at the tips of the claws. A good way to find pseudoscorpions is by peeling apart layers of damp leaves in a compost pile.

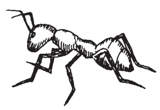


Spiders (Phylum Arthropoda, Class Arachnida, Order Araneae): Spiders feed on insects and other small invertebrates in compost piles.

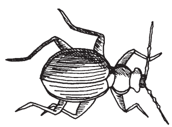
INSECTS

Springtails (Phylum Arthropoda, Class Insecta, Order Collembola): Springtails are small, wingless insects that are numerous in compost. A tiny spring-like lever at the base of the abdomen catapults them into the air when they are disturbed. If you pull apart layers of decaying leaves, you are likely to see springtails hopping or scurrying for cover. They feed primarily on fungi, although some species eat nematodes or detritus.

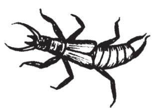
Flies (Phylum Arthropoda, Class Insecta, Order Diptera): Flies spend their larval phase in compost as maggots, which do not survive thermophilic temperatures. Adults are attracted to fresh or rotting food, and they can become a nuisance around worm bins or compost piles if the food scraps are not well covered. Fruit flies and fungus gnats, both of which can become pests in poorly managed compost piles, are in this order.



Ants (Phylum Arthropoda, Class Insecta, Order Hymenoptera): Ants eat a wide range of foods, including fungi, food scraps, other insects, and seeds. Ant colonies often can be found in compost piles during the curing stage.



Beetles (Phylum Arthropoda, Class Insecta, Order Coleoptera): The most common beetles in compost are the rove beetle, ground beetle, and feather-winged beetle. Feather-winged beetles feed on fungal spores, while the larger rove and ground beetles prey on other insects, snails, slugs, and other small animals.



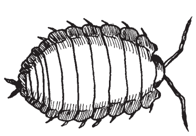
Earwigs (Phylum Arthropoda, Class Insecta, Order Dermaptera): Earwigs are distinguished by jaw-like pincers on the tail end. Some species are predators and others eat detritus. They are usually 2–3 cm long.

OTHER ARTHROPODS

Millipedes (Phylum Arthropoda, Class Diplopoda): Millipedes have long, cylindrical, segmented bodies, with two pairs of legs per segment. They are slow moving and feed mainly on decaying vegetation. Stink glands along the sides of their bodies provide some protection from predators.

Centipedes (Phylum Arthropoda, Class Chilopoda): Centipedes can be distinguished from millipedes by their flattened bodies and single pair of legs per body segment. They are fast-moving predators found mostly in the surface layers of the compost heap. Their formidable claws possess poison glands used for paralyzing small worms, insect larvae, and adult arthropods including insects and spiders.

CRUSTACEANS

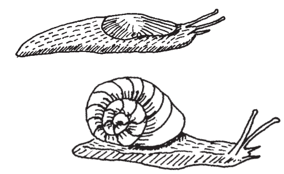


Sowbugs and Pillbugs (Phylum Arthropoda, Class Crustacea, Order Isopoda): Sowbugs, also called isopods, potato bugs, or wood lice, are the only terrestrial crustacean. Because they lack the waxy cuticle common to most insects, they must remain in damp habitats. They move slowly, grazing on decaying wood and resistant tissues such as the veins of leaves. Pillbugs, or rollypolies, are similar to sowbugs, except they roll into a ball when disturbed, whereas sowbugs remain flat.

NEMATODES

Nematodes (Phylum Nematoda): Under a magnifying lens, nematodes, or roundworms, resemble fine human hair. They are cylindrical and often transparent. Nematodes are the most abundant of the invertebrate decomposers—a handful of decaying compost probably contains several million. They live in water-filled pores and in the thin films of water surrounding compost particles. Some species scavenge decaying vegetation, some eat bacteria or fungi, and others prey on protozoa and other nematodes.

MOLLUSKS



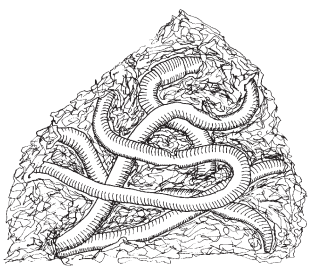
Slugs and Snails (Phylum Mollusca, Class Gastropoda): Some species of slugs and snails eat living plant material, whereas others feed on decaying vegetation. Unlike many other invertebrates, some snails and slugs secrete cellulose-digesting enzymes rather than depending on bacteria to carry out this digestion for them.

EARTHWORMS[4]

It may be doubted whether there are many other animals which have played so important a part in the history of the world, as have these lowly organized creatures.

Charles Darwin 1881[5]

If your only encounter with earthworms has been those shriveled-up specimens that didn't make it back to the grass after a rainstorm, you may not have the same appreciation for these lowly creatures that Charles Darwin did. But if you are a backyard or worm composter, you might have become fascinated by these burrowing invertebrates, and even have some questions about their role in the compost pile. What are they actually eating, and what comes out the other end? Are worm castings finished compost, or do they get broken down further? How do worms interact with compost microbes during decomposition? Can worm compost enhance the growth of plants?



To answer these questions, it is important to understand that if you've seen one worm, you definitely haven't seen them all. When aquatic forms are included, there are about 3,000 species of earthworms or members of the class Oligochaeta worldwide. Among these species, there is great variety in size, ranging from 10 mm–1.2 m in length and 10 mg–600 g in weight. Earthworms also exhibit diverse eating habits and ecological and behavioral characteristics. Thus, the answers to the above questions are complicated; what is true for one species is not necessarily true for another. Furthermore, because scientific research has been limited to only about 5% of the total number of worm species, we do not know the answers to many questions for most species of worms.

The information presented below is a synthesis based on many scientific experiments, though there could be exceptions to some of the generalizations for any one species. We also include information specific to the Lumbricidae, which is one of the most important earthworm families in terms of human welfare, and to one of its members, *Eisenia fetida*, the species most commonly used in vermicomposting.

EARTHWORM FEEDING AND DECOMPOSITION

Scientists have used several methods to determine the role of worms and other invertebrates in decomposition. In one experiment, organic materials of known weight were placed in mesh bags with different-size holes. The bags were then buried in soil. Several months to a year later, the scientists dug out the bags and determined the dry weight of the remaining organic material. It turned out that more decomposition had occurred in bags with holes large enough for earthworms than in those that allowed only smaller invertebrates access to the organic materials.

Through these and similar experiments, researchers have determined that much organic matter, particularly the tougher plant leaves, stems, and root material, breaks down more readily after being eaten by soil invertebrates. And, of all the invertebrates who play a role in the initial stage of organic matter decomposition, earthworms are probably the most important.

Research Possibility: *Do organic wastes in compost break down more readily in the presence of worms than through composting that depends solely on microbial decomposition?*

Worms that are active in compost are detritivores, feeding primarily on relatively undecomposed plant material. Some species live and feed in the upper organic or litter layer of soil. *Eisenia fetida*, the species most commonly used for vermicomposting, is one example of this type of worm. Other species live in deep soil burrows and come to the surface to feed on plant residues in the litter layer. By pulling leaves and other food down into their burrows, they mix large amounts of organic matter into the soil. *Lumbricus terrestris*, a worm commonly seen in North American gardens, is typical of this group. A third type of worm is not commonly seen in gardens or compost piles because it burrows deep beneath the surface and ingests large quantities of soil containing more highly decomposed plant material.

Anyone who has ever observed earthworm castings will recognize that they contain organic particles that are reduced in size relative to the leaves or other organic matter that the worms ingest. Organic matter passing through a worm gut is transformed chemically as well as physically. However, most worms are able to digest only simple organic compounds such as sugars. A few species, including *Eisenia fetida*, apparently are able to digest cellulose. No species has been found that breaks down lignin.

Worms both influence and depend on microbial populations in soil and compost. They feed on soil microorganisms, including fungi, bacteria, protozoa, amoebae, and nematodes. These organisms are probably a major source of nutrients for worms. Preferential feeding on different microorganisms may alter the microbial populations in soil or compost. Worms have also developed a symbiotic relationship with microbes inhabiting their digestive tract. The mucus found in the worm's intestine provides a favorable substrate for microorganisms, which in turn decompose complex organic compounds into simpler substances that are digestible by the worm. Some of the worm's mucus is excreted along with the casts, and it continues to stimulate microbial growth and activity in the soil or compost. The high levels of ammonia and partially decomposed organic matter in casts provide a favorable substrate for microbial growth. Thus, fresh worm casts generally have high levels of microbial activity and high decomposition rates. This activity decreases rapidly over a period of several weeks as degradable organic matter becomes depleted.

Research Possibility: *How do respiration rates, a measure of microbial and invertebrate activity, vary in worm compost and other composts over time? How do chemical and physical properties differ between worm and other composts?*

WORMS AND PLANT GROWTH

Nutrients are transformed during their passage through the worm gut into forms more readily available to plants, such as nitrate, ammonium, biologically available phosphorus, and soluble potassium, calcium, and magnesium. Because of these and other changes in soil and organic matter chemistry, physical properties, and biology brought about by worms, plants generally grow faster in soils with worms than in soils without them. Furthermore, studies have shown that extracts from worm tissues enhance plant growth.

Research Possibility: *Much of the research on vermicompost and plant growth has been conducted with worms grown on sewage sludge. Does worm compost produced from other organic materials enhance plant growth? How do vermicomposts produced from various organic materials differ in terms of nutrient content? How do vermicomposts compare to composts produced by microbial activity alone? To composts that have a diversity of soil invertebrates?*

Vermicompost is a finely divided material that has the appearance and many of the characteristics of peat. In some studies, it has been shown to enhance soil structure, porosity, aeration, drainage, and moisture-holding capacity. Its nutrient content varies depending on the original organic materials. However, when compared with a commercial plant-growth medium to which inorganic nutrients have been added, vermicompost usually contains higher levels of most mineral elements, with the exception of magnesium. It has a pH of about 7.0, and because most plants prefer slightly acidic conditions, vermicompost should be acidified or mixed with a more acid material such as peat, prior to use as a growth medium. Another adjustment sometimes made when using vermicompost for plant growth is to add magnesium. Because vermicomposting does not achieve high temperatures, sometimes a thermophilic stage is used prior to adding worms to kill insects and pathogens.

Research Possibility: *In some experiments, plants did not show increased growth when planted in fresh worm castings. Does aging or "curing" worm castings increase their ability to enhance plant growth? Are there chemical differences between fresh and older worm castings? Should worm compost be mixed with soil before being used to grow plants?*

Research Possibility: *In China, farmers dig parallel trenches and fill them with organic wastes mixed with cocoons of* Eisenia fetida. *Soybeans planted in rows between the trenches are highly productive. Can you design and test a planting system using vermicompost?*

EARTHWORMS AND WATER

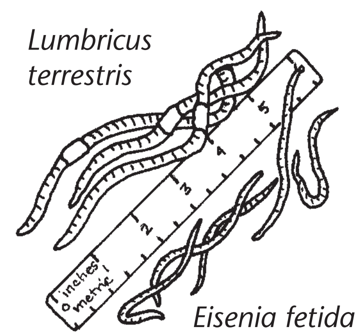
Earthworms require large amounts of water, which they ingest with food and absorb through their body walls. The water is used to maintain a moist body surface that aids the worm's movement through soil and protects it against toxic substances. A moist body surface is also necessary because worms obtain oxygen by absorption in solution through their cuticle. A soil moisture content of 80–90% by weight is considered optimal for *Eisenia fetida*. Many worms, including *Lumbricus terrestris*, can tolerate poorly ventilated soils because of the high affinity of their hemoglobin for oxygen. However, under saturated soil conditions, worms will come to the surface, sometimes migrating considerable distances. It is unknown whether low oxygen levels or chemicals in soil solution cause this behavior.

Because most water uptake and loss occurs through the thin permeable cuticle, worms are at constant risk of dehydration. Although worms have no shell or waxy cuticle to maintain body moisture, they can survive low moisture conditions. Some species migrate to deeper soil levels when surface soil dries out.

LUMBRICIDAE

The family Lumbricidae is the dominant family of worms in Europe. As European agricultural practices spread throughout much of the world, so did Lumbricid worms. These worms were able to successfully colonize new soils and became dominant, often replacing endemic worm species. They are now the dominant family in most temperate, crop-growing regions around the world, including North America.

Lumbricus terrestris is one of the most common earthworms in northern North America. It lives in a wide range of habitats, including grasslands, agricultural fields, gardens, and forests. It feeds on leaves and other plant materials, dragging them into its burrows in the soil.



Eisenia fetida is the favored species for use in vermicomposting. It is particularly well suited to composting because it is extremely prolific, thrives in high organic matter habitats, can tolerate a wide range of temperatures and moisture conditions, and can be readily handled. Its natural habitat is probably under the bark of dead tree trunks, but it is most commonly found in animal dung, compost, and other accumulations of decaying plant material. Originally from Europe, it has become established throughout much of the world.

Just how prolific is *Eisenia fetida*? When it is given high-energy and nitrogen-rich food (such as horse manure or activated sewage sludge—yum!), adequate moisture, and optimum temperatures (25°C), cocoon production in *Eisenia fetida* starts 35 days after the worms hatch, and it reaches its maximum at 70 days. The cocoons, each carrying one to six eggs, are produced in the clitellum, or swollen region along the worm's body. Between three and four cocoons are produced each week. Nineteen days later, the young worms or hatchlings emerge and the process begins again. Thus, under "luxury" conditions, a population of *Eisenia fetida* can have four generations and produce 100 times its own weight in one year. Low food quality, overcrowding, or suboptimal temperatures or moisture levels reduce these reproductive rates. For example, growth is 24 times faster at 25°C than at 10°C, and temperatures below 0°C and over 35°C are considered lethal.

***Research Possibility:** How do different food sources affect reproductive and growth rates of* Eisenia fetida*?*

Cocoons of *Eisenia fetida* may survive dryness and possibly other adverse conditions for several years and then hatch when favorable conditions return. In compost piles, adults may move from areas of less favorable conditions to areas with conditions conducive to their growth. For example, in winter months, they may migrate to the warm center of a large outdoor pile. Perhaps through these “mini-migrations” or through cocoon survival, *Eisenia fetida* are able to survive winters in regions where temperatures dip well below those that are lethal in the laboratory.

Research Possibility: Eisenia fetida *does best in wastes with pH between 5.0 and 8.0. How sensitive are cocoons to pH? Will they hatch after being exposed to extreme pH? How sensitive are they to extreme drought or temperatures?*

Does the use of *Eisenia fetida* in composting serve to further spread this exotic species, possibly interfering with native earthworm populations? To answer this question, it is useful to consider the fact that populations of earthworms are already much altered throughout the globe. In North America, for example, there are 147 species of worms, 45 of which were probably introduced. In fact, when Europeans first arrived in formerly glaciated parts of North America, they claimed there were no earthworms present. (It is assumed that earthworms in northern North America were wiped out during glaciation.) Thus, the species that are currently in these regions were either introduced in soil from imported plants or spread northward from southern regions of North America. *Eisenia fetida* is thought to have been introduced to North America in organic soils brought in with imported plants. Because it is adapted to compost and other organic substrates, it is unlikely to spread into neighboring soils and compete with soil-inhabiting worms.

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[1] Kayhanian, M. and G. Tchobanoglous. 1992. Computation of C/N ratios for various organic fractions. *BioCycle* 33(5): 58–60.

[2] Michel, F. C., Jr., L. J. Forney, A. J.-F. Huang, S. Drew, M. Czuprenski, J. D. Lindeberg, and C. A. Reddy. 1996. Effects of turning frequency, leaves to grass mix ratio and windrow vs. pile configuration on the composting of yard trimmings. *Compost Science & Utilization* 4: 26–43.

[3] F. C. Michel, Jr., NSF Center for Microbial Ecology, Michigan State University (personal communication).

[4] The information on earthworms was compiled from the following sources:

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Lee, K. E. 1985. *Earthworms: Their Ecology and Relationships with Soils and Land Use*. Academic Press, Australia.

[5] Darwin, C. 1881. *The Formation of Vegetable Mould Through the Action of Worms With Observations on Their Habits*. Currently published by Bookworm Publishing Co., Ontario, CA.