READING LIST
FOR

"Soil Food Web Interactions and Benefits to Plant Production"

Southern Cross University, Lismore campus, NSW, Australia.
July 9 – July 20, 2007.

Essential Reading

Ingham, RE., *et al* (1985). Interactions of bacteria, fungi and their nematode grazers: Effects on nutrient cycling and plant growth. *Ecological Monographs* 55: 119-140.

Ingham, ER., *et al* (1986). Trophic interactions and nitrogen cycling in a semiarid grassland soil. Part I. Seasonal dynamics of the natural populations, their interactions and effects on nitrogen cycling. *J. Applied Ecology* 23: 597-614.

Ingham, ER., *et al* (1986). Trophic interactions and nitrogen cycling in a semiarid grassland soil. Part II. System responses to removal of different groups of soil microbes or fauna. *J. Applied Ecology* 23: 615-630.

Background/Reference Material

Ingham, ER. (1999). Soil Biology Primer. USDA

Lines-Kelly, R *et al* (2000). Soil Sense: Soil Management for NSW North Coast Farmers. 2nd Edition. Wollongbar Agriculture Institute.

Lines-Kelly, R (2001). Soil Health – The foundation of sustainable agriculture. Wollongbar Agriculture Institute.

Sylvia, DM., *et al* (1995). Principles and Applications of Soil Microbiology. Prentice Hall. The first two chapters are supplied.

Also recommended, but not supplied

Dindal. (1993). Soil Biology Guide. Wiley Interscience.

Principles and Applications of Soil Microbiology

♦

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Chapter 1

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Introduction and Historical Perspective

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Society has its roots in the soil.
Charles Kellogg

Soil microbiology is a branch of soil science concerned with microorganisms found in the soil and their relationship to soil management, agricultural production, and environmental quality. Hence, the soil microbiologist studies the numbers and kinds of microorganisms found in soil and the effect of these and introduced microorganisms on soil-ecological processes (e.g., nutrient cycling). The applications of these studies have important consequences for crop production, environmental quality, and the restoration of compromised environments.

The Soil Habitat

The soil is a complex habitat for microbial growth. It differs markedly from the environment microorganisms encounter in traditional microbiological culture media in two crucial ways:

- In its natural state, the soil is a heterogeneous medium of solid, liquid, and gaseous phases, varying in its properties, both across the landscape and in depth.
- In soil, **competition** exists among a wide variety of organisms for nutrients, space, and moisture. Competition occurs among bacteria, actinomycetes, and fungi, as well as with other living forms in soil, including animals and plant roots.

If we are to understand soil microorganisms, then developing a knowledge of the habitat in which they grow is of utmost importance.

The Nature of Cellular Organisms

The basis of living matter is the cell. Each cell is a unique entity made up of a complex mixture of chemical materials and subcellular components. The cell is bounded by the **cytoplasmic membrane,** separating the interior of the cell, known as the **cytoplasm,** from the external environment.

Box 1–1

Characteristics of Living Cells. Madigan et al. (1997) recognize five key characteristics that separate living cells from nonliving chemical systems:

- *Self-feeding or nutrition:* The capacity to take up and use chemicals from the environment and transform these chemicals into usable products, including energy to grow or survive.
- *Self-replicating or growth:* The capacity to self-direct synthesis, growing by division, forming two cells from one.
- *Differentiation:* The capacity to undergo change in form or function, often in response to environmental changes or normal growth processes.
- *Chemical signaling:* The capacity to interact with other cells through chemical signals.
- *Evolution:* The capacity to change genetically, which may affect the overall fitness of the cell to survive in a particular environment.

Two fundamental types of living cells are recognized: **prokaryote** (from *pro,* meaning "before," and *karyon,* meaning "nucleus") and **eukaryote** (from *eu,* meaning "true"). Major structural differences exist between the two types of cells. The nucleus of the eukaryote is in the cytoplasm, bounded by a nuclear membrane and containing several DNA molecules. The eukaryote undergoes division by the well-known process of mitosis. The prokaryote has no nucleus; a nuclear region is recognized, but it is not bounded by a membrane and consists of a single, circular DNA molecule (chromosome). Cell division in the prokaryote is usually by binary division (i.e., nonmitotic). Additional differences between prokaryotic and eukaryotic cells are presented in Table 1–1. **Bacteria** (including cyanobacteria and actinomycetes) and **Archaea** are prokaryotes, while all other organisms are eukaryotes.

Classification of Organisms

The study and use of microorganisms is based on our ability to recognize and establish the identity of individuals. Most classification schemes are organized to show relationships among organisms. This orderly arrangement allows us to communicate descriptive information about the organism to others. These data can also be entered into various microbial databases, allowing retrieval of information about related organisms.

Table 1–1 **A structural comparison of prokaryotic and eukaryotic cells.**

Organelle	Prokaryotes Bacteria & Archaea	Eukaryotes Fungi	Algae	Protozoa
Cytoplasmic membrane	+	+	+	+
Nuclear division	+	+	+	+
Nuclear membrane	−	+	+	+
Ribosomes	70S	80S	80S	80S*
Endoplasmic reticulum	−	+	+	+
Golgi complexes	−	+	+	+
Mitochondria	−	+	+	+
Cytosketeton	−	+	+	+
Chloroplasts	−	−	+	−
Vacuole	−	+	+	+
Cell wall	+	+	+	+

*S = Svedberg unit

Microbiologists use the Linnean system of **binomial nomenclature** to name the microorganisms with which they work. An organism's name is made up of genus and species. In higher organisms, species are defined as groups of interbreeding or potentially interbreeding natural populations; however, many microorganisms do not reproduce sexually so this definition is not very useful. Microbiologists define **species** as a group of *similar* individuals that are sufficiently *different* from other individuals to be considered a recognized taxonomic group. A collection of species that share a major property (or properties), making them a distinct grouping, permits the group to be considered a **genus** (plural, genera). Hence, the Latin binomial name, *Thiobacillus thiooxidans* (abbreviated *T. thiooxidans* after it is used the first time in the text) is representative of a group of individuals (species: *thiooxidans*) that have the capacity to oxidize sulfur and share some common characteristics with other organisms in the genus *Thiobacillus*. Often microorganisms are named for an outstanding feature they possess (e.g., *T. thiooxidans;* a rod-shaped bacterium capable of oxidizing reduced sulfur for the generation of energy). In other cases organisms are named to commemorate the contributions of an outstanding scientist in the field (e.g., *Nitrobacter winogradskyi,* named in honor of the Russian soil microbiologist Sergei Winogradsky).

Historically, microorganisms were classified on the basis of taxonomic features, which were relatively easy to measure. These characters include structure, morphology, staining reactions, and physiological parameters (e.g., ability to use a particular carbohydrate). However, these features are **phenotypic** (based on physical characteristics) rather than **phylogenetic** (based on genetic relationships) and may obscure important relationships among related groups of organisms.

The technology of molecular sequencing has introduced a totally new way of determining relationships among organisms. Phylogenetic "trees," showing relationships among organisms, are constructed directly from comparisons of informational macromolecules, such as ribosomal RNA (rRNA) genes, occurring in living cells. The traditional classification scheme recognized five kingdoms of organisms: bacteria, fungi, protista (including algae and protozoa), animals, and plants. However, molecular phylogeny shows that there are three **domains** of living organisms: **Bacteria, Archaea**

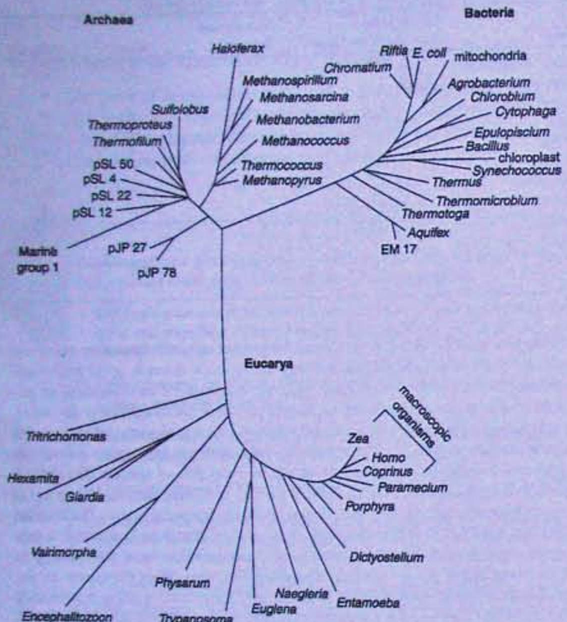


Figure 1–1 Universal phylogenetic tree for living organisms, based on comparative sequencing of 16s or 18s ribosomal RNA. Note that microorganisms comprise most of the biological diversity found on earth. *From Pace (1996). Used with permission.*

and **Eucarya** (Fig. 1–1; Woese et al., 1990). Although the placement of organisms into three domains was defined by differences within the rRNA gene, subsequent studies reveal that organisms in these domains also differ in cell wall properties, lipid composition, and protein synthesis. Below the three domains, eight or more kingdoms have been recognized. Our new understanding of the universal tree of life contradicts several long-held beliefs (Pace, 1996). For example:

- The deep divergence between Archaea and Bacteria shatters the notion of evolutionary unity among prokaryotes.
- It appears that the Eucarya line is as old as the prokaryotic lines.

- Most genetic diversity is microbial. Indeed, from the standpoint of rRNA variation, the multicellular life forms are relatively minor twigs at the tip of the eucaryal branch.

In these classification schemes there is no place for **viruses.** Viruses are not cells because they lack a cytoplasmic membrane with internal cytoplasm. Only when viruses are associated with another organism (e.g., bacterium, plant, animal) are they able to fulfill the basic life processes as stated in Box 1–1.

Organisms in the Soil

Organisms in the soil are both numerous and diverse. Many soil organisms are small and cannot be seen without the aid of magnification (Table 1–2). The smallest organisms—bacteria, actinomycetes, fungi, and algae—are referred to collectively as the **microflora.** Soil animals range in size from microscopic (**microfauna**) to earthworms and small mammals (**macrofauna**). With the exception of some soil animals and fungi, most soil organisms are single cells. Chapters 3 to 7 of this book describe the microorganisms present in soil.

Bacteria are the most abundant microorganisms in soil, attaining populations in excess of one hundred million (10^8) individuals per gram (g^{-1}) of soil and representing perhaps as many as 10^4 to 10^6 different species. The actinomycetes and fungi are the next most numerous microorganisms in soil, numbering 10^6 to 10^7 and 10^4 to 10^6 g^{-1} soil, respectively. Numbers of soil animals vary widely in the soil, ranging from just a few to as many as 10^6 g^{-1} soil. It is important to note, however, that we must consider more than the number of individuals in a gram of soil if we are to understand microbial function in soil. Microorganisms have a wide range of sizes and morphologies; thus, numbers alone may not provide a very good indication of the importance of a microbial group in the soil. For example, even though bacterial numbers are usually several orders of magnitude greater than fungi, the fungi generally have a greater total biomass in the soil (Table 1–2).

The relative position and size of soil microorganisms within the soil habitat is illustrated in Figure 1–2. The physical, chemical, and even biological properties of the soil habitat and their interactions with the resident community of soil

***Table 1–2* Microbial groups with representative size, numbers,† and biomass† found in soil.**

Microbial group	Example	Size (μm)	Numbers (no. g^{-1} of soil)	Biomass (kg wet mass ha^{-1} of soil)
Viruses	Tobacco mosaic	0.02 × 0.3	$10^{10} - 10^{11}$	
Bacteria	*Pseudomonas*	0.5 × 1.5	$10^8 - 10^9$	300 – 3,000
Actinomycetes	*Streptomyces*	0.5 – 2.0‡	$10^7 - 10^8$	300 – 3,000
Fungi	*Mucor*	8.0‡	$10^5 - 10^6$	500 – 5,000
Algae	*Chlorella*	5 × 13	$10^3 - 10^6$	10 – 1,500
Protozoa	*Euglena*	15 × 50	$10^3 - 10^5$	5 – 200
Nematodes	*Pratylenchus*	1,000§	$10^1 - 10^2$	1 – 100
Earthworms	*Lumbricus*	100,000§		10 – 1,000

†Data from Metting (1993).
‡diameter of hyphae
§length

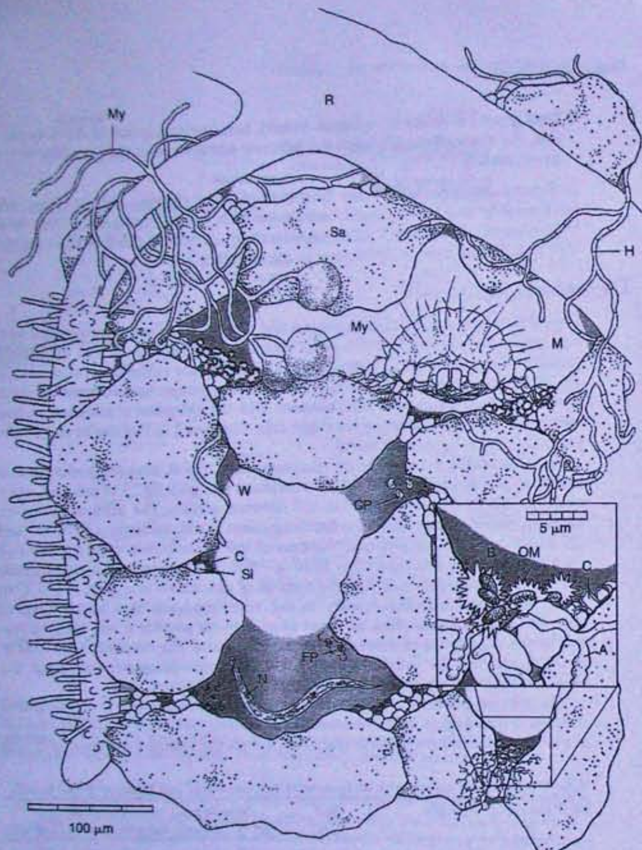


Figure 1–2 A soil habitat containing mineral soil particles (sand-Sa, silt-Si, and clay-C), organic matter (OM), water (W), plant root with root hairs (R), and soil organisms (bacteria-B, actinomycetes-A, mycorrhizal spores and hyphae-My, hyphae of a saprophytic fungus-H, a nematode-N, ciliate protozoa-CP, flagellate protozoa-FP, and a mite-M. This soil can be a habitat of enormous complexity and diversity even over small distances. For example, the actual size of the soil in this drawing is < 1 mm in both directions yet may contain habitats that are acid to basic, wet to dry, aerobic to anaerobic, reduced to oxidized, and nutrient-poor to nutrient-rich. Realizing this complexity and diversity is the key to understanding soil microbiology. *Original drawing by Kim Luoma.*

Box 1–2

Scientific Notation. For convenience, soil microbiologists express the numbers of microorganisms in soil in an exponential manner, a convention known as scientific notation. Two million organisms per gram of soil is written, $2 \times 10^6 \text{ g}^{-1}$. The same number can also be expressed as a logarithmic number, $\log_{10} 6.30 \text{ g}^{-1}$.

microorganisms have a significant impact on growth and activity of microorganisms. As our understanding of these complex relationships develops, we should be better able to manage the soil and its microorganisms for the maintenance and improvement of soil without damaging the soil as a resource.

Microorganisms have an enormous diversity of functions in the soil. For example microorganisms decompose organic compounds releasing inorganic elements, oxidize reduced forms of elements (e.g., elemental sulfur → sulfate) (Chapters 11, 12, 15, and 16), and reduce oxidized forms of elements (e.g., nitrate → dinitrogen) (Chapters 11, 12, 15, and 16). Also the reduction of dinitrogen to a biologically usable form, ammonia (Chapters 13 and 14), or degradation of organic wastes and pollutants to carbon dioxide and water (Chapters 20, 21, and 22) are important functions of soil microorganisms. Interactions among different organisms, including plant roots, can lead to benefits for some participating organisms, while others have a detrimental effect on growth or development (Chapters 17, 18, and 19). Other microorganisms may alter levels of global gases (Chapter 23). In the second and third sections of this book we explore all these functions.

The Historical Context of Soil Microbiology

The development of soil microbiology is inextricably linked with the development of microbiology as a science and cannot be understood in isolation. Here we highlight significant accomplishments before 1950 that led to the development of both microbiology and soil microbiology (Table 1–3). After 1950 the list of those making significant contributions becomes too long to mention individual accomplishments; thus the contributions are considered more generally.

Pre-Nineteenth Century

The first historical mention of the presence of microscopic organisms in soil is attributed to a Roman writer in about 60 B.C. (Waksman, 1927). Writing about marshes, Columella noted they gave up "noxious and poisonous steams," breeding "animals armed with poisonous stings," from which "hidden diseases are often contracted, the causes of which even physicians cannot properly understand." Even prior to that time, there are reports in the Old Testament of people who practiced strict isolation and cleanliness codes, particularly to those afflicted with leprosy, suggesting they understood that disease had some relationship to an unseen cause. Likewise, there is good evidence that the Romans recognized that leguminous plants enriched for soil productivity and practiced crop rotations with leguminous plants. However, no one really understood the involvement of microscopic organisms in these phenomena.

Although Robert Hooke reported on the fruiting structures of molds in 1664, we most often think of the Dutch microscope builder, Anton van Leeuwenhoek—with his newly constructed microscope—as the first individual to describe microorganisms

Table 1–3 **Some of the outstanding individuals contributing to the development of soil microbiology.**

Name	Country	Area of contribution
Leeuwenhoek	Netherlands	Inventor of the microscope
Pasteur	France	Repudiation of spontaneous generation, biological nature of nitrification
Tyndall	England	Repudiation of spontaneous generation, understanding of sterilization processes
Cohn	Germany	Understanding of sterilization processes and taxonomy of *Bacillus* (particularly the endospore)
Koch	Germany	Koch's Postulates, gelatin plates for studying soil microorganisms
Winogradsky	Russia	Isolation and taxonomy of chemoautotrophic bacteria, especially nitrifiers and sulfur oxidizers
Beijerinck	Netherlands	Isolation of legume root nodulating bacteria, Director of The Delft School of Microbiology
Gram	Denmark	Differential staining procedures
Lipman	USA	Concept of soil as a complex, living entity
Russell	England	Development of importance of soil-plant-microorganism interactions in agriculture and the environment
Starkey	USA	Microbiology of the sulfur bacteria
Waksman	USA (Russia)	Discovery of antibiotics from actinomycetes

(Madigan et al., 1997). In his paper to the Royal Society of London in 1684, van Leeuwenhoek reported the presence of "wee animalcules" in pond water. These observations were confirmed by others, but little was known about these organisms and their relation to the environment in which they grew.

The Nineteenth Century

During the nineteenth century, two important questions were answered that would lay the scientific foundations for both microbiology and soil microbiology:

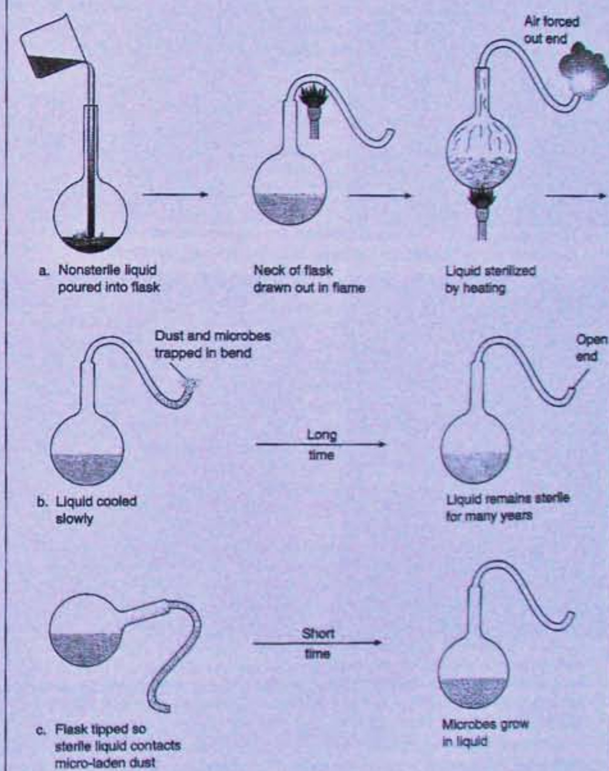
- Does spontaneous generation occur?
- What is the origin of contagious disease?

The eminent French scientist, Louis Pasteur, in a simple and elegant experiment (Box 1–3), demonstrated that it was microorganisms present in the air that were capable of initiating growth in an exposed sterile culture medium. Microbes simply did not arise spontaneously in a suitable medium.

Pasteur's simple experiment effectively settled the controversy surrounding the prominently held theory of **spontaneous generation,** vigorously debated at the time. Similar experiments were also conducted by Spallanzani, the Italian scientist, and the Englishman John Tyndall. Tyndall's original flasks can still be viewed at the Royal Institute near Piccadilly Square in London. The rejection of the theory of spontaneous generation provided the foundations for **aseptic (sterile) technique.** While conducting his experiments, Tyndall also noted difficulties in trying to sterilize

Box 1–3

Pasteur's Experiment Disproving Spontaneous Generation. (a) Pasteur introduced a nonsterile broth into each of two flasks, drew out the flask to a swan-necked shape to provide a dust trap, and sterilized the contents of each by heating. The broth in one flask (b) was not allowed to contact the dust that settled in the trap, and no growth occurred even after a long incubation. After the broth had cooled in the second flask (c) it was brought into contact with dust collecting at the low point near the mouth of the swan neck. After a short period of incubation, the broth became turbid, indicating that growth had occurred in this flask.



From Madigan et al. (1997). Used with permission.

preparations from hay infusions. Further investigations by Tyndall, and also by Ferdinand Cohn of Germany, led to the discovery of organisms that were producing **endospores** in these difficult-to-sterilize preparations.

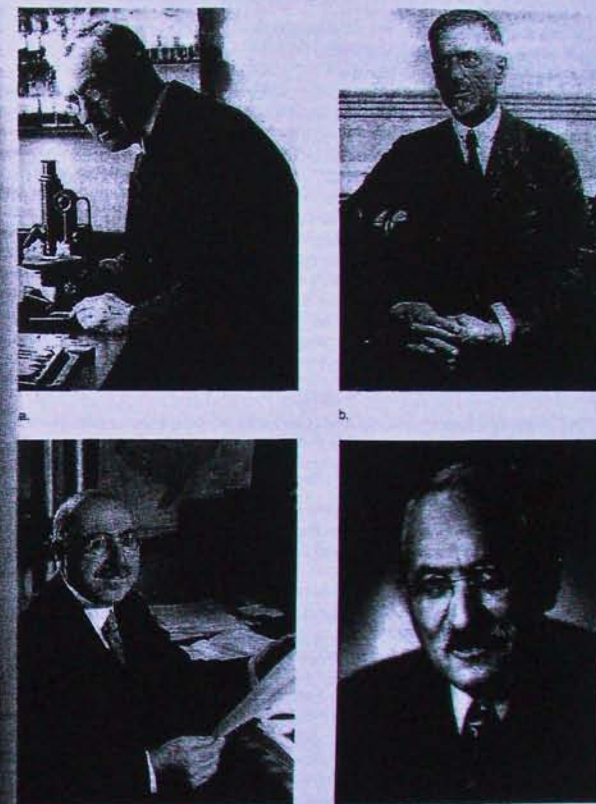
During this same period, there was a widely-held belief that disease was caused by something called "contagion." After microorganisms were discovered, they were accepted as the responsible agents, but rigorous proof was lacking. Although Ignaz Semmelweis and Joseph Lister (after whom the product Listerine was named) provided evidence that microorganisms caused human disease, it was not until the seminal work of Robert Koch that the **germ theory of disease** had a solid scientific basis. Koch reasoned that to prove that a microorganism was the causative agent of a disease, the following should apply:

- The organism should be consistently present in the subject exhibiting the disease symptoms, but not in the healthy subject.
- The organism should be grown in pure culture away from the subject.
- When the organism is used to inoculate a healthy susceptible subject, the disease symptoms should appear.
- The organism should be reisolated from the exposed subject and recultured in the laboratory to confirm its similarity with the original organism.

This series of steps became known as **Koch's Postulates,** which are important for several reasons. First, by following these steps, it is possible to demonstrate that a specific organism is responsible for a specific disease or for some microbiological process (e.g., sulfur oxidation). Second, they suggest the importance of the laboratory culture of organisms, and third, they recognized that specific organisms have specific functions. Acceptance of Koch's Postulates brought the science of microbiology to the point that others could now make specific contributions in more applied fields, such as soil microbiology. Another of Koch's significant developments, reported in 1881, was the use of a gelatin culture medium to study microorganisms *in vitro*. Five years later the Danish physician Christian Gram described a staining procedure based on differential properties of cell walls, leading to important taxonomic decisions. Now soil microorganisms could be studied in a systematic fashion (Waksman, 1927).

In the few remaining years until the turn of the century, significant developments in soil microbiology came in rapid succession. One notable advance was the discovery of biological **dinitrogen fixation** (Chapters 13 and 14). In 1886, Hellriegel and Wilfarth showed that microbial activity in nodules on leguminous plants was able to convert atmospheric nitrogen to a form a plant could use. Subsequently, the Dutch scientist Martinus W. Beijerinck (pronunciation: "buy-a-rink," Fig. 1–3a) isolated the microorganism responsible for nodulation of leguminous plants and named it *Bacillus radicicola* (Chung and Ferris, 1996). In 1889 Frank renamed the bacterium *Rhizobium*, replacing the genus name used by Beijerinck. These actions set in motion a wave of activity in the study of biological nitrogen fixation, which continues to this day.

A second important advance during this period was the discovery of **chemoautotrophy** (Chapter 10) through the study of **nitrification** (Chapter 12). Building on the foundational work of Koch (i.e., that specific organisms have specific effects),



a. b. c. d.

Figure 1–3 Several important individuals in the development of soil microbiology. (a) Martinus Beijerinck, (b) Sergei Winogradsky, (c) Jacob Lipman, and (d) Selman Waksman. *Figures a, b, and d are courtesy of the Waksman Institute at Rutgers University. Figure c is from the American Society of Microbiology Archives.*

Sergei Winogradsky (Fig. 1–3b) began studying the nitrifying bacteria. He was able to demonstrate that nitrification was really a two-step process, the first being the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and the second being the oxidation of NO_2^- to nitrate (NO_3^-). These two steps were mediated by two distinctly different bacteria. Winogradsky isolated representatives of each group and named them, *Nitrosomonas* for the NH_4^+ oxidizers and *Nitrobacter* for the NO_2^- oxidizers. Given the meager understanding of bacterial metabolism at that time, this was a truly remarkable discovery. For these and many other ground-breaking accomplishments, Winogradsky is considered by many to be the Father of Soil Microbiology.

By 1895 developments in microbiology had reached such a point that the Delft School of Microbiology in the Netherlands was established. First headed by Beijerinck—considered by some to be the Father of Microbial Ecology—and then by A. J. Kluyver and C. B. van Niel, the Delft School had a lasting influence on the study of soil microbiology through discoveries in microbial biochemistry, biodiversity, and biotechnology. These individuals posed the following basic questions about microbial physiology that drew the study of microbiology and the environment closer together:

- How does the intact organism interact with its abiotic and biotic environment?
- How can the fundamental principles of microbiology be brought to bear on applied problems?
- What is the place of microorganisms in the natural world?

These questions are as valid now as they were in the nineteenth century. Certainly the ubiquity and diversity of physiological function of microorganisms in the environment is underscored by *Beijerinck's Rule*: "Everything is everywhere and the milieu selects."

The Twentieth Century

If Winogradsky is considered the Father of Soil Microbiology, then Jacob G. Lipman (Fig. 1–3c) is the founder of American soil microbiology. He considered soil as a complex and living entity which needed to be understood and studied from the standpoint of soil fertility and crop production. This revolutionary concept stands as a milestone in soil microbiology (Clark, 1977) and has been carried across the United States and throughout the world.

Two seminal works on soil microbiology were published in the early 1900s: *Handbuch der landwirtschaftlichen Bakteriologie* (Handbook of Agricultural Bacteriology), a comprehensive treatise on soil bacteriology by F. Löhnis, and *Bacteria in Relation to Country Life* by Lipman. Although these works emphasized the role of bacteria in soil fertility, they also directed attention to other organisms residing in soil, including fungi, actinomycetes, algae, protozoa, nematodes, and insect larvae. Sir John Russell, Director of the Rothamsted Experiment Station in Great Britain, was a particularly strong advocate of the importance of protozoa in soil fertility, suggesting that when soil protozoa were absent or few in number, soil fertility would be low, and conversely, when protozoa were numerous, soil fertility would be high.

Two prominent individuals who shared Lipman's revolutionary concept of soil were Selman A. Waksman (Fig. 1–3d) and Robert L. Starkey. Besides promoting the "Lipman Philosophy," Waksman's book, *Principles of Soil Microbiology*, and a later work by Waksman and Starkey, *The Soil and the Microbe*, were standard soil microbiology texts for much of the period between 1925 and 1950. However, in many circles Waksman is remembered less for his contributions to soil microbiology than for his discovery of the antibiotic streptomycin, for which he was awarded the 1952 Nobel Prize in physiology and medicine. It should be noted that the native environment of the streptomycin-producing organism (an actinomycete) was the soil! Thus, the quote attributed to Waksman, "From the earth will come our salvation," was prophetic.

Perhaps the greatest contribution of these noteworthy individuals was not so much their scientific papers, published books, inventions, or even patents, but the students they trained, who themselves went on to productive and noteworthy careers. The contributions of these individuals, now too numerous to mention, have enhanced crop production and fostered sound use of the environment worldwide.

Current and Future Directions

No look to the future can be made without first looking to see where we have been. If we neglect this first step, then we are relegated to repeat the mistakes of the past. Given the urgency of some of the issues we face and the shrinking resources we have at our disposal, it is prudent to step back and look at where we have been, before deciding on the next meaningful step. In the previous section we discussed the historical roots of soil microbiology. Here we summarize important topics in soil microbiology and suggest future research priorities.

Nutrient Transformations

From the moment Winogradsky first characterized the nitrifying bacteria, soil microbiologists have studied organisms involved in nutrient transformations and tried to understand the factors affecting the various processes. The poor nutrient-use efficiencies of common crops and the expense of fertilizers for standard cropping systems drove soil microbiologists to characterize the magnitude of nutrient losses, the conditions under which poor nutrient-use efficiencies might occur and, to a lesser extent, fertilizer management to reduce losses.

Emphasis on nutrient transformations has now shifted to new concerns. Environmental issues, such as how much nitrous oxide (N_2O), a "greenhouse" gas, is produced during denitrification and nitrification (Chapters 12 and 23), became important topics studied by soil microbiologists. Other environmental issues include the microbial transformations not only of nitrogen, but of sulfur (Chapter 15), phosphorus (Chapter 16), and more recently some of the metallic cations (Chapter 16) such as copper, mercury, iron, and aluminum. These issues grow more urgent as soils are increasingly used to recycle or dispose of a variety of waste products (Chapter 22).

Organic Matter

For most of the twentieth century, studies were dominated by attempts to characterize the chemical composition of the **soil organic matter** (referred to by many as **humus**). Such research is still underway and has been complemented by newer studies designed to provide a clearer understanding of soil organic matter as a group of functional pools (i.e., which pools turn over most rapidly and what is in them). These ideas have brought a fresh approach to this complex topic. This research was driven initially by the importance of soil organic matter in agriculture, but more recently a strong interest in global-scale transformations of carbon with respect to climate change has contributed to the importance of soil organic matter studies. In years to come, these ideas should help us to understand the potential for nutrient cycling from within the soil organic fraction and its relationship to sustainable agricultural practices.

As we move closer to a better understanding of soil organic matter, perhaps we may gain new insights for further studies. A challenge of the next century and beyond will be to manage our organic resources while maintaining clean air and water. The emphasis must be on salvaging resources such as plant nutrients through recycling. For example, municipalities have captured methane from landfills and water treatment facilities for supplemental energy generation. Another topic deserving attention is the disposal of organic waste by converting it to high-grade, single-cell protein.

Perhaps other opportunities exist at the frontiers of space. If space travel is ever to become a reality, waste products must be recycled in closed systems. For the soil microbiologist, who already understands the processes of decomposition of organic substances, the application of that knowledge to a closed spaceship would not require newly developed technologies (Alexander et al., 1989). The knowledge transfer to this problem is only a matter of scale and control in a closed environment.

Biological Dinitrogen Fixation

Soil microbiologists have received great acclaim for their work in the area of biological dinitrogen (N_2) fixation (Chapters 13 and 14). In fact, as early as the 1960s, some scientists stated categorically that we knew all we needed to know about biological N_2 fixation! Funding for research became more difficult to obtain, and some individuals were diverted into other fields of soil microbiology. However, the fuel crisis of the early 1970s in the United States changed all this. Suddenly biological N_2 fixation was "rediscovered" and new opportunities abounded for enterprising scientists.

For a long time this research topic was dominated by selection of superior strains of rhizobia (i.e., the N_2-fixing bacteria) and refinement of inoculation practices. Many questions were posed during this period, and some still await satisfactory answers:

- Why is it so difficult to displace the indigenous and decidedly inferior strains of rhizobia with superior stains?
- What is the composition of the indigenous population of rhizobia?
- Do manageable plant-rhizobia combinations exist?
- What are the biochemical mechanisms of N_2 fixation?
- What is the exact taxonomic composition of the family Rhizobiaceae?

In the last question, molecular genetic procedures have revealed new species of rhizobia, particularly as scientists have examined rhizobia from tropical regions. Undoubtedly, there are exciting times ahead as the full story of the rhizobia continues to unfold and the field of biological N_2 fixation remains a meeting ground, uniting scientists from a variety of disciplines.

Mycorrhizae

In 1885 A.B. Frank first applied the term **mycorrhizae** to the **symbiotic** associations between tree roots and fungi. Foresters found that certain fungi grew between the cortical cells of the feeder roots and covered the root surface; these fungal-plant associations were termed **ectomycorrhizae.** Not until the 1930s was the role of mycorrhizae in plant nutrition appreciated. Scientists confirmed that mycorrhizal plants grew better and had greater nutrient contents, especially phosphorus, than nonmycorrhizal plants. Through a series of carefully designed experiments, researchers proved that phosphorus from the soil was taken up by the soil hyphae of the mycorrhizal fungus and transferred to the host plant. Conversely, the **mutualistic** nature of the association was confirmed by the introduction of radio-labeled carbon dioxide ($^{14}CO_2$) to the top of the plant and the detection of radioactive carbon (^{14}C) in the fungal portion of the mycorrhiza.

A broader significance of these findings was realized when we discovered that most plants had some sort of mycorrhizal association. Although the ectomycorrhizae were present on only a small proportion of all plants (i.e., certain trees and shrubs), **endomycorrhizae** were found on a wide range of plants, including many of agronomic importance. Endomycorrhizae also assist in nutrient absorption and are especially important for plants growing under environmental stress (e.g., drought conditions).

There is now a growing awareness of the important contribution of mycorrhizae to soil structure because of the large amounts of carbonaceous materials that flow to the soil through the network of fungal hyphae. Reports of interactions with plant pathogens also suggest the potential to use mycorrhizal fungi as biological control agents. Currently soil microbiologists interact with scientists from numerous disciplines (e.g., agronomy, ecology, genetics, forestry, molecular biology, and plant physiology) to gain understanding of the role of mycorrhizae in agricultural and natural landscapes.

Biodiversity of Soil Populations

The early phases of soil microbiology were often dominated by attempts to characterize soil populations using **selective media.** While these attempts produced valuable information, little more could be said other than that there was some number of **colony-forming units** (cfu) g^{-1} of soil. As we approach the end of the 1990s, we are becoming increasingly aware that our knowledge of the soil microbial community is far from complete. During the past 10 years we learned that many microorganisms existing in the soil are viable (alive) but nonculturable (Chapter 9). Some suggest that these organisms may exceed 99% of the total soil population. This means that in our studies of microbial communities, we perhaps have observed less than 1% of the soil population. Increasingly, questions are being raised about the effects of soil management on the composition of the microbial community, particularly in relation to soil quality. Thus, it remains important to develop procedures to characterize soil microbial populations. Until such time, we will be unable to determine whether species are becoming extinct or are undergoing evolutionary change.

Some of the more recently developed molecular tools are proving useful in characterizing soil populations. For example, techniques that rely on amplifying DNA, such as various **polymerase chain reaction** (PCR) procedures, will contribute to our understanding of the diversity of the soil microbial community (Chapters 8 and 9).

Biological Control

Compared to the chemical control of pests, the advantages of **biological control** (or biocontrol) are numerous. Biological control is a natural mechanism that leaves no **xenobiotic** residues after treatment (Chapter 19). Early attempts at biological control using soil microorganisms followed Waksman's discovery of antibiotic-producing microbes in the soil. Unfortunately most, if not all, of these attempts failed outright.

Since that time, soil microbiologists learned that it is not sufficient just to increase the number of biocontrol agents in the soil to achieve success, but that a basic understanding of the ecology of the biocontrol agent is needed. Amelioration of the factor limiting the growth or survival of the control agent is necessary for biocontrol to work. While successful biocontrol experiments are few in number in comparison to failures, biocontrol research continues to be an area where soil microbiologists make significant contributions. As we learn more about biocontrol agents and their pest-suppression mechanisms, ecology, and genetics, this area of soil microbiology research should continue to increase in importance.

Biotechnology

Soil microbiologists are interested in discovering microorganisms with superior traits, including better N_2 fixers, superior biocontrol agents, and agents for bioremediation processes. In the past, we relied on natural variation and selection from natural populations to obtain organisms with better environmental fitness; however, with the various molecular techniques now available, it is becoming possible to make specific modifications in the organism's genome to obtain specific phenotypic properties. This capacity can affect processes carried out by soil microorganisms—from methane production to denitrification in groundwater.

As these potential opportunities move to reality, questions on the fate of genetically engineered or modified microorganisms deliberately released into the environment assume primary importance. How do these genetically modified organisms grow, compete, move, and survive in the soil environment? Can the traditional models of growth describing carrying capacity of organisms help us understand what might happen upon release of genetically modified organisms? Questions and opportunities abound and the likelihood that soil microbiology will remain an important field of investigation is very strong.

Summary

Many microorganisms have their origin in the soil or are closely associated with the soil environment. Throughout history these microorganisms have had a substantial impact on humankind. In some instances the impacts have been beneficial while others have been detrimental (Doyle and Lee, 1986). On the beneficial side, microorganisms have a major role in nutrient cycling and thereby contribute to the sustainability of life. On the detrimental side, microorganisms contribute to some environmental problems, such as global warming and groundwater contamination with nitrate.

As we approach the twenty-first century, soil microbiologists are faced with at least two choices. Will our emphasis be on those areas that have brought us to our present position, or will we be willing to take advantage of opportunities that will

permit us to step aggressively into the next century? Traditionally, soil microbiologists have been opportunists in their work for the betterment of society. In light of the environmental problems associated with unesthetic substrates such as sewage, animal manures, food processing wastes, and industrial wastes, the efforts of soil microbiologists will be needed to make these substrates less objectionable. Solutions to these problems are likely to come from existing technologies and those yet to be developed. Along with the time-tested techniques of traditional soil microbiology, new analytical procedures and genetic manipulations will contribute to the solution of environmental problems, whether these are associated with agricultural or other environmental issues. In the future, we should be able to advance our understanding of the microbial ecology of soil, enhance opportunities for bioremediation and understand the diversity of the soil population. The future of soil microbiology seems unlimited. Perhaps the solution of a food-production or environmental issue somewhere in the future will propel a soil microbiologist (perhaps yourself) into the ranks of the Nobel Prize winners, just as Selman Waksman's work was honored.

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Worldwide Web Sites of Interest to Soil Microbiology

American Society of Microbiology: http://www.asmusa.org/

Digital Learning Center for Microbial Ecology: http://commtechlab.msu.edu/CTLProjects/dlc-me/

International Culture Collection of VA Mycorrhizal Fungi (INVAM): http://invam.caf.wvu.edu/

Microbial Underground: http://www.ch.ic.ac.uk/medbact/microbio.html

Soil Science Society of America: http://www.soils.org/sssa.html

The Tree of Life: http://phylogeny.arizona.edu/tree/phylogeny.html

The Worldwide Web Virtual Library (for Microbiology): http://golgi.harvard.edu/ biopages /micro.html

World Data Center for Microbiology: http://www.wdcm.riken.go.jp/

Study Questions

1. In what ways is soil a unique environment for microorganisms?
2. What individual(s) and event(s) have had the greatest influence on the development of soil microbiology?
3. Why is Sergei Winogradsky often considered the Father of Soil Microbiology?
4. What is the contribution of Jacob G. Lipman to soil microbiology?
5. What are some of the challenges for soil microbiology in the twenty-first century?

Chapter 2

♦

The Soil Habitat

Peter G. Hartel

♦

Whatever our accomplishments, our sophistication, our artistic pretension, we owe our very existence to a six-inch layer of topsoil—and the fact that it rains.

Anonymous, *The Cockle Bur*

This chapter covers soil description, soil physical and chemical characteristics, and soil abiotic factors. Together, these elements help define the habitat for soil microorganisms. Although it may seem obvious that one needs to understand "soil" in order to understand soil microbiology, this is not an easy concept. Soil is dynamic. Because soil forms from the interaction of climate (especially temperature and rainfall) and living organisms (especially native vegetation) as influenced by topography (e.g., elevation) and type of parent material (i.e., the original composition of the minerals and organic matter) over time, soil is the most complex and variable of all microbial habitats. Therefore, soil does not conform easily to our conclusions and rules. The key to understanding the role of "soil" in soil microbiology is always to think of soil as the sum of many interrelated parts. By thinking constantly of these interdependencies, the science of soil microbiology will be much easier to understand.

Soil Description

Definition and Types of Soil

Soil is defined as a mantle of weathered rock which, in addition to organic matter, contains minerals and nutrients capable of supporting plant growth. Soil scientists may describe a particular soil this way: "The Ap horizon of a Tifton loamy sand

Figure 2–1 A soil profile with unusually distinct horizons. This forest soil, from the lower coastal plain of Georgia (U.S.), has a thin O horizon (2 to 3 cm of pine needles in various stages of decomposition), an A horizon (10 to 12 cm; light black), an E horizon (the bleached layer of variable thickness), and a B horizon (black layer). Soil corer, 122 cm (48 in.). *Photograph courtesy of L. West, Univ. of Georgia.*

(pH 5.6; 18.0 g organic matter kg^{-1}, 54 g of clay kg^{-1}, and 825 g of sand kg^{-1}) from Tifton, Georgia, was collected and passed through a 2 mm sieve." This single sentence describes several important characteristics of soil: horizons, series name, and texture.

There are two broad types of soil: mineral and organic. The definition of an organic soil varies according to the amount of clay and water saturation, but generally an **organic soil** contains at least 20% organic carbon; a **mineral soil** does not. Only 0.9% of the world's soils are organic (Miller and Donahue, 1995); therefore, the vast

majority of soils in the world are mineral soils. Edwards muck (pH 7.6, 572 g organic matter kg^{-1}) contains 57.2 g of organic matter 100 g^{-1} of soil or 57.2% organic matter; it is an organic soil. Because Tifton loamy sand has 18.0 g of organic matter kg^{-1} (1.8 g of organic matter 100 g^{-1} of soil or 1.8%), it is not an organic soil but a mineral soil.

Horizons

A soil is composed of layers, each with distinct characteristics, called **horizons.** A slice of soil is called a **profile** (Fig. 2–1). Each horizon is identified with the letters (beginning from top to bottom) O, A, E, B, or C. Not every soil has all horizons. The topmost layer, the *O horizon*, is formed from plant and animal (organic) litter; it is an organic horizon. Because it is easily disrupted by human activity, the O horizon often does not exist in many soils. A forest is a good place to find a soil with an O horizon. The next horizon, the *A horizon*, is the first mineral horizon. The A horizon is distinguished from the O horizon by having less organic matter. Because minerals and nutrients leach down from this horizon, the A horizon is referred to as the zone of **eluviation.** In some soils, an *E horizon* underlies the A horizon. In this case, both horizons are eluviated, but the A horizon is darkened by organic matter whereas the E horizon is more lightly colored. Beneath the A or E horizon is the *B horizon*, called the zone of **illuviation,** because here minerals and nutrients accumulate. At the bottom of the soil layer, below the B horizon, is the *C horizon*, or unconsolidated parent material.

Horizons can have subdivisions that differentiate one horizon from another or show a transition zone from one horizon to another. In the case of Tifton loamy sand, the soil has an Ap horizon, where "p" stands for "plowed." Typically, the Ap horizon is the depth of a plow—a "furrow slice"—or about 20 cm (2.54 cm = 1 inch; 20 cm ≙ 8 inches).

Box 2–1

Furrow Slice. In old notation, the approximate weight of a "furrow slice" was 2,000,000 lb of soil $acre^{-1}$; in new notation, this is approximately 2,200,000 kg of soil ha^{-1} (1 hectare = 2.47 acres and 1 kg = 2.2 lb; hence, multiply lb of soil $acre^{-1}$ by 1.12 to convert to kg of soil ha^{-1}). The weight of a "furrow slice" is useful for determining application rates of soil amendments (e.g., fertilizer).

Soil Names

Tifton loamy sand is a **soil phase** name. The soil phase name includes the **series** name and the texture of the A horizon. The series name represents the lowest level of soil classification and is usually taken from a locale where the series was first described (i.e., the name of a town, county, or some local feature). In this case, Tifton is Tifton, Georgia. Names and complete classification of soils in the United States may be found in Natural Resources Conservation Service (formerly the Soil Conservation Service) publications (e.g., Soil Conservation Service, 1959) or State Experiment Station bulletins (e.g., Perkins et al., 1986). These publications are available in libraries and are arranged by county or counties. In addition to classifying soils (information that is often required by scientific journals), these publications provide important information on the chemical and physical characteristics of each soil and locate the soils on a map. The vast majority of soils in the United States have already been mapped.

Soil Physical Characteristics

Soil Texture

The **texture** of a soil is determined by the size distribution of the individual inorganic grains in soil. The grains are separated into three particle-size fractions: sand, silt, and clay. For the U.S. Department of Agriculture system of classification:

- Sand is soil particles with diameters from 0.05 to 2.0 mm.
- Silt is soil particles with diameters from 0.002 to 0.05 mm.
- Clay is soil particles with diameters < 0.002 mm.

In the case of Tifton loamy sand, a 2 mm sieve eliminated all the larger-size groups (i.e., stones and gravel).

Based on the particle-size distribution, all mineral soils can be placed into one of 12 major textural classes. The textural class of a soil is determined by means of a soil textural triangle (Fig. 2–2). The sample from the Ap horizon of Tifton soil contained 54 g of clay kg^{-1} (5.4%) and 825 g of sand kg^{-1} (82.5%) and is therefore a loamy sand (sand + silt + clay totals 100% of the < 2 mm inorganic particles, so it is understood that the remaining percentage, 12.1%, is silt). The texture of a soil does not change quickly with time and is considered a basic soil property. Soils may also be described as coarse or fine; a coarse-textured soil has more sand, whereas a fine-textured soil has more clay. A soil whose properties are equally influenced by sand, silt, and clay is called a *loam* or *loamy soil*. The properties of texture are important in the aeration and drainage of soil. It is important to note that these classes of soil texture do not apply to organic soils: an organic soil is classified as a muck, peaty muck, mucky peat, or peat depending on the state of decomposition of its organic matter. Mucks have well-decomposed organic matter; peats do not.

Soil Density

A soil has both a particle density and a bulk density. Density is the weight per unit volume. The **particle density** is determined by the weight of the solid soil particles divided by the volume of the solid soil particles. If 1 cm^3 of solid soil particles weighs 2.65 g, its particle density is 2.65 g cm^{-3}. To get solid soil particles, one can imagine compressing a soil sample so as to eliminate the pore spaces (Fig. 2–3a). Because quartz, feldspar, and colloidal silicates make up the major portion of mineral soils, the particle density for mineral soils is relatively narrow and typically ranges from 2.60 to 2.75 g cm^{-3}. The **bulk density** is determined by dividing the weight of the soil by the total volume of the soil, including the weight of the solid soil particles and the pore spaces (Fig. 2–3b). If 1 cm^3 of soil weighs 1.38 g, its bulk density is 1.38 g cm^{-3}. The bulk density of mineral soils typically ranges from 1.00

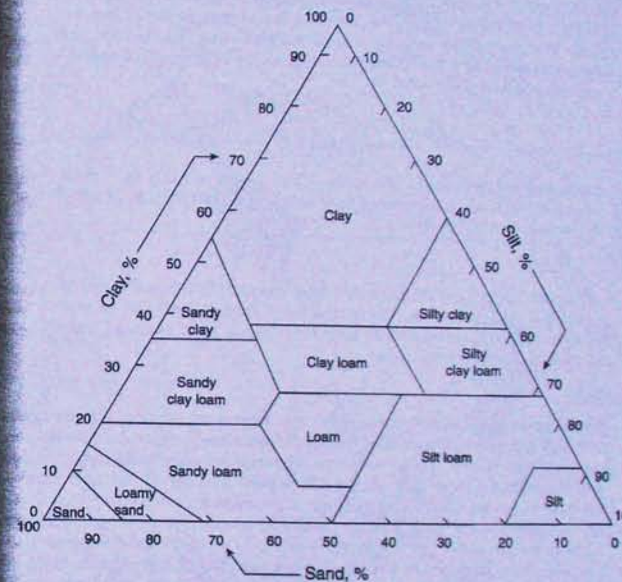


Figure 2–2 Soil textural triangle. To use the triangle, determine any two of the percentages of sand, silt, and clay in a soil. Follow the arrow in the direction of the tic marks at the appropriate percentage. The texture of the soil is identified at the intersection of the two lines. *Adapted from Soil Survey Staff (1975).*

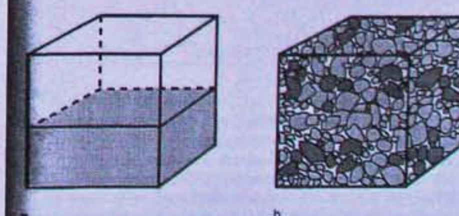

a. b.

Figure 2–3 Particle density (a) versus bulk density (b). Particle density considers only the space occupied by soil solids; bulk density considers the total soil space.

to 1.80 g cm^{-3}. Because organic material is highly porous and has a particle density of only 1.20 to 1.50 g cm^{-3}, the incorporation of organic matter into the soil decreases both the particle and the bulk densities of a soil. The bulk density divided by the particle density, multiplied by 100, gives the percentage of solid space. The remaining space is pore space.

Box 2–2

Calculating Soil Pore Space. If a soil has a bulk density of 1.38 g cm^{-3} and a particle density of 2.65 g cm^{-3}, the percentage of solid space would be (1.38/2.65)(100)= 52%; the pore space would be 48%.

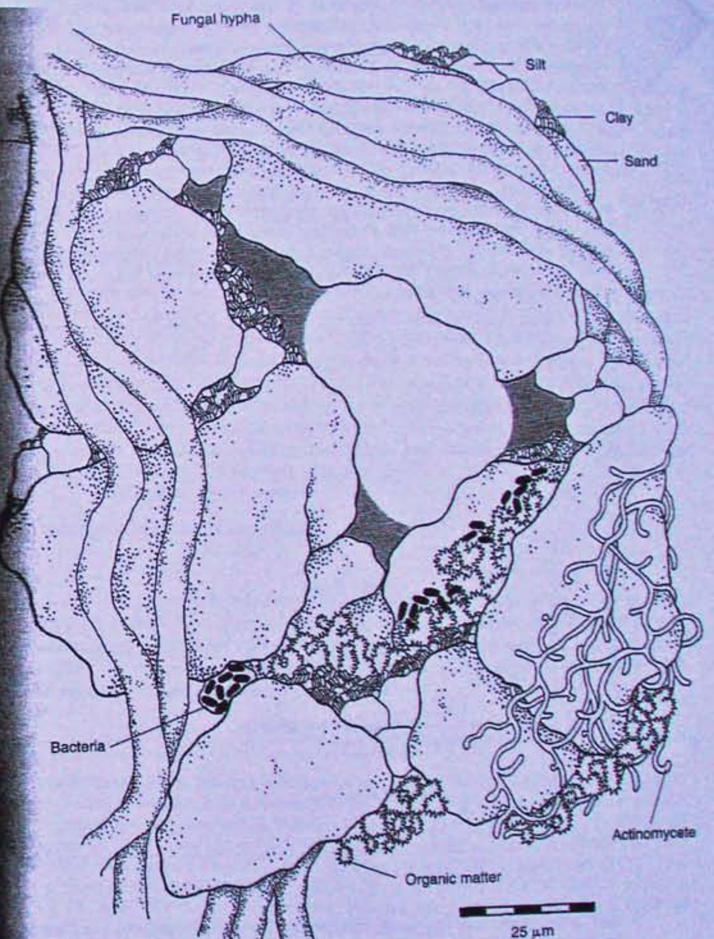
A typical mineral soil contains 50% solid material (45% minerals and 5% organic matter) and 50% pore space. The pore space will be occupied by air or water, and these two are inversely related: as the volume of soil water increases, the volume of soil air decreases, and vice versa.

Soil Pores

Soil pores play a major role in water and air movement. Also, soil microorganisms reside in pores. Coarse-textured (sandy) soils have higher bulk densities and less total pore space (35% to 50%) than fine-textured (clay) soils that have lower bulk densities and more pore space (40% to 60%). The size of the pores, however, is just as important as the total quantity of pore space. Two classes of pore sizes are recognized: macropores and micropores. The minimum diameter of a **macropore** has been a source of debate, but is generally accepted to be between 30 and 100 μm. Pores smaller than this are **micropores.** Macropores characteristically allow the rapid movement of soil gases and soil water. Sandy soils have less total pore space, but those spaces are mostly macropores; thus, sandy soils usually drain rapidly. In contrast, clayey soils have more total pore space, but these spaces are mostly micropores. Soils high in clay usually drain slowly because the micropores restrict the water flow. This is why a sandy soil has a relatively low water-holding capacity and a clayey soil has a relatively high water-holding capacity.

Box 2–3

Soil Nanopores. One interesting recent development has been the concept of soil **nanopores** (nano = 10^{-9}; Pignatello and Xing, 1996). There are numerous examples of the long-term persistence of intrinsically biodegradable compounds in soil even when environmental conditions are not limiting for microbial growth. One possible mechanism for this reduced bioavailability is the slow (weeks to months) diffusion of organic chemicals into soil nanopores—soil pores so small that any organic compounds within them are beyond microbial or even enzymatic attack. This emerging concept may have important ramifications for biodegradation and bioremediation.

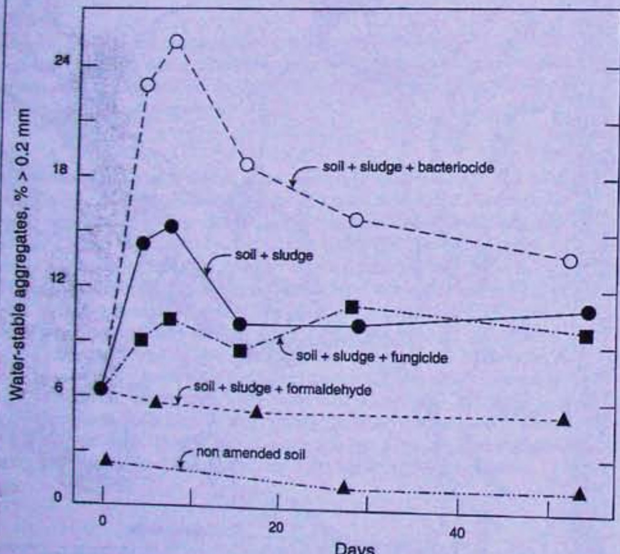


re 2–4 A typical soil aggregate. Here sand, silt, and clay particles, cemented by organic matter, cipitated inorganic materials, and microorganisms, bind the soil particles together to form an aggate. Note how the water forms a meniscus surrounding the air space (*center*). Bacteria (rods in anic matter, rods in a polysaccharide "plug," and actinomycete) and fungus (hyphae only), as ell as the sand, silt, and clay particles are all to scale. Also note how an aggregate can offer a dirse set of microsites for microbial habitation over very small distances. *Original drawing by Kim oma.*

Box 2–4

Effect of Biosolids on Soil Aggregation. Several researchers (Metzger et al., 1987) tested the ability of sewage sludge (i.e., biosolids) to promote water-stable aggregates in soil. (Water-stable aggregates are aggregates that do not fall apart when raindrops hit them. This is measured by determining the percentage of soil aggregates remaining on a sieve after repeatedly dipping the sieve in a container of water.) To determine the extent to which microbes were responsible for this aggregation, the sludge was amended with various antimicrobial agents; the controls included one treatment without any antimicrobial agents (sludge only) and one treatment of nonamended soil (no sludge added). The researchers then measured the percentage of water-stable aggregates in each treatment over time.

After 30 days, the largest increase in water-stable aggregates was measured in a) soil amended with sludge and a bacteriocide, to a lesser extent in b) soil amended with sludge only, and c) soil amended with sludge and a fungicide. No increase in water-stable aggregates was observed in nonamended soil or in soil amended with sludge and formaldehyde. These results suggest that following the addition of sewage sludge, fungi were most responsible for soil aggregation.



Effect of microorganisms on the percentage of water-stable aggregates in a Gilat sandy clay loam mixed with sewage sludge. The sewage sludge promotes microbial growth. The soil-sludge mixture with fungicide kills fungi (and allows the preferential growth of bacteria); the soil-sludge mixture with bacteriocide kills bacteria (and allows the preferential growth of fungi); and the soil-sludge mixture with formaldehyde kills all soil microorganisms. *Adapted from Metzger et al. (1987). Used with permission.*

Structure

When groups of soil particles cohere more strongly to each other than to other adjoining particles, these groups form a **soil aggregate.** These aggregates can range in size from 0.5 to 5 mm in diameter and can even form clusters of aggregates (see Chapter 1, Fig. 1–2). Depending on their shape, these aggregates define **soil structure.** For example, spheroid aggregates have more pore space and more rapid permeability than aggregates that are block-like or prism-like. Soil scientists are interested in soil structure and soil aggregation because these attributes influence soil productivity.

egrating Soil Aggregation and Soil Microorganisms

Although abiotic factors like the parent material, climate, tillage practices, and adsorbed cations (e.g., Na^+ ions tend to disperse soil particles, and Ca^{2+} ions tend to flocculate soil particles) are important in the formation of soil aggregates, biotic factors also play a major role. Plant roots disrupt the soil and promote granulation. Organic matter not only lightens the soil, but also binds it. Most important for this discussion, soil microorganisms can promote soil aggregation though the production of extracellular polysaccharides and hyphae. In this manner, soil microorganisms can physically bind soil particles (Fig. 2–4). Thus, soil microorganisms are fundamental to soil structure and as an aspect to soil formation.

Soil Chemical Characteristics

pH

Soil pH is important because microorganisms and plants respond markedly to chemicals in their environment. Acid soils are most prevalent where rainfall is sufficient to leach bases from the soil; where rainfall is insufficient, the soils are usually alkaline. Not surprisingly, the majority of alkaline soils are found in arid and semiarid regions.

Box 2–5

Understanding Soil pH. pH is defined as the negative log of the hydrogen ion (H^+) concentration in solution. This is the same as pH = $\log_{10} 1/[H^+]$, where the brackets indicate concentration in moles per liter. Because the $[H^+]$ in pure water is 1×10^{-7} at 25°C, pure water has a pH of $\log 1/[1 \times 10^{-7}] = 7$; this is considered neutral. The pH scale is based on the dissociation of water (H^+ and OH) from 1.0 *M* H^+ (pH 1; acid) to 1.0 *M* OH^- (pH 14; basic; 0.00000000000001 *M* H^+ remaining). As an example, the pH of 0.001 *M* HCl is $\log 1/[1 \times 10^{-3}] = 3$. It is important to remember that pH is a log scale; if two solutions differ by 1 pH unit, then one solution has 10 times more H^+ ions than the other.

Most soil microorganisms and plants prefer a near-neutral pH range of 6 to 7 because the availability of most soil nutrients is best in this pH range. For example, actinomycetes prefer neutral conditions and do not tolerate acid conditions well. Nevertheless, microorganisms can be found in soils from pH 1 to 13. Most fungi are acid tolerant and commonly are found in acid soils. Microorganisms also have the ability to alter soil pH. Under anaerobic conditions, some microorganisms produce organic acids; under aerobic conditions, some microorganisms can oxidize ammonia and sulfur with the concomitant production of H^+.

Soil Anion and Cation Exchange Capacity

Soils can possess both positive and negative charge. The ability of positively charged materials in soil to hold negative ions (e.g., orthophosphate, $H_2PO_4^-$) is the **anion exchange capacity** (AEC) of the soil, and the corresponding ability of soil to hold positive ions (e.g., K^+, Ca^{2+}) is the **cation exchange capacity** (CEC). Because the ability of a soil to hold cations often exceeds its ability to hold anions, soil scientists typically report only the CEC of a soil. This does not mean that the AEC of soils is unimportant; the AEC is particularly important in the subsoil of highly weathered soils. The CEC is important because it can alter soil physical properties, and it affects soil pH and fertility (most plants obtain K^+, Ca^{2+}, and Mg^{2+} from exchangeable sites).

The exchange capacity of a soil is determined by the type and amount of clay and organic matter in the soil. In this section, the CEC of clay is considered; the CEC of organic matter follows. An understanding of clay mineral structure is necessary to understand the source of the exchange capacity in clay minerals. Most clays are composed of crystalline sheets of silica and alumina; hence, they are aluminosilicate clays. One sheet of silica and one sheet of alumina give a 1:1 clay like kaolinite (Fig. 2–5). One alumina sheet between two silica sheets gives a 2:1 clay like smectite. These sheets give clays their characteristic layered effect (Fig. 2–6) and contribute to their large surface areas.

Clays have two sources of charges. One source is **isomorphous substitution,** which is the substitution in the crystalline sheet of one atom by a similarly sized atom of lower valence. In the case of a sheet of silicon tetrahedra, Si^{4+} (radius of 0.041 nm) is replaced by Al^{3+} (radius of 0.051 nm) or Fe^{3+} (radius of 0.064 nm). In

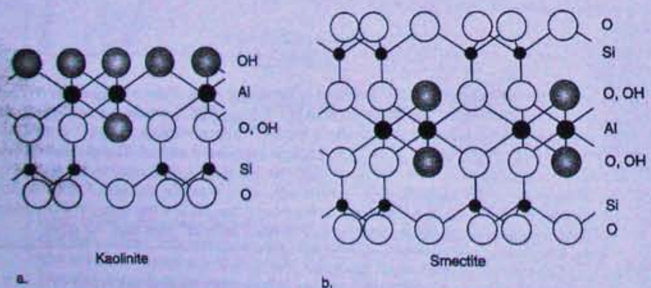


Figure 2–5 Sheets of silica and alumina layered together to form (a) kaolinite, a 1:1 clay, and (b) smectite, a 2:1 clay. The O atoms are shown as large, open circles; the OH^- atoms are shown as large, shaded, bold circles. *Adapted from Brady and Weil (1996). Used with permission.*

Figure 2–6 A scanning electron micrograph of kaolinite, a 1:1 clay. Bar, 100 μm. *Micrograph courtesy of N. White, Texas A&M Univ.*

each tetrahedron where this occurs, the tetrahedron will have an overall net −1 charge because the total negative charges of the O are no longer satisfied. This same type of substitution can occur in a sheet of aluminum octahedra where Mg^{2+} (radius of 0.066 nm), Fe^{2+} (radius of 0.070 nm), and Zn^{2+} (radius of 0.074 nm) can replace the Al^{3+} atom with the same overall net −1 charge. These charges are considered permanent charges and are *not* affected by soil pH.

A second source of charge on clays is broken edges. These are the actual edges of the silica and alumina sheets where ionizable H^+ atoms, as part of the hydroxyl ions, are held tightly by the O atoms under acid conditions (Fig. 2–7a). Here the charge of the broken edges is neutral. However, when the soil pH is > 6, the H^+ atoms are held more loosely and can be exchanged with such cations as Ca^{2+} and Mg^{2+} (Fig. 2–7b). This difference is the charge attributed to broken edges. This charge is pH-dependent, and this pH dependency is what distinguishes it from charge due to isomorphous substitution. Most of the charge in 2:1 clays is due to isomorphous substitution, and most of the charge in 1:1 clays is due to broken edges.

The AEC is also located at broken edges. Where OH^- is broken off or Al^{3+} or Si^{4+} is exposed, some anions (e.g., $H_2PO_4^-$) have the right size and geometry to be adsorbed; other anions (e.g., nitrate, NO_3^-) do not fit well and are not adsorbed.

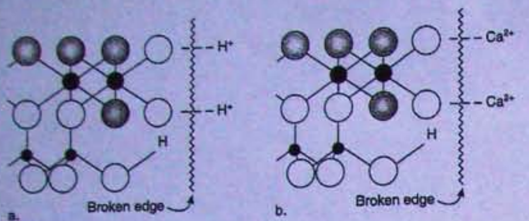


Figure 2–7 Broken edge of kaolinite under (a) acid and (b) alkaline conditions. *Adapted from Brady and Weil (1996). Used with permission.*

Table 2–1 **Relative size and surface areas of soil particles. For the sake of simplicity, the particles are assumed to be spherical and the largest size possible.**

Particle	Diameter (mm)	No. of particles (no. g^{-1})	Surface area ($cm^2\ g^{-1}$)
Very coarse sand	2.00 to 1.00	90	11
Coarse sand	1.00 to 0.50	720	23
Medium sand	0.50 to 0.25	5,700	45
Fine sand	0.25 to 0.10	46,000	91
Very fine sand	0.10 to 0.05	722,000	227
Silt	0.05 to 0.002	5,776,000	454
Clay	<0.002	90,260,853,000	8,000,000

Adapted from Foth (1990). Used with permission.

There is an important relationship between the exchange capacity of a soil and soil texture. The adsorption of water, nutrients, and gases and the attraction of particles are all surface phenomena—and the greater the surface area of the soil particles, the greater the adsorption. Because the particle surface area per unit mass increases logarithmically as the particle diameter decreases, clay has 50 to 100 times more surface area than the equivalent amount of silt or fine sand (Table 2–1). For this reason, clay dominates the adsorption of water, nutrients, and gases and the attraction of particles in a soil.

The CEC of organic matter far exceeds that of clay. Unlike clay, the structure of organic matter is poorly understood. It is composed primarily of carbon, hydrogen, and oxygen and is chemically heterogeneous. The charge of organic matter is similar to that of broken edges, except the source of the charge is primarily carboxyl (—COOH) groups because these dissociate at the pH of most soils. Phenolic hydroxyls and other groups also play a less significant role. Like broken edges, the H^+ ions are strongly held under acid conditions and are not easily replaced by other cations. As the pH increases, the H^+ ions of the carboxylic acid

are gradually replaced by other cations. For this reason, the CEC of organic matter is pH-dependent.

The CEC and AEC of a soil are expressed as centimoles (a centimole is 0.01 *M*) of positive or negative charge per kg of soil [i.e., cmol (+) kg^{-1} of soil or cmol (−) kg^{-1} of soil], respectively.

Box 2–6

Units for Expressing the Ion Exchange Capacity of Soils. In old notation, the AEC and CEC were measured in milliequivalents (meq) 100^{-1} g of soil. The old and new terms are directly equivalent: 1 meq 100^{-1} g of soil = 1 cmol (+) kg^{-1}.

The number of centimoles of an anion or cation a soil can hold depends on the valency of the anion or cation. A monovalent cation (e.g., K^+) can satisfy one −1 charge; a divalent cation (e.g., Ca^{2+}) can satisfy two −1 charges. Therefore, a soil can hold only half as many Ca^{2+} cations as it can hold K^+ cations.

Box 2–7

Calculating Ion Retention in a Soil. Assume a soil is at a constant pH, so that its CEC is fixed. The atomic weights of K^+ and Ca^{2+} are 39 (1 mole = 39 g) and 40 (1 mole = 40 g), respectively. If a silt loam has a CEC of 10 cmol (+) kg^{-1} of soil, it can hold (39 g × 10 cmol) or 3.9 g of K^+ kg^{-1} of soil. Similarly, the same silt loam can hold (40 g × 10 cmol) or 4.0 g of $Ca^{2+}kg^{-1}$ of soil. But Ca cations are divalent, and each cation can satisfy two negative charges, so the soil can hold only 2.0 g of Ca^{2+} kg^{-1} of soil.

The CEC and AEC of some "soils" are shown in Table 2–2, and the relation of the CEC of organic matter and smectite to soil pH is shown in Fig. 2–8. Because soils are mixtures, the CEC and AEC of typical soils are much lower than pure clays or organic matter.

Table 2–2 **Cation and anion exchange capacity for selected "soils."**

"Soil"	CEC (cmol (+) kg^{-1})	AEC (cmol (−) kg^{-1})
Pure organic matter	240	1
Pure smectite	118	1
Pure kaolinite	7	4
Typical sand	5	ND
Typical loam	15	ND
Typical clay	30	ND
Tifton sandy loam	3	ND

Adapted from Brady and Weil (1996) and Miller and Donahue (1995). Used with permission.
ND, not determined.

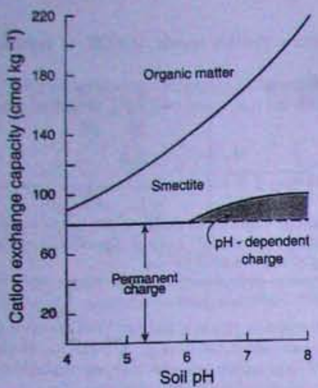


Figure 2–8 Charge of smectite and organic matter with varying pH. *Adapted from Brady and Weil (1996). Used with permission.*

Integrating Soil Microorganisms with AEC and CEC

The anion and cation exchange sites of a soil are important not only because they can attract or repel anions or cations, but also because they can attract and repel charged organic molecules. Because the surfaces of microorganisms are composed of organic molecules, which are positively or negatively charged (e.g., $—COOH \rightarrow —COO^-$; $NH_2 \rightarrow NH_3^+$) depending on the soil pH, soils have the capacity to attract and repel microorganisms. In contrast to physical binding, this means soil microorganisms can chemically adsorb or bind to soil particles. How this is done is not fully understood. At typical soil pH values (pH 5 to 8), soil microorganisms are negatively charged. Because clays and organic matter are negatively charged at these pH values as well, some soil microbiologists have suggested that divalent cations "bridge" soil microorganisms and clays (hence the term *divalent cation bridging*). Evidence for this is unconvincing (Stotzky, 1985). More likely a variety of mechanisms is responsible for microorganisms chemically adsorbing or binding to clay and organic matter. These mechanisms include:

- attraction by ion exchange (where pH affects the charge of various groups),
- weak attractive forces like van der Waals forces, where fluctuating dipoles give rise to an instantaneous attraction between nonpolar molecules,
- coordination bonding (sharing electrons), and
- hydrogen-bonding (bonding of H^+ to an electronegative atom like O) as a result of protonation or water bridging.

In protonation, protons from the surface of the clay are transferred to the soil microorganism to make the soil microorganism neutral or positively charged. In water bridging, soil microorganisms form hydrogen bonds with water molecules that form part of the hydration shell of an exchangeable cation.

... Abiotic Factors

... ter

Soil water is essential for soil microorganisms. Without some water, there is no microbial activity. Soil water also affects gas exchange and a variety of soil chemical reactions (e.g., as a reactant in hydrolysis). Water in soil flows from an area of higher energy to an area of lower energy (this is an expression of the Second Law of Thermodynamics), and this spontaneous flow of water is measured in terms of a water potential. Therefore, a **water potential** is the measure of the potential energy (per unit mass or volume) of water at a point in a system relative to the potential energy of pure, free water.

Box 2–8

Kinetic versus Potential Energy. Energy is the ability to do work. Kinetic energy is the energy a body possesses because of its motion and mass. Potential energy is the energy a body possesses because of its position or arrangement with respect to other bodies. Therefore, potential energy is not a constant property but a relative measure with reference to an arbitrarily chosen zero level. The potential energy of an apple in a tree and the ground depends on the relative height of the apple to the ground. When the apple falls from a tree, the apple's kinetic energy increases and its potential energy decreases.

Because pure, free water is usually assigned a water potential of zero, and the water potential in soil is usually lower in potential energy than pure, free water, the water potential in soil is usually a negative number. The water potential of a soil is assigned the Greek letter Ψ (psi) and is the sum of various forces.

Box 2–9

Water Potential versus Water Content. In addition to the energy term, Ψ, soil water can be measured in terms of its volumetric or gravimetric water content. In these cases, the Greek letter θ_v (theta) and θ_w are used, respectively.

Although there are many forces comprising the total water potential, the three major forces in soil are:

- osmotic potential (Ψ_π),
- matric potential (Ψ_m), and
- gravitational potential (Ψ_g).

The **osmotic potential** (Ψ_π) is primarily the attraction of solute ions for water molecules and is always a negative number. Because the osmotic potential arises from the dissolution of solutes (e.g., various salts), the potential is significant in saline soils or in soils amended with organic wastes or fertilizer. The **matric potential** (Ψ_m) is the sum of adsorption of water to the surfaces of soil particles and capillary forces arising from water being trapped in very fine pores. Like the osmotic potential, the matric potential is always a negative number. The matric potential is most significant in unsaturated soils. Water will move from a more saturated soil (high free energy; high potential) to a less saturated soil (low free energy; low potential).

Box 2–10

Capillary Water. To observe capillary water, place a fine glass tube in water. Because of the surface tension of water and the attraction of water molecules to the sides of the tube, the water rises in the tube according to the tube diameter. The smaller the tube, the greater the rise of water.

The **gravitational potential** (Ψ_g) is the force of gravity pulling water towards the earth's center and may have a positive or negative potential depending on the reference level of the water. If the reference level is the lower edge of the soil profile (the usual case), then the gravitational potential will be positive.

Box 2–11

Units for Expressing Water Potential. In practice, all energy potentials in soil, whether gravitational, matric, osmotic, or other potentials, are united in equivalents of pressure expressed as kiloPascals (kPa) or MegaPascals (MPa; a Pascal is a Newton m^{-2}; a Newton is a measure of force required to accelerate 1 kilogram 1 meter per second per second). Previously, soil water was measured in bars or atmospheres (1 bar = 0.987 atmospheres). To convert bars to kPa or MPa, multiply bars by 100 or 0.1, respectively (e.g., −1 bar = −100 kPa or −0.1 MPa). To convert atmospheres to kPa or MPa, multiply by 101 or 0.101, respectively.

Soil texture affects soil water relations (Fig. 2–9). Over the entire range of water pressure, a soil high in clay, with its greater percentage of micropores, retains a larger amount of water than a soil high in silt, which in turn retains a larger amount of water than a soil high in sand. These curves are called moisture characteristic curves, or **moisture release curves.** The moisture release curves of most agricultural soils lie between the curves for clay and sandy soils. If organic matter were added, the curve would shift upward. Recent soil microbiology literature reports both the soil water content and the water potential.

Although the water potential in soil is measured most accurately in terms of potential (or pressure), it may be measured less accurately in terms of its physical and biological characteristics. These terms have persisted because they are useful for relating soil water to plant growth. When a soil is saturated with water and the water is allowed to drain freely, the water drains only from the soil macropores. This is "gravitational water" and is of little use to plants because it reduces soil aeration (see

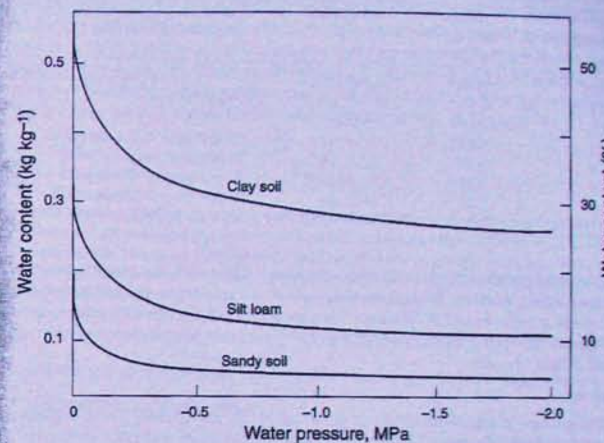


Figure 2–9 Water potential–water content relationship for a sandy soil, a silt loam, and a clay soil. *Adapted from Papendick and Campbell (1981). Used with permission.*

next section). When gravitational water and water that moves readily at high matric potential have drained (macropores now empty), the soil is at *field capacity* (also called water-holding capacity). In terms of water potential, field capacity is approximately −0.03 MPa (−33 kPa; −0.33 bar), except for sandy soils, where field capacity is approximately −0.01 MPa (−10 kPa; −0.10 bar). Most soil micropores are still full of water, which is available for plant growth. When a plant uses all of this water (micropores now empty), almost all water remaining in the soil is *hygroscopic water,* water bound too tightly to the soil solids for plants to use. At this point, plants permanently wilt and do not recover, even when water is added. This is the *permanent wilting point* and is approximately −1.5 MPa (−1500 kPa; −15 bar). While field capacity and permanent wilting point remain in use because they are still good terms for plant scientists to describe the upper and lower limits of plant available water, these terms should not be confused with water potential (or water pressure). They do not have the word "potential" (or pressure) associated with them.

Box 2–12

Water Activity. The water requirement for microorganisms frequently was measured in water activity (a_w), which is the ratio of the vapor pressure of the solution over the vapor pressure of pure water at the same temperature. This term was used primarily in food microbiology. If a_w is multiplied by 100, it is the same as relative humidity (an a_w of 0.99 = 99% relative humidity). The use of a_w has now been replaced by water potential.

Table 2–3 Microbial tolerance to matric-controlled (Ψ_m) water stress.

Water potential (MPa)	Water activity (a_w)	Water film thickness	Microbial activity limited (example of genus)
−0.03	0.999	4.0 μm	movement of protozoa, zoospores, and bacteria
−0.1	0.999	1.5 μm	
−0.5	0.996	0.5 μm	
−1.5	0.990	3.0 nm	nitrification; sulfur oxidation
−4.0	0.97	<3.0 nm	bacterial growth (*Bacillus*)
−10.0	0.93	<1.5 nm	fungal growth (*Fusarium*)
−40.0	0.75	<0.9 nm	fungal growth (*Penicillium*)

Adapted from Harris (1981).

The water potential in soil also has a profound effect on soil microorganisms and soil microbial processes. Some microorganisms and processes are tolerant of moisture stress; others are not (Table 2–3). Also, as soil water becomes limited, microbial movement becomes limited. Some of these water-related effects are covered in more detail in later chapters.

Soil Aeration

Soil aeration is a measure of the oxygenation of the soil. Ideally, a well-aerated soil would have sufficient oxygen for the respiration of plant roots and the function of most aerobic microorganisms (i.e., **aerobes**). Under these conditions, roots and aerobic microorganisms oxidize organic compounds to CO_2. High CO_2 levels may indicate that the soil is poorly aerated. A poorly drained soil is not necessarily detrimental to all soil microorganisms; **facultative anaerobes** can grow both in the presence or absence of oxygen, whereas **obligate anaerobes** grow only in the absence of oxygen.

Soil aeration is highly dependent on soil moisture, soil texture, and soil porosity. The earth's atmosphere is the major source of oxygen; thus, oxygen can get into the soil only by **mass flow** or **diffusion.** Because mass flow is based on total air pressure differences, mass flow of oxygen into the soil is relatively unimportant beneath the top few centimeters of soil. Therefore, the major mechanism for replenishment of oxygen in the soil is diffusion. Soil texture affects this diffusion. If the soil has a high percentage of clay, then it will have a high percentage of micropores. The small diameter of the micropores will slow diffusion. Soil water will also affect diffusion of oxygen because the diffusion coefficient of oxygen in air is 0.189 $cm^2\ sec^{-1}$, but in water is only 0.000025 $cm^2\ sec^{-1}$ (e.g., Papendick and Campbell, 1981). In other words, oxygen diffuses through water 10,000 times more slowly than through air. This 10,000-fold difference means soil pores filled with water will reduce considerably the diffusion of oxygen into the soil. Because the moisture release curves are higher for clay soils than sandy soils, it is no surprise that clay soils, with their higher percentage of micropores, are often poorly aerated. Under these conditions, the CO_2 produced by soil animals, plant roots, and microorganisms accumulates, and it is possible to have clayey soils with CO_2 concentrations hundreds of times higher than the atmosphere.

Soil aeration is commonly measured in terms of a redox (*red*uction—*ox*idation) potential. The **redox potential** is the measure of the tendency of a compound to accept or donate electrons. As electrons are transferred, a potential difference is created, and this difference is measured in millivolts (mv); the potential itself is abbreviated

E_h. As a substance loses electrons (e.g., $Fe^{2+} \rightarrow Fe^{3+}$), it becomes more positive (more oxidized); as it gains electrons (e.g., $Fe^{3+} \rightarrow Fe^{2+}$), it becomes more negative (more reduced). The more oxidized (aerobic) a soil becomes, the more positive the millivolt reading. Waterlogged soils, especially those with an available carbon source, generally have a low redox potential, and these environments are conducive to anaerobic processes like methane production and sulfate reduction. In general, aerobic soils are "oxidizing" environments and anaerobic soils are "reducing" environments. For a more detailed description of redox reactions, refer to Chapter 10.

Box 2–13

Soil Aeration, Redox Potential, and Soil Color. There is an interesting relationship between soil aeration and soil color (a soil physical characteristic). When soil is well-aerated, elements like iron and manganese are oxidized and soil colors of red, yellow, and reddish-brown predominate. When soil is poorly aerated, these elements are reduced, and soil colors of blue and gray predominate. When soils have mixed zones of good and poor aeration, soils will have a mottled appearance.

Thus, the soil atmosphere differs from the overlying air in two important ways:

- it contains less oxygen and
- it contains a much higher concentration (10- to 100-fold) of carbon dioxide.

These differences arise from the respiration of roots, soil animals, and soil microbes as well as the physical constraints on diffusion.

Temperature

Soil temperature greatly influences the rates of biological, physical, and chemical processes in the soil. It is well known that, within a limited range, the rates of chemical reactions and biological processes double for every 10°C increase in temperature. This is often stated as the "Q_{10} for biological systems" (i.e., $Q_{10} = 2$). In addition, soil temperature and soil moisture are inextricably linked. Water has a high specific heat; that is, it requires a considerable amount of energy to raise 1 cm^3 of water by 1°C. When water is added to soil, it is easy to understand how the high specific heat of water and the natural high density of soil combine to moderate rapid changes in soil temperature. This effect increases with soil depth. As soil depth increases, the temperature of the soil *below* the soil surface lags behind the temperature of the soil surface and the temperature fluctuation is reduced (Fig. 2–10). This is one important way that soil microbiology differs from aquatic microbiology: the mass of soil moderates the rapid fluctuation of environmental parameters more commonly found in aquatic systems (Alexander, 1977).

grating Soil Physical Characteristics and Soil Abiotic Factors h Microorganisms

Tillage is a mechanical stirring of the soil surface to provide a suitable environment for seed germination and root growth. In conventional tillage, almost 100%

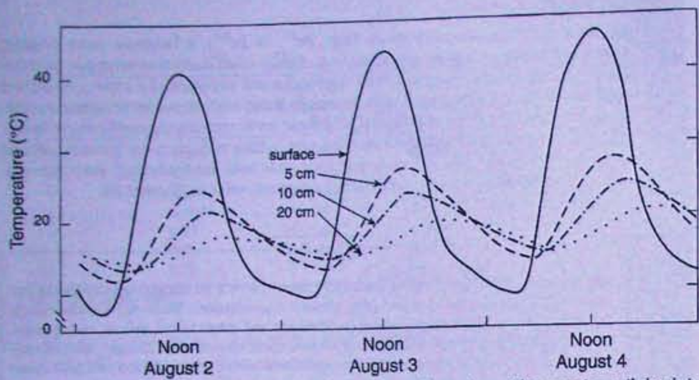


Figure 2–10 Increasing lag and moderation of temperature fluctuation with increasing soil depth in a bare soil from Rothamsted, U. K. *Adapted from Wild (1988). Used with permission.*

of the soil surface is overturned, usually with a moldboard plow (Fig. 2–11a and 2–11b). This helps to control weeds and other pests. In contrast, in reduced tillage, only a fraction of the soil surface is overturned, usually with a chisel plow (Fig. 2-11c). Although it is harder to control weeds and other pests with reduced tillage, the practice does leave large amounts of crop residues on the soil surface, which serve as a mulch to conserve moisture and reduce soil erosion. Also, by not turning over as much soil, reduced tillage saves time, fuel, labor, and equipment.

In a study of the effects of reduced tillage versus conventional tillage on soil microorganisms, soil microbiologists looked at several soil characteristics (Table 2–4, Part A; Linn and Doran, 1984). Because crop residues are substrates for the formation of organic matter, the total organic C and N are significantly higher in reduced till soils than in conventional till soils for the 0 to 7.5 cm depth. In addition, the crop residues, with their low particle and bulk densities, were not incorporated into the soil; consequently the bulk densities of the reduced till soils were significantly higher (i.e., the soils were more compact) than the conventional till soils at both soil depths. When combined with the mulching effect of organic matter, the higher bulk densities in the reduced till soils trap more of the soil moisture (and hence more water-filled pore space) than conventional till soils at both depths.

The increases in C and N (more nutrients) for the 0 to 7.5 cm depth of reduced till soil increase the bacterial populations of total aerobes, facultative anaerobes, and total anaerobes (Table 2–4, Part B). How were populations of anaerobes able to grow so near to the soil surface? Possibly, the higher amount of water-filled pore spaces prevented O_2 diffusion into the soil, and portions of the soil became more anaerobic (i.e., there were anaerobic microsites).

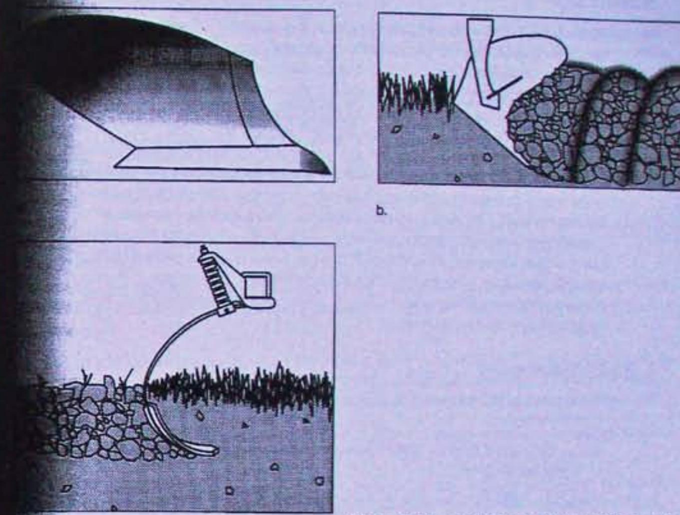


Figure 2–11 A moldboard plow viewed from the side (a) and rear (b), and a chisel plow (c).

Table 2–4 **Physical and chemical (A) and microbiological (B) differences between reduced tillage and conventional tillage in soils at six locations**

Soil characteristic	Ratio of reduced tillage: conventional tillage at two soil depths	
	(0 to 7.5 cm)	(7.5 to 15.0 cm)
A. Physical and chemical properties		
Total organic C	1.41*	0.99
Total N	1.29	1.01
Bulk density	1.04	1.05
Water-filled pore space	1.28	1.11
B. Microbial group		
Total aerobes	1.35	0.66
Bacteria	1.41	0.68
Fungi	1.35	0.55
Facultative anaerobes	1.31	0.96
Total anaerobes	1.27	1.05

*A ratio of more than 1.00 means the value for reduced tillage was higher than conventional tillage.
Adapted from Linn and Doran (1984). Used with permission.

Summary

This chapter covered soil description and the principal soil characteristics and factors that define the soil habitat, the most complex of all microbial habitats. Soil description includes differences between mineral and organic soils, horizons, series name, and textural class; soil physical properties include bulk density, particle density, and pore spaces; soil chemical properties include pH and anion and cation exchange capacity; and soil abiotic factors include soil water, soil aeration, and soil temperature. Some of these characteristics and factors are integrated with soil microorganisms to illustrate how soil conditions can influence soil microorganisms. However, it is equally important to understand that soil microorganisms can, in turn, influence some of these conditions and characteristics positively or negatively. Knowing this interdependency helps explain the enormous heterogeneity in soil—how, within the space of a few millimeters, some microorganisms will grow and others will die and how some microbial processes will begin and others will stop. Knowing this interdependency is the key to understanding "soil" and, indeed, understanding soil microbiology.

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Study Questions

1. A sample of the Eel soil series from upstate New York contains 158 g of clay kg^{-1} and 279 g of sand kg^{-1}. Using the soil triangle in Figure 2-2, determine the textural class of this soil.
2. The CEC of the Ap horizon of Tifton loamy sand is 2.6 cmol kg^{-1} of soil; the CEC of the Ap horizon of an Eel soil series is 10.6 cmol kg^{-1} of soil. What is CEC and how would the CEC differences between Eel and Tifton soils be important to soil microorganisms?
3. Discuss the source of electrical charge in (a) an aluminosilicate clay, (b) organic matter, and (c) a typical bacterium.
4. A 10 cm layer of sand is on top of a 10 cm layer of clay. Water is poured on the top of the sand. (a) Diagram how the water moves through the sand into the clay. (b) Which layer has the greater water potential and why?
5. A soil microbiologist is walking from one laboratory to another carrying a flask containing a sterile, nonselective broth for growing bacteria. He accidentally trips and falls. He's all right but the medium has spilled on a patch of bare soil. (a) In the portion of soil that has been wetted, how would the ability of soil microorganisms to physically and chemically bind the soil be affected? (b) What other soil properties and characteristics would be affected that would, in turn, affect soil microorganisms?

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TROPHIC INTERACTIONS AND NITROGEN CYCLING IN A SEMI-ARID GRASSLAND SOIL

I. SEASONAL DYNAMICS OF THE NATURAL POPULATIONS, THEIR INTERACTIONS AND EFFECTS ON NITROGEN CYCLING

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SUMMARY

(1) Organism trophic structure and interactions and soil nutrient levels were assessed for a semi-arid grassland steppe monthly between April and October 1982. The observed trophic interactions with resultant changes in soil nitrogen were interpreted on the basis of simple predator–prey microcosm studies and models.

(2) Seasonal responses in trophic interactions and N mineralization–immobilization processes were: (i) in the spring, predator groups (protozoa and nematodes) increased as their food sources (bacteria and fungi, mainly) increased, subsequently reducing microbial biomass; (ii) reduced decomposer and increased grazer numbers occurred concomitant with increases in soil inorganic N; (iii) increased decomposer numbers (fourfold increase in bacterial numbers in September, for example) corresponded to decreased levels of soil inorganic N.

(3) The complex, highly interconnected, and multi-linked food web that exists in the shortgrass prairie appeared to be stable in spite of considerable abiotic fluctuations (temperature extremes, water stress, and short period of active plant growth). The ability of predators to use more than one prey group provided a stabilizing influence.

INTRODUCTION

Predicting the outcome of perturbation of natural ecosystems requires an understanding of the functions, interactions and processes carried out by the communities within that ecosystem. Characterization of the communities in an ecosystem in terms of the functions carried out by the component groups (such as detritus processing, predation, nutrient cycling) is most important to understanding why and how that ecosystem exists (Cairns 1982). Several models of energy and nutrient cycling have shown that it is necessary to determine microbe-predator interactions in order to accurately determine turnover rates (e.g. Heal & MacLean 1975; Hunt *et al.* 1984). The soil community in arid grasslands consists of populations of bacteria, including actinomycetes, fungi, protozoa, nematodes, microarthropods and macroarthropod groups. Some cyanobacteria are found on the undersides of small rocks on the soil surface and are a negligible portion of the total

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microbial biomass. Numbers and types of soil organisms differ between ecosystems, and these differences may change the manner in which nutrients are utilized within a system.

Conceptual model

The model consists of two parts: first, a hypothesized, generalized decomposer food web, the structure of which is shown in Fig. 1 and, second, assumptions of potential controls influencing interactions within the food webs; these are indicated in the following text.

Environmental controls exist on all groups and flows. Abiotic factors, such as temperature and rainfall (moisture), affect the growth and survival of all organism groups in the model and temperature effects were included as Q_{10} effects (Hunt *et al.* 1984). For instance, plant growth was based on seasonal observations for blue grama (Singh & Coleman 1977) and on model-generated data (Bachelet *et al.* 1983). Plants contribute either carbon or nitrogen substrates via various pathways such as exudates, root sloughage, litter and root production.

Other flows, not explicitly shown in Fig. 1, are those to which each organism group contributes—for example, the organic substrate pool via dead biomass and atmospheric CO_2 via respiration. Previous research, and models, such as those by Parton *et al.* (1984) and Hunt *et al.* (1984) have shown that the organic substrate pool could be split into several fractions; however, in order to simplify the model, these flows and fractions were not differentiated. Thus, in this version of the model, primary decomposers (i.e. the bacteria

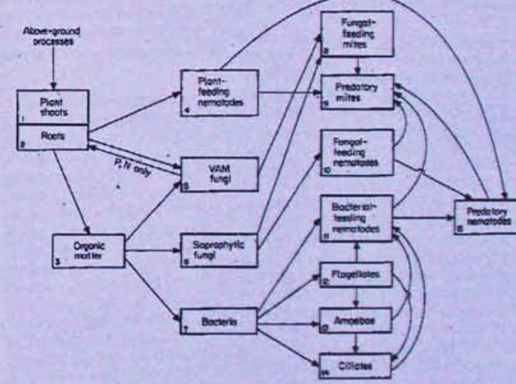

FIG. 1. Conceptual model of belowground trophic food web. Each box contributes dead biomass to organic matter, inorganic N and P and C to CO_2 evolution, which are not shown. VAM: vesicular-arbuscular mycorrhizae.

and fungi) compete for the same limiting resources and affect each other's maximum growth potential.

Bacteria are preyed upon by four groups: flagellates, amoebae, ciliates and bacterial-feeding nematodes. Depending on mouth size, some bacterial-feeding nematodes feed on protozoa as well as bacteria. Amoebae have been observed to engulf flagellate trophs and cysts, and certain ciliates have been observed feeding on flagellates and on occasion feeding on amoebae (E. T. Elliott personal communication).

Saprophytic fungi are preyed upon or grazed by two groups: fungal-feeding nematodes and microarthropods. Fungal-feeding nematodes must puncture fungal cell walls by means of a stylet whereby they remove the cytoplasmic contents. Thus the C/N ratio of substrates utilized by fungal-feeding nematodes is that of cytoplasm (C/N of 3 or 4) and not of whole fungal hyphae (C/N of 10–40). The second group, fungal-feeding microarthropods, may graze upon any fungal hyphae they encounter, although they have been shown to prefer actively growing hyphae as opposed to dead, empty (i.e. contain no cytoplasm) hyphae (J. C. Moore, E. R. Ingham & D. C. Coleman unpublished). Thus, the C/N ratio of their substrate is that of whole hyphae.

Vesicular-arbuscular mycorrhizal fungi (VAM) are included as distinct from saprophytic fungi because of their unique method of obtaining carbon. They enter into a symbiotic relationship with plants where the fungus obtains its carbon from the plant and in return improves the plant phosphorus and nitrogen nutrition (Ames, Ingham & Reid 1982; Ames *et al.* 1984; Tinker 1984). Collembola feed upon VAM fungi (Moore, St. John & Coleman 1985; Warnock, Fitter & Usher 1982) but little evidence exists that fungal-feeding nematodes utilize VAM hyphae in soil (Hussey & Roncadori 1982). Thus, no nutrient flow from VAM fungi to nematodes was included in the model; we assessed this flow in the present experiment.

Plant-feeding nematodes have stylets which penetrate plant root cell walls and extract plant cytoplasm. Thus, plant-feeding nematodes mineralize nitrogen, as their food resource is high in nitrogen relative to their metabolic need for nitrogen (Ingham *et al.* 1985).

The two higher level predators are the predatory mites and nematodes. Both groups graze on bacterial-, fungal- and plant-feeding nematodes. The predatory mites also prey on fungal-feeding microarthropods and predatory nematodes.

Experimental approach

From previous microcosm experiments (Coleman *et al.* 1977, 1978; Anderson *et al.* 1978; Anderson, Coleman & Cole 1981; Trofymow *et al.* 1983; Ingham *et al.* 1985) it was found that, first, ingestion of bacteria or fungi resulted in release of nitrogen as ammonium because dead microbial biomass, especially cytoplasm, should be easily utilized and the nitrogen associated with it quickly ammonified. Second, during bacterial and fungal growth, available nitrogen is immobilized in biomass if the C/N ratio of the substrate is high, as in the case of glucose, cellulose, or chitin. If the C/N ratio of the substrate utilized is low, as with amino sugars or cytoplasm, bacteria and fungi may actually mineralize or release nitrogen. The importance and role of organism groups on each of the above processes of mineralization and immobilization in field situations could be determined by removal of bacterial, fungal, or grazing organism groups. Third, increased bacterial or fungal activity or numbers will be followed by increases in predator populations. When two or more predators use one prey source, a decrease in one predator results in a concomitant increase in the other(s). Fourth, when bacterial or fungal growth becomes limited by

inorganic nutrients, grazing will stimulate growth by releasing nutrients sequestered in the microflora.

Interactions that have been observed in controlled microcosm studies should be observable under field conditions. Furthermore, because the structure and interactive flows of the model were developed from simple agglomerative (Usher, Booth & Sparkes 1982) microcosm studies, experiments conducted in a natural ecosystem will allow *in situ* observation of the processes encompassed in the trophic structure of the conceptual model.

Aspects of food chain length and omnivory in the conceptual model can be tested. The stability hypothesis (Pimm 1982; May 1973) states that the greater the number of species and connectedness, the more unstable the web will be and the more prone the system will be to collapse. The trophic structure in this grassland ecosystem contains several three- to five-link food chains and even one of seven steps (bacteria–flagellates–amoebae–ciliates–bacterial-feeding nematodes–predatory nematodes–predatory or mesostigmatid mites) and many groups are omnivores (protozoa, bacterial-feeding nematodes, mesostigmatid mites), and so our experiment can test whether long chain length or omnivory is destabilizing.

This experiment was designed to observe seasonal trophic interactions in a semi-arid grassland and to validate the conceptual model developed from earlier controlled microcosm studies.

MATERIALS AND METHODS

Site description

On 15 March, 1982, twenty-seven aluminium cylinders 15 cm deep × 10 cm in diameter were placed on predominantly blue grama grass (*Bouteloua gracilis* (H. B. K.) Griffiths) sods at the Central Plains Experimental Range (CPER) (formerly the Pawnee site of the U. S. IBP Grassland Biome) near Nunn, in north-eastern Colorado. The soil is an Ustollic haplargid, coarse-loamy, mesic, mixed.

Experimental design

Timing for sample dates was based on previous knowledge of seasonal cycles of abiotic factors and plant growth (Singh & Coleman 1977; Bachelet *et al.*, 1983; Lauenroth & Milchunas *in press*). On each of the eight sample dates (Fig. 2)—5 April (date 1), 19 April, 3 May, 7 June, 12 July, 3 August, 13 September and 11 October 1982 (date 8)—three cylinders containing soil were randomly chosen, removed from the field and returned to the laboratory within 1 h. All plant material, including crowns, was removed, separated into live and dead biomass, dried (60 °C), and weighed. The N and P concentrations of live shoots were determined according to Thomas, Sheard & Mayor (1967). The soil was divided into depths of 0–5 and 5–10 cm. Cores 5 cm in diameter were removed from each depth for microarthropod extraction (modified Tullgren) (Macfadyen 1962; Merchant & Crossley 1970). The remaining soil from each depth was gently mixed to homogenize it. One gram of soil was removed and added to 9 ml sterile reference soils solution (RSS) (Herzberg, Klein & Coleman 1978). A dilution series was prepared and aliquots removed for bacterial and fungal agar plate counts, protozoan total and cystic MPN enumerations (Singh 1946), both active (Söderström 1979; Ingham & Klein 1982, 1984) and total (Jones & Mollison 1948) hyphal length estimates, and total bacterial (FITC) (Babiuk & Paul 1979) estimations. Media used for bacterial plate counts were nutrient agar and typtone agar, and fungal plate counts were performed using Martin's medium (Difco Laboratories 1953).

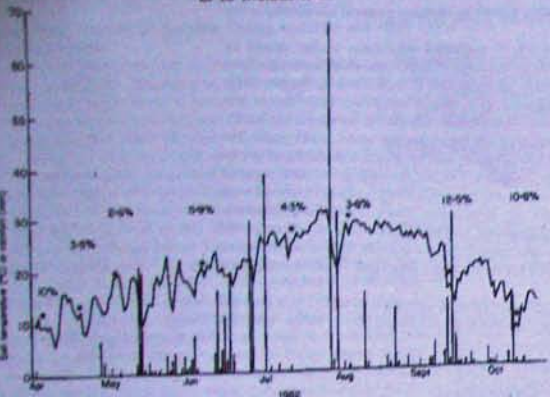

FIG. 2. Soil temperature (at depth of 0–5 cm) and rainfall occurring at CPER from April to October 1982. Solid line represents daily temperatures (°C), vertical bars represent rainfall events (mm of water collected) and stars indicate the times when soil was sampled, with the soil moisture (% H_2O g^{-1} soil) at that time given above the star.

Five grams of soil were weighed, dried for 24 h at 105 °C, and reweighed to determine soil moisture. Four grams of soil were extracted in KCl (Bremner 1965) and NH_4^+-N and NO_3^- + NO_2^--N (referred to as NO_3^--N below) in the extract determined by the methods of Searcy, Reardon & Foreman (1967) and Henriksen & Selmer-Olsen (1970), respectively. Extractable inorganic P was extracted in $NaHCO_3$ and assayed according to the method of Olsen *et al.* (1954). Five grams of soil were extracted for nematodes on Baermann funnels (Anderson & Coleman 1977) and corrected for extraction efficiency. The remaining soil, generally 150 g dry weight, was weighed and sieved (<2 mm) and the root material sorted into dead and new (white-appearing) roots. The lengths of new, mycorrhizal, and total roots were determined by the line-intercept method (Marsh 1971). Active mycorrhizal colonization of roots were quantified using the autofluorescence method of Ames, Ingham & Reid (1982) and total VAM colonization of new roots by clearing and staining (Phillips & Hayman 1970).

Statistical analyses

Statistical analyses were performed using the Statistical Package for the Social Sciences (Nie *et al.* 1975). Least-significant differences ($P \leqslant 0·05$) were calculated only when the F value indicated significance using ANOVA. Only significant differences are given in tables or text, unless otherwise indicated.

RESULTS

Abiotic conditions

Abiotic factors are very important in determining organism responses to perturbations. The cool (<15 °C), dry weather (Fig. 1) through the middle of May limited biological activity. No shoot or root growth was observed until 3 May. The initial (5 April) soil moisture was 10%.

Between 3 and 20 May, temperatures increased (up to 20 °C), although one cold period (<10 °C) occurred. Spring rains began during this time and plants began to respond by increased growth. By 6 June, the fourth sample, growth conditions for both plants and soil organisms were increasingly favourable.

From 20 May to 27 June, temperatures fluctuated around 20 °C, and many small rain showers occurred so that growth conditions remained very favourable. Weather typical of the prairie summer then prevailed from 27 June to 4 September. Temperatures ranged between 25 and 30 °C, with occasional thunderstorms during the sunny, dry days. Soil moisture had been low since mid-April, in the range previously observed during the dry spring period between 1 April and 3 May. Little plant growth occurred during July or August, although green shoot material and new root length were maintained.

Temperatures began to decline, starting on 5 September and continuing through October. Soil moisture reflected increased rainfall and decreased evaporation during this period. Even though moisture was not stressing for organisms, the cool temperatures probably kept activity at low levels.

Bacteria

For both depths (0–5 and 5–10 cm), total bacterial numbers ranged from 1×10^8 to $2 \times 10^8 \cdot g^{-1}$ dry soil in early spring to midsummer in July, except that bacterial numbers were initially higher ($4 \times 10^8 \cdot g^{-1}$ soil) in the 5–10 cm depth than the upper 0–5 cm depth ($1 \times 10^8 \cdot g^{-1}$ soil). In August and October, bacterial counts decreased noticeably from the values on the previous date, dropping from 2×10^8 in July to $0·5 \times 10^8$ in August and from a high value of $6·5 \times 10^8$ in September to 4×10^8 in October. Numbers of viable bacteria or bacterial colonies that grew on tryptone for both depths were approximately an order of magnitude lower than total counts and fluctuated in a manner similar to that for total bacterial counts.

Fungi

Total hyphal lengths for the 0–5 cm depth (Fig. 3) were initially 45 m g^{-1} soil, decreased on the next date when soil temperature was low, but then increased through the growing season. Hyphal lengths decreased in October. In the 5–10 cm depth, total hyphal lengths followed the same pattern except that in general, hyphal lengths were lower, 100 m g^{-1} soil, at the peak in August.

Actively growing hyphal lengths (FDA-stained hyphae) in the 5–10 cm depth followed patterns similar to total hyphal lengths, with active hyphae about 10% of the total lengths. Active hyphae decreased in April and May, with lengths in depths of 5–10 cm initially two-fold higher than in 0–5 cm (Fig. 3). However, in soil depths of 0–5 cm, active hyphae increased rapidly in June and July and then abruptly decreased in August, and remained at that level during September and October. The rate of increase of total hyphae was reflected by the active hyphae present in the previous sample date.

Viable fungi or colony-forming units fluctuated between 5 and 15×10^4 g^{-1} soil.

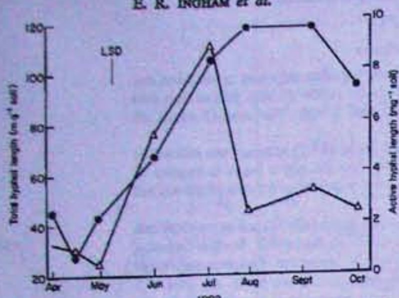

FIG. 3. (Δ) Active and (●) total hyphal length (soil depth of 0–5 cm) g^{-1} soil from April to October 1982. L.S.D., least significant difference.

Vesicular-arbuscular mycorrhizal fungi

Very little new or active mycorrhizal colonization (autofluorescence method) was observed in our study; percentages were usually between 0 and 2%. However, on two dates, July and September, total colonization of new roots was 16·5% and 31% in the 0–5 cm and 5–10 cm depths, respectively. In September, 46% and 33% of new roots were infected, while less than 1% were colonized with active VAM.

Protozoa

Total flagellate numbers maintained steady levels after increasing from lower overwintering numbers (Fig. 4a). In the 5–10 cm depth, numbers were initially higher (10^4 g^{-1} soil), decreased to lower levels than in 0–5 cm on 3 May (70 g^{-1} soil), then maintained slightly lower numbers than in the upper depth (6×10^3 g^{-1} soil) for the remaining sample dates.

Numbers of cystic flagellates were measured only in the 0–5 cm depth because the preponderance of protozoa occur in the top 5 cm (Elliott & Coleman 1977). Cysts were below detection levels initially, slowly increased in June, and fluctuated considerably through October (Fig. 4a). In early spring (April), all the flagellates were active (few cysts), but in May and June, nearly all the flagellates were encysted as cyst numbers nearly equalled total numbers. In July, though, cyst counts decreased (7 g^{-1} soil) while total numbers increased (10^2 g^{-1} soil), so that most flagellates were in active stages. Total numbers remained high and cysts proportionately low through the rest of the season, except for September, when a higher proportion was encysted.

Total amoebal numbers in the 0–5 cm depth were initially extremely low (80 g^{-1} soil) but increased by 3 May remaining between 2×10^3 and 6×10^3 throughout the rest of the summer (Fig. 4b). The population fluctuations for amoebae were different for the 5–10 cm depth. In April and May, amoebal numbers were considerably higher (9×10^2) than in the 0–5 cm depth (90 g^{-1} soil), decreased in June and July and then increased in August, and remained at those levels through September and October. Amoebal cysts

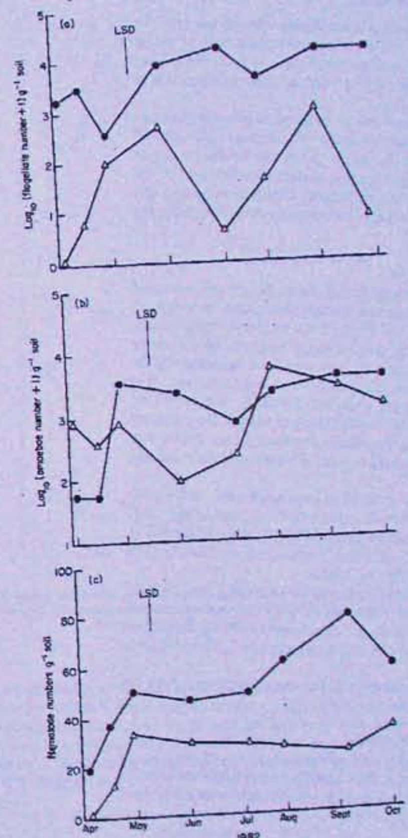

FIG. 4. (a) (Δ) Cystic and (●) total flagellate numbers (at soil depth of 0–5 cm) g^{-1} soil from April to October 1982. (b) Total amoebal numbers in depths of (●) 0–5 and (Δ) 5–10 cm g^{-1} soil from April to October 1982. (c) Total nematode numbers in depths of (●) 0–5 cm and (Δ) 5–10 cm g^{-1} soil from April to October 1982.

(measured only in the 0–5 cm depth) followed the same fluctuations as observed for flagellate cysts except that they increased to 10^3 g^{-1} soil in June, decreased to 30 g^{-1} soil in July, and then returned and remained at 10^2 g^{-1} soil the rest of the summer. Only in May and July did large numbers (between 0·8 and $6·0 \times 10^3$ g^{-1} soil) of active amoebae exist in the soil.

Ciliate numbers were always considerably lower than amoebal or flagellate numbers. In the 0–5 cm depth, total ciliate numbers fluctuated considerably, between 150 and 250 ciliates g^{-1} soil, after an initial spring increase. In the 5–10 cm depth, ciliate numbers fluctuated slightly between 5 and 100 g^{-1} soil from April to August, then increased to 280 g^{-1} soil in September and decreased to 180 g^{-1} soil in October. Ciliate cysts were always low, between 0 and 5 g^{-1} soil. In general, cyst numbers of all protozoa increased during dry periods and decreased during rainy periods.

Nematodes

Total nematodes in the 0–5 cm depth were initially low, about 30 g^{-1} soil, increased rapidly to 71 g^{-1} soil in May, then slowly increased through the summer to a peak of approximately 125 g^{-1} soil in September (Fig. 4c). In the 5–10 cm depth, no nematodes were detected on the first sample date. Numbers then increased rapidly to 54 g^{-1} soil by May, decreased to about 40 g^{-1} soil for June through September, and increased slightly (not significantly) in October to 88 g^{-1} soil. Nematodes were separated into four categories: tylenchid (fungal and plant feeders), rhabditid (bacterial and protozoan feeders), plant dorylaimids (plant feeders), other dorylaimids (omnivores). No predatory nematodes were observed in any sample. Both dorylaimid populations were usually low (0–4). Thus, variations in nematode numbers were a result of changes in rhabditid and tylenchid numbers.

Rhabditid nematodes showed trends similar to those of total nematodes. In the 0- to 5-cm depth, they were initially 19 g^{-1} soil on 5 April, increased to 53 g^{-1} soil in May, then generally remained constant in summer and reached a peak of 75 g^{-1} soil in September. In the 5- to 10-cm depth, numbers rose to 32 g^{-1} soil in May, remained at that level through midsummer, then increased to a peak of 106 g^{-1} soil in August.

Tylenchid (plant- and fungal-feeding) nematode dynamics differed slightly from those of total nematodes. In the 0–5 cm depth, numbers were initially 7 g^{-1} soil and remained at this level through May. An increase in June to 21 g^{-1} soil occurred and was maintained through July, with increases in August (35 g^{-1}) and September (49 g^{-1}) and then a decrease in October to 38 g^{-1} soil.

The ratio of rhabditids to tylenchids ranged from 1·5 (September and October) to 7·6 (May) but averaged about 2·0 (not including the May date).

Microarthropods

Microarthropod numbers were highly variable, usually in the range of 0–20 per 100 g of soil for any set of three replicates. Because of this variability and the low numbers, no significant differences were observed except on the last sample date in October, when numbers increased to 45 g^{-1} soil.

Soil N and P

Concentrations of $NO_3^- + NO_2^-$-N generally decreased through the summer except for two peaks in the 0–5 cm depth in May and August (Fig. 5a) and one in May in the 5–10 cm depth. Ammonium-N concentrations at both depths showed gradual decreases

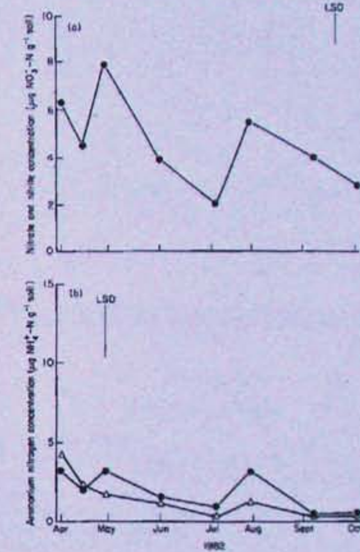

FIG. 5. (a) Nitrate and nitrite nitrogen concentration (at soil depth of 0–5 cm) g^{-1} soil from April to October 1982. (b) Ammonium nitrogen concentration in depths of (●) 0–5 and (△) 5–10 cm g^{-1} soil from April to October 1982.

throughout the sample period except for the August increase as also observed for NO_3^--N (Fig. 5b). In the upper depth, NH_4^+-N concentration was initially lower than in the 5–10 cm depth but steadily decreased to <1 μg g^{-1} soil in October at both depths. Inorganic extractable phosphorus concentrations maintained uniform levels in both depths although it was always higher in the upper depth, 20–30 μg g^{-1} soil as compared to the lower depth concentrations of 8–18 μg g^{-1} soil.

Plant roots

Total root length increased early in the season, decreased through June, increased in July after rainfall and then decreased to levels observed at the beginning of the season. Total root length in the 5–10 cm depth mirrored that in the 0–5 cm depth, except it was

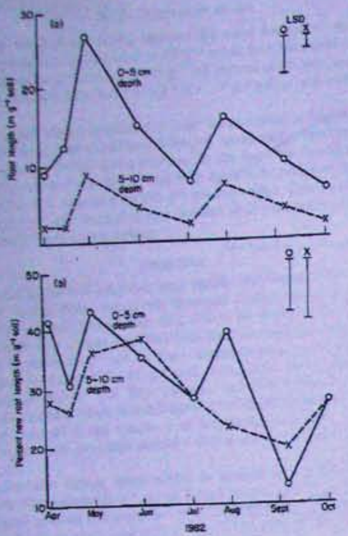

FIG. 6. (a) Total root length (m g^{-1} soil) from April to October 1982. (b) Per cent of new root length in m g^{-1} soil from April to October 1982. (O——O), depth of 0–5 cm; (×——×), depth of 5–10 cm.

threefold lower (Fig. 6a). Per cent of new or live root length fluctuated considerably at the 0–5 cm depth but not as much at 5–10 cm (Fig. 6b). Major peaks in per cent new roots corresponded to peaks in total root lengths in May and July.

Plant shoots, N, and P

Typical blue grama growth responses through the sampling season were observed (Fig. 7). Live shoot weight was below detection level in April before growth began and increased to a maximum in August. In contrast the N concentration in live shoots peaked in May and then decreased slowly through the summer. A small, non-significant ($P \geqslant 0{\cdot}05$) increase to 1·2% N occurred in October. Total P in live shoots followed a pattern similar to N. In May, P concentration was at 0·37%, slowly decreased through August and September (0·16%), and increased slightly but not significantly to 0·18% in October.

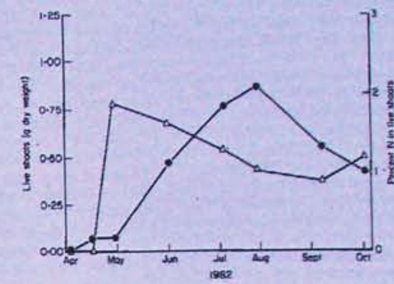

FIG. 7. (●) Live shoot dry weight produced per cylinder and (Δ) percentage nitrogen in live shoots per cylinder (75 cm^2 surface area) from April to October 1982.

DISCUSSION

Trophic interactions

Bacterial–predator interactions

Evidence of predation decreasing bacterial populations was observed in seasonal bacterial responses. Increased bacterial populations would be expected in early spring as growth conditions become favourable. While bacterial increases were not observed in April, amoebal and ciliate numbers increased considerably. These protozoa grazed bacteria and kept the standing crop of bacteria from increasing. Nematodes, primarily bacterial-feeders, increased at times of the bacterial increases in May and September. As bacteria increase in activity and numbers, increasingly more N should be immobilized in their biomass, assuming a wide C/N ratio substrate (see Experimental Approach above), thus reducing N available for plant growth. Both NO_3^-- and NH_4^+-N decreased (were immobilized) between 5 and 19 April, but then NO_3^--N increased from near 4 to 8 μg NO_3-N on 3 May, at the same time that ciliate and amoebal populations increased by one to two orders of magnitude. Ciliates and amoebae mineralize N from bacterial biomass (Stout 1980; Anderson, Coleman & Cole 1981; Bryant *et al.* 1982; Ingham *et al.* 1985) making N available to other organisms because it is no longer sequestered in microbial biomass. Although the mineralization process is generally considered to release NH_4^+-N, nitrification can occur quickly. During plant growth in natural systems, the predator-prey interaction and subsequent N release following grazing cannot be followed by measuring soil inorganic N, because of N uptake during plant growth. Thus, after 3 May, when plants began to grow, to July, when plant growth essentially ended, inorganic N in the soil was constantly depleted by plant uptake.

Another interaction of bacteria and grazers was evident at the end of the summer. With the hot, dry weather in July and August, bacterial numbers decreased twofold. Decreased bacterial growth reduced N immobilization by bacteria while dead bacterial biomass continued to be mineralized. This resulted in increased N availability, as both increased

NO_3^--N and NH_4^+-N concentrations in soil were observed. Plants maintained the live shoot weight and shoot N concentration attained earlier under more favourable growth conditions, and their demand for N was less. Thus, the effect of reducing bacterial populations on N cycling was observed.

In August, total ciliate numbers decreased by nearly one order of magnitude, reflecting perhaps both decreased bacterial numbers and adverse abiotic effects. While total amoebal numbers did not decrease, the number encysted increased by nearly two orders of magnitude, so that few active amoebae remained (Fig. 4b). Total flagellate numbers were halved, and cystic flagellates increased by an order of magnitude, leaving few active flagellates (Fig. 4a, number active indicated by area between the two lines) to graze the bacterial population. Total nematode numbers increased slightly at this time in all categories of nematodes. After the dry August period when decreased activity was observed in many groups, total bacterial numbers increased nearly fourfold. This large increase was probably a bacterial response to improved abiotic conditions (Fig. 2), decreased predation pressure by ciliates, amoebae, and flagellates, and dead biomass, which could be utilized as substrate. Whereas in August, when many active flagellates were present (Fig. 4a), encysted flagellates increased in September by another order of magnitude as compared to the August date, leaving few active flagellates. However, active ciliates (total minus cysts) showed an increase in September, perhaps in response to increased bacterial numbers. Since ciliates did not encyst to escape the adverse conditions in August, their low population in August was essentially all active and able to respond to an increase in bacterial numbers. Amoebae and flagellates appeared to respond to stress by encysting which would decrease their ability to respond rapidly to increased bacterial numbers.

Bacterial numbers decreased in October possibly as a result of cooler temperatures. Only the number of active flagellates increased between September and October, as encysted forms decreased while totals remained constant. Amoebae and ciliates remained at the same numbers as in September, with no change in totals or cysts while all classes of nematodes decreased. No significant change in inorganic N was noted, although an increase might have been expected because of N released from the reduced bacterial population. Two explanations are possible: (i) only enough bacterial biomass was mineralized by reduced grazer populations to reduce the deficit in N observed in August, and (ii) plants may have been responsible for uptake of mineralized N because new root length increased, as did the percentage of N in live shoots at this time. It is typical of blue grama to increase N in live shoots and to undergo root growth during the autumn, when moisture is not limiting (Ares & Singh 1974).

Bacterial-feeding nematode numbers increased from 61 to 75 g^{-1} soil in September in response to increased bacterial numbers but not enough to significantly reduce the bacterial population. The increase in bacterial numbers could have immobilized 8·3 μg N g^{-1} soil, and observed decreases in NH_4^+-N and NO_3^--N totalled approximately 4 μg g^{-1} soil in the 0–5 cm depth. Therefore, inorganic N in soil decreased in September, as bacteria immobilized more N into biomass.

Fungal–predator interactions

Since fungal increases and decreases correlated better with seasonal trends and not nematode dynamics, nematode predation of fungi did not appear to be a major factor controlling fungal populations. Total hyphal lengths in these prairie soils (50–100 m g^{-1} soil) are low compared with those in other systems. Forest soils and litter contain from 390 to 16 500 m hyphae g^{-1} soil (Berg & Söderström 1979), 140 to 66 900 m g^{-1} soil (Bååth &

Söderström 1979), and 3287 to 6909 m g^{-1} soil (Domsch *et al.* 1979). Agricultural soils contain 178–387 m hyphae g^{-1} soil (Domsch *et al.* 1979) and up to 1000 m g^{-1} soil (Schnurer, Clarholm & Rosswall 1983), but most undisturbed semi-arid grassland soils contain much lower amounts of hyphae, between 50 and 300 m g^{-1} soil (Clark & Paul 1970; Nakas & Klein 1980). These low fungal levels may mean that not enough biomass exists in such soils to support large populations of fungal-feeders. The lengths of active hyphae in this soil were similar to, or greater than, those of active fungi in forest litter, agricultural, or fertilized-grass systems (Warcup 1957; Söderström 1979; Domsch *et al.* 1979). Explanations for this higher proportion of active hyphae may be that dead hyphae persist longer in other systems or that some organism may be present in this grassland that quickly degrades empty fungal hyphae. The organisms that utilize fungal hyphae are specific bacteria, especially actinomycetes, fungi, fungal-feeding nematodes and certain arthropods. Reports of amoebae that attack and degrade fungal hyphae have been made (Chakraborty, Old & Warcup 1983) but have not been observed in this system (J. Frey personal communication).

Fungi also immobilize nitrogen in their biomass, which is then mineralized when hyphae are grazed. A higher percentage of the N is contained in cytoplasm (e.g. proteins, enzymes), while less is immobilized in fungal cell walls. Thus, when active hyphae are attacked by nematodes, which remove only the cytoplasm and leave the wall material, N will be excreted into the soil because the C/N ratio of nematodes is higher than that of fungal cytoplasm, 8:11 as opposed to 3:5 (Ingham *et al.* 1985). If active hyphae become inactive through abiotic stress or lack of substrate, cytoplasm is utilized to produce resting stages, such as spores, sclerotia, or fruiting bodies, leaving empty hyphae in the soil. Nitrogen in these inactive and/or dead, empty hyphae can be utilized by arthropods, other fungi or bacteria.

In early spring, active and total hyphal lengths decreased slightly (56 μg fungal biomass g^{-1} soil), concomitant with an increase in nematodes. Most of this increase was due to bacterial feeders, but fungal- and plant-feeding nematodes also significantly increased (by perhaps 25 fungal-feeding nematodes). No change was noted in arthropod numbers (0–4 per 100 g^{-1} soil) at this time or later in the summer, so this reduction in hyphal biomass may be attributed to the fungal-feeding nematodes, since this population was calculated to consume 53 μg fungal biomass g^{-1} soil. The increase in concentration of inorganic N on 3 May (5 μg N g^{-1} soil, 0–5 cm depth) may have been partly the result of N released by nematode predation on fungal hyphae, which was calculated as 9 μg N g g^{-1} soil.

The increases in active hyphal lengths (tenfold between May and June and twofold between June and July) were reflected by increases in total hyphal lengths. Nematodes did not increase in number and thus did not increase predation pressure on fungi during this time. Arthropod numbers increased from 0–4 to nearly 15 per 100 g soil during this period. While arthropods may have consumed and kept nematode numbers low, they did not appear important in reducing fungal hyphae.

Active hyphal lengths decreased significantly in August, concomitant with the large decrease in bacterial numbers. It is possible that much of the decrease in hyphae was caused by abiotic factors, but nematodes also increased by this sample date. The increase in inorganic-N concentrations at this time was noted previously, in discussing bacterial–predator interactions, and was probably contributed to by the 4 μg N g^{-1} soil mineralized by nematode predation on active hyphae.

Nematodes continued to increase between August and September, and actively growing hyphae remained at the level to which they had decreased in August. This indicates that hyphal production was high enough to support the increased nematode population. Some balance between N immobilization caused by hyphal uptake and N mineralized by nematode predation occurred. These processes, coupled with bacterial immobilization (fourfold increase in bacteria between August and September), probably resulted in the decreased inorganic N observed in September.

Total hyphal lengths declined between August and October, the period during which active hyphal lengths were kept low by nematode predation. Some empty or inactive hyphae were degraded during this time or total hyphal lengths would have been maintained at the peak reached in July. Total hyphae (but not active hyphae, which remained constant), nematodes, and bacteria decreased between September and October. Arthropods increased, though, from 15 to about 45 per 100 g soil and could have utilized both nematodes and fungi for food while bacteria were grazed by the protozoa. An increase in inorganic-N levels would have been expected as bacteria and fungi were grazed, but, as mentioned, plant uptake (greater shoot N observed) may have been responsible for the net decrease in soil inorganic N.

Vesicular-arbuscular mycorrhizal fungi

Active VAM fungal-colonization of plant roots, as measured by autofluorescence, was low throughout the summer. Allen (1983) has shown that arbuscular or active infection corresponds with periods of active plant growth and nutrient uptake. This agrees with the peak of active VAM-fungal colonization in June, concomitant with the peak in active saprophytic hyphal lengths and just after maximum new root length production. However, the maximum active colonization observed (2%) was below the 4–6% active mycorrhizal colonization that is needed to influence the source of nitrogen and its distribution within root and shoot tissues of plants grown in an N-deficient soil (Ames *et al.* 1984).

The clearing and staining technique gave higher values (16–46%) for mycorrhizal roots but these were lower than previously reported values (90%) in this system (Davidson & Christensen 1977). The clearing and staining method measures both active and inactive, arbuscular and non-arbuscular infection, while the autofluorescence method measures only active arbuscular infection. Thus, the higher levels of total infection indicate cumulative infection throughout the growth of these roots, and may not reflect the actual benefit the plant receives from VAM infection. The low active and total VAM infection observed during summer 1982 suggest that adverse conditions occurred that reduced infection. Causes of reduced infection in control treatments will be discussed in Ingham *et al.* (1986).

Conclusions

Evidence for several trophic interactions was observed. In spring, protozoa, bacterial-feeding and fungal-feeding nematodes increased as they grazed and reduced bacterial and fungal numbers, resulting in mineralization of N. Later in the summer, conditions were dry and hot, possibly killing many organisms. Bacteria, fungi, amoebae and ciliate numbers were reduced although flagellates and bacterial- and fungal-feeding nematodes increased. This reduced immobilization and increased mineralization resulted in peaks of soil nitrate and ammonium. By September, growth conditions improved, with increases in new roots and a fourfold increase in bacterial numbers, resulting in immobilization of soil N. At the same time arthropods increased, grazed and reduced total hyphae and nematodes.

These trophic interactions resulting in changes in soil N concentrations support results observed in microcosm experiments (Anderson *et al.* 1978; Cole *et al.* 1978; Coleman *et al.* 1978; Anderson, Coleman & Cole 1981; Clarholm 1981; Woods *et al.* 1982). Grazing

of bacteria and fungi by predators resulted in increased soil inorganic N, predator populations declined following reduction of prey, and plant growth increased after decreases in nematode populations.

The three- to seven-link food chains which exist in this grassland ecosystem, along with the many omnivore groups, were seen to be stable and, if anything, the ability of predators to utilize more than one prey group appeared to stabilize their populations. These observations do not support the hypothesis that greater connectedness increases the probability of the system to collapse (Pimm 1982).

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TROPHIC INTERACTIONS AND NITROGEN CYCLING IN A SEMI-ARID GRASSLAND SOIL

II. SYSTEM RESPONSES TO REMOVAL OF DIFFERENT GROUPS OF SOIL MICROBES OR FAUNA

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SUMMARY

(1) Perturbations were performed on organisms in a below-ground trophic food web in a semi-arid grassland, using five separate biocide treatments to observe changes in trophic structures, interactions, and nutrient cycling. Changes in N mineralization and trophic interactions as predicted on the basis of simple predator–prey microcosm studies were observed following removal of particular groups.

(2) Five biocides: streptomycin (bactericide), captan and PCNB (fungicides), carbofuran (insecticide–nematicide), and cygon (acaricide) were applied *in situ* to soil in cylinders containing predominantly blue grama grass. The response of microbes, fungal grazers, soil inorganic N and plants were followed monthly between April and October 1982.

(3) Grazing of bacteria or fungi by predators resulted in one or more of the following occurrences: (i) increased soil inorganic N, decreased predator populations following reduction of prey or increased plant growth after reduction of nematodes; (ii) reduction of one group of decomposers, e.g. bacteria, allowed a second decomposer group, e.g., fungi, to increase in numbers; (iii) compensatory responses of microbial feeders, e.g. decreases in bacterial feeders (protozoa and bacterivorous nematodes) were followed by compensatory increases in fungal feeders, which increased following the increase in their fungal food supply.

(4) Continuing changes in nitrogen cycling were not observed, presumably because the function of the reduced group was compensated by increased numbers of the second group performing a similar function. Nematode–VAM interactions must be considered in food web and nutrient flows, as the percentage of VAM colonization of plant roots increased markedly when nematode populations were decreased by nematicide treatment. Production of predator biomass was as important as microbial and plant production in determining nutrient flow in this system.

INTRODUCTION

Experimental approach

The holistic method of investigating the function of communities in natural systems consists of perturbing the system, watching what happens, and inferring from these observations the organization of the system (Usher, Booth & Sparkes 1982). Most

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perturbation experiments have usually examined only the effect of the perturbing agent on a specific population or process instead of demonstrating trophic interactions and community structure by observing changes in non-target groups as well. Two types of perturbations have been described. One, a transient change in a population or system function, is a 'pulse', while the other, depressing and maintaining this status, is termed 'press' (Bender, Case & Gilpin 1984).

Recent studies by Stanton, Allen & Campion (1981), Santos, Phillips & Whitford (1981), Santos & Whitford (1981), Whitford *et al.* (1983), and Parker *et al.* (1984) show that various biocides successfully limit activities of certain target groups of soil organisms. Reduction of mites, fungi or nematodes by these researchers resulted in shifts in decomposition processes, populations of competing organisms, and, in some cases, significant increases in plant growth.

One difficulty with biocide applications is lack of knowledge concerning either direct or indirect effects of these biocides on non-target organisms (Anderson 1978). For example, captan is known to reduce *Verticillium* and *Fusarium*, two fungal plant pathogens (de Bertoldi *et al.* 1977), but its effects on bacteria, nematodes, microarthropods and many plant species are not well documented (Ingham *et al.* 1985). As an initial step in observing the effects of eight biocides on organisms in simple soil microcosms and to facilitate choice of effective biocides, preliminary experiments were carried out with bacteria, fungi and protozoa, with and without plants (Ingham & Coleman 1984). Based on these initial microcosm results, five biocides, described below, were chosen for the field study.

One further undertaking was to determine the duration of the effect of a one-time-only application on target populations. Preliminary experiments showed that target organism effects lasted for at least one month (Ingham & Coleman 1984).

Conceptual model

The perturbation experiments performed in this experiment allowed further validation of the conceptual model developed for the shortgrass prairie (see Ingham *et al.* 1986). Specifically, testing involved removal or reduction of bacteria, two different functional groups of fungi, nematodes or microarthropods, to determine the effects on other organism groups and on nutrient cycling. The following assumptions were used to hypothesize what would happen if particular organism groups were removed: (i) with respect to the C/N ratio of the organism utilizing the substrate, low C/N ratio substrates generally result in mineralization of N and high C/N ratio substrates result in immobilization; (ii) reduction in a predator results in increased numbers of prey; (iii) reduction in a resource results either in a reduction of predator numbers or forces the predator to switch to other resources, if possible; and (iv) competition for common food resources occurs and a decrease in one group will allow an increase in a competing group.

These perturbation experiments also allowed further testing of the ability of each biocide to reduce its specific target group in field conditions, the effects of removal of different organisms on nutrient cycling and community structure and the duration of these effects. Furthermore, the stability of food chains of three to seven steps which also contain omnivorous organism groups was tested.

MATERIALS AND METHODS

Site description

On 15 March 1982, 150 aluminium cylinders 15 cm deep × 10 cm in diameter were placed on predominantly blue grama grass (*Bouteloua gracilis* (H. B. K.) Griffiths) sods at

TABLE 1. Biocides, target group, amount added, C/N ratio and N added in field biocide experiment

Biocide*	Target group	Amount used (g^{-1} soil)	C/N ratio of biocide	Amount N added with biocide ($\mu g\ g^{-1}$ soil)
Streptomycin	Bacteria	3 mg	6	500
Captan	Fungi (saprophytic)	25 µg (50% a.i.)†	18	0·72
PCNB	VAM fungal infection Phycomycetes Basidiomycetes	100 µg	21	5
Carbofuran	Nematodes (+ higher insects)	25 µg (10% a.i.)	17	0·15
Cygon	Microarthropods	0·2 mg (4 lb gal^{-1}, 44% a.i.)	12	8

* Biocides were applied only once, on 3 April 1982.
† a.i., active ingredient.

the Central Plains Experimental Range (CPER) (formerly the Pawnee site of the U. S. IBP Grassland Biome) near Nunn, in north-eastern Colorado. There were three replicate soil cylinders for each of six biocide treatments including controls on each of eight sample dates. The soil is an Ustollic haplargid, coarse-loamy, mesic, mixed.

Experimental design

On 3 April 1982, five biocides (Table 1) and water alone in the control treatments were applied by injecting 250 ml of tap water in 50 ml aliquots to five points in the cylinder and delivering approximately 12 ml of solution or suspension at each 5-cm increment, starting at 15 cm and ending at the surface. Soil within the cylinder received concentrations (per gram soil) as follows: 3 mg streptomycin, 25 µg (50% active ingredient, or a.i.) captan, 47 µg (44% a.i.) cygon (Cygon 400, American Cyanamid Corp.), 25 µg (10% a.i.) carbofuran (Furadan 10, FMC Corp.), and 100 µg penta-chloronitrobenzene (PCNB) (Table 1).

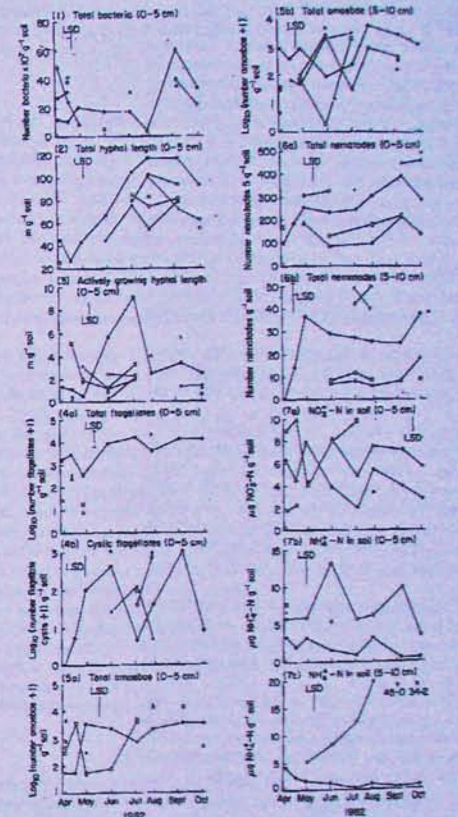
Sampling procedures and assays used to determine the effects of biocides on organism groups, nutrient levels and plant responses are the same as in Ingham *et al.* (1986).

RESULTS

No biocide treatment affected total microarthropod numbers, total root lengths, percentage of new root length, litter or dead shoot dry weights. No predatory nematodes were extracted in our samples, although they are known to be present at the CPER (C. R. Morley personal communication).

Only significant differences of treatments from controls are discussed in the following sections, unless specifically noted. Significant effects ($P \leqslant 0·5$), based on control values, will be expressed as direct effects of the biocide when in fact the effect may have been secondary (the biocide reduced group A, which then caused a resulting secondary effect on group B).

Abiotic conditions for the sampling period, April–October 1982, are described in Ingham *et al.* (1986).



FIGS 1–7. Responses of organisms or chemical components g^{-1} soil to seasonal changes (●——●) or biocide applications: (○) bactericide (streptomycin); (×) fungicide (captan); (△) nematicide (carbofuran); (☆) VAM fungal infection reducer (PCNB); (□) acaricide (cygon). Biocide response points are shown only when significantly different ($P \leqslant 0·05$) from control values and are connected when they were significantly different from controls for consecutive sample dates. LSD, least significant difference.

Bacteria

Streptomycin did not consistently reduce total or viable bacterial numbers. There was one increase in total bacterial numbers, in April, and three decreases in the summer, in June, September and October (Fig. 1). PCNB initially increased total bacterial numbers (April) but otherwise had no lasting effect on bacterial populations. Carbofuran initially resulted in increased total bacterial numbers (Fig. 1), decreased them in May and then increased again in July. While bacterial populations in all treatments decreased in August, bacteria did not increase in September in the carbofuran treatment to the value exhibited by the control. Control total bacterial numbers decreased in October, while bacterial numbers in carbofuran treatments remained the same as those observed in September. Treatment with either captan or cygon did not affect total or viable bacterial numbers in either depth.

Fungi

Streptomycin reduced active hyphal lengths in both depths on the 20 April sample date and the last four samples (Figs 2 and 3) while increases in viable fungi occurred in August and September in both depths.

Captan initially reduced only total hyphal lengths in the upper depth (Fig. 2) but decreased both total and active hyphal lengths (Figs 2 and 3) during the last half of the summer. Captan appeared to be more of a fungistatic agent, as no effect on viable fungal numbers was observed.

In PCNB treatments, total hyphal lengths in the 0–5 cm depth levelled off at 50–80 m g^{-1} soil from May to August, while the controls continued to increase. In September and October total hyphal lengths increased up to 100 m g^{-1} soil, while in controls they decreased (Fig. 2). In depths of 5–10 cm, PCNB decreased total hyphal lengths beginning in June, hyphal lengths remained between 50 and 75 m g^{-1} soil, which was significantly lower than controls, during July–September and finally increased to control levels, similar to the pattern at 0–5 cm, in October. Active hyphal lengths in both depths were significantly lower than controls from June to October except for August (Fig. 3).

Viable fungal numbers were not affected by carbofuran, while total hyphal lengths were decreased only in August and September in the 0–5-cm depth (Fig. 2). Although the pattern of actively growing hyphal length responses in carbofuran treatment were similar to those of the control, the increases began later (June) and ended later (August) than in controls (Fig. 3).

Cygon reduced total hyphal lengths in both depths from July to October (Fig. 2), and initially increased and then reduced active hyphal lengths in the 0–5 cm depth (Fig. 3). Active hyphal lengths in the 5–10 cm depth were increased in May but were reduced in July–August as were observed at depths of 0–5 cm. Viable fungal numbers were not affected in the 0–5 cm depth but were reduced in May in June at the lower depth.

Vesicular-arbuscular mycorrhizal fungi

Mycorrhizal colonization was not affected by streptomycin or cygon. In captan-treated soils the percentage of vesicular-arbuscular mycorrhizal (VAM) fungal-colonized roots (8%) increased in the 5–10 cm depth only from July through October. PCNB effects on VAM fungal-colonized roots were indistinguishable from controls (0–2%).

In carbofuran treatments, mycorrhizal colonization was increased to 15% in both depths in July and to 10% in August in the 5–10 cm depth. These increases in active VAM

fungal-colonization (autofluorescence, Ames, Ingham & Reid 1982) were corroborated by later, significant increases in total colonization from 30 to 45%, using the clearing and staining method.

Protozoa

In streptomycin treatments, cystic flagellates were greater in July and August, while totals were reduced in May (Fig. 4a, b). Total amoebal numbers in the soil depth of 0–5 cm were initially increased in April but then recovered (Fig. 5a). In the 5–10 cm depth of the streptomycin treatment, fluctuations in amoebal populations and the controls were not synchronous (Fig. 5b). Streptomycin did not change ciliate responses.

In captan treatments total flagellate numbers were initially depressed but returned to control levels (Fig. 4a). In captan treatments cystic flagellate numbers were reduced significantly in June and August (Fig. 4b) so that more of the flagellates were active. Total amoebal numbers were reduced until June in the 0–5 cm depth, but then were the same as control numbers. Only an initial reduction of amoebal numbers in the lower depth and no effect on cystic amoebae was observed (Fig. 5a, b). Ciliate numbers were not affected by captan.

In general, PCNB initially increased (0–5 cm) or reduced (5–10 cm) all protozoa, followed by a return to control levels. Cystic flagellate numbers were greater in June and August so that fewer active flagellates were present on these two dates than in controls (Fig. 4a, b). Total amoebae in the 5–10 cm depth tended to fluctuate in an opposite manner from the control (Fig. 5b). Cystic amoebal numbers tended to be lower, although not always significantly, indicating that more amoebae were active in this treatment. Ciliate numbers also tended to fluctuate close to control numbers.

Carbofuran did not affect flagellate numbers, either total or cystic (Fig. 4a, b), increased total amoebal numbers in April in the 0–5 cm depth but decreased them in the 5–10 cm depth, then fluctuated inversely to the control, generally ending lower than the control (Fig. 5a, b). In the 0–5 cm, total ciliate numbers were divergent from controls on two dates only, tenfold lower, thirty-two instead of 560 (controls) in May, and 100-fold higher, 2800 as opposed to thirty-two in controls, in August.

Flagellates, both total and cystic, were not affected by cygon (Fig. 4a, b). In both soil depths, total amoebal numbers fluctuated in an opposite manner than observed in controls (Fig. 5a, b). Cystic amoebal numbers were similar to controls, indicating that in May and June the amoebae were probably all encysted. In the lower soil depth, cygon generally reduced total amoebal numbers (Fig. 5b), so that the population was probably all encysted here also. Ciliates were generally not affected by cygon.

Nematodes

Nematode numbers were not affected by PCNB.

In carbofuran treatments, nematode numbers were significantly reduced in both the 0–5 cm and the 5–10 cm depths for nearly all sample dates from May onwards (Fig. 6a, b). On the first two sample dates, there were nearly twice and one-third times as many bacterial-feeding nematodes as controls, respectively. By May, however, there were fewer bacterial-feeding nematodes than controls; this continued to be so throughout the rest of the samples. Numbers of fungal- and plant-feeding nematodes were reduced only on the last three sample dates.

Nematode numbers were generally reduced by cygon application (Fig. 6a, b), especially late in the summer, although numbers of bacterial-feeding nematodes increased on the first sample date.

Nematode numbers were increased in streptomycin treatments in May, June and October in the 0–5 cm depth (Fig. 6a). In the 5–10 cm depth, increases occurred in July and August (Fig. 6b). In June, the increases in the upper depth were in either fungal-feeding or dorylaimid nematodes, not in bacterial feeders, while in May and October the reverse was true and increased bacterial feeders corresponded to increases in bacterial numbers. When total bacterial numbers decreased, bacterial-feeding nematodes decreased also. Fungal-feeding (tylenchid) nematodes were increased once in the 0–5 cm depth, on the last sample date (October), and twice in the 5–10 cm depth, on the fifth and sixth dates (July and August).

Nematode numbers in both depths increased in captan treatments (Fig. 6a, b), and most of these increases occurred in bacterial-feeding nematodes. The increases occurred in the last half of the summer, at the same time as decreased hyphal lengths were observed.

Microarthropods

Microarthropod numbers were highly variable, usually in the range of zero to twenty for any set of three replicates. Because of this variability and the low numbers, there were no significant differences between treatments.

Soil N and P

Streptomycin increased NO_3^--N in the 0–5 cm depth (Fig. 7a), and NH_4^+-N in both depths (Fig. 7b) although in the 5–10 cm depth, the increases later in the summer were higher than those observed in the 0–5 cm depth (Fig. 7c). Soil P_i in the upper depth generally fluctuated in an opposite manner from the control.

Captan had no effect on NO_3^--N or NH_4^+-N, but just after application (first sample date) increased soil P_i by 13 μg (43 μg as opposed to 30 μg in the control) in the upper depth and by 8 μg (12 μg in control) in the lower depth.

PCNB decreased NO_3^--N twice during the summer in the 0–5 cm depth (Fig. 7a) while NH_4^+-N and P_i were not changed in either depth.

Carbofuran increased NO_3^--N initially followed by a decrease in May, but no further effects observed after these dates in either depth (Fig. 7a). The increase in NO_3^--N corresponded to the two dates that bacterial-feeding nematodes and amoebae were increased. Ammonium-N and P were not affected by carbofuran.

Cygon decreased NO_3^--N in May and then increased both NO_3^--N and NH_4^+-N in June and July in the upper depth (Fig. 7a) with generally similar effects in the lower depth. Inorganic P was increased from the control average 25–40 μg g^{-1} soil in July and October in the 0–5 cm depth and was increased in August and September from the control average of 9–17 μg g^{-1} soil in the lower depth.

Plant roots

Plant root length was not affected by any biocide treatment (see Ingham *et al.* 1986).

Plants shoots, N and P

Streptomycin, after an initial lag in June, increased live shoot dry weight from July to October (Fig. 8) and the proportion of N from May to September (Fig. 9) but did not affect P concentration in live shoots. In captan treatments, live shoot dry weight, percentage of N

FIG. 8.

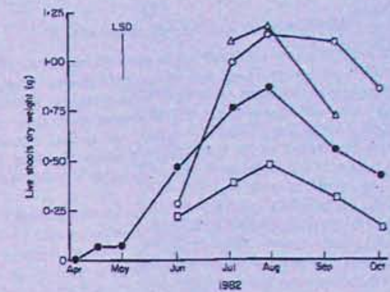
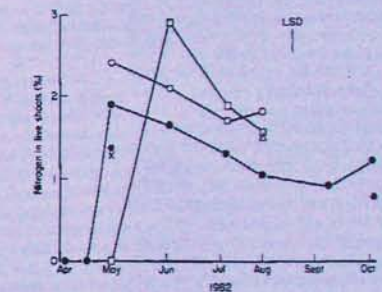


FIG. 9.



FIGS 8 & 9. Responses of plant components per cylinder surface area (78·5 cm^2) to seasonal changes (●——●) or biocide applications: Symbols as in Figs. 1–7. Biocide response points are shown only when significantly different ($P \leq 0{\cdot}05$) from control values and are connected when they were significantly different from controls for consecutive sample dates.

and P_i in live shoots was not different from controls. PCNB treatments had decreased plant shoot N in May and October (Fig. 9) but not live shoot weight or shoot P_i concentration. Live shoot weights were increased in carbofuran treatments in April, July, August, and September (Fig. 8), as was the percentage of N in shoots in August (Fig. 9). No effect on P in shoots was observed. Phosphorus concentration in plant shoots was not affected by cygon, but cygon did reduce live shoot weight (Fig. 8) from June onward and the percentage of N in live shoots that did occur was increased (Fig. 9).

DISCUSSION

Biocide responses

No long-term effects on non-target organisms were expected based on preliminary experiments, where only initial transient effects on non-target organisms and long-term (30 d) effects on target organisms were observed (Ingham & Coleman 1984) (Table 2).

Biocides probably had little effect in April and May because of a general reduction in biological activity caused by the cold, dry weather. As a rule, biocides more effectively reduce active than inactive organisms (Hill & Wright 1978). For example, streptomycin inhibits transfer-RNA function and thus prevents protein formation, leading to bacterial death. Active organisms are more likely to be killed by this type of inhibition than dormant ones. Thus, distinguishing direct from indirect biocide effects is more difficult in the field than in laboratory studies, as direct effects may not have occurred until organisms began growing in May or June, the same time as indirect effects caused by organism interactions would begin.

All five biocides continued to have effects on some, and usually several, populations for as long as the experiment continued. Even in cases where no long-lasting effect on the target group could be measured, the system did not return to control levels. Two examples of this are (i) streptomycin did not reduce total bacterial populations initially or continue to affect viable populations after May, yet continued to improve plant growth and %N in shoots, and changes in N cycling were observed; (ii) PCNB did not reduce VAM fungal infection, but total and active saprophytic hyphal lengths were reduced.

The major conclusions from biocide applications are as follows:

(i) The bactericide, streptomycin, did not reduce the entire bacterial population but appeared to decrease only a small portion, those bacteria that nitrify ammonia. Use of streptomycin to remove bacterial populations to quantify fungal respiration is questionable. Changes in bacterial- and fungal-feeding predators, both protozoan and nematode, occurred. Plant growth and N content was enhanced by the continuing N release from the streptomycin 'fertilizer' amendment.

(ii) Captan reduced a portion of its target population and appeared to change fungal species composition. Decreases in fungal populations later in the summer were the result of increased predation by fungal-feeding nematodes. Bacteria increased, and were then reduced by increased bacterial-feeding nematode numbers. No overall change in N cycling occurred due to these opposing trophic interaction effects.

TABLE 2. Effects of biocides on micro-organism target and non-target group as determined from preliminary experiments (Ingham & Coleman 1984)

Biocide*	Effect on target group	Effect on non-target group
Streptomycin	Initial† decrease total bacteria; decrease viable bacteria	Initial decrease active fungi; increase total fungi
Captan	Decrease active and viable fungi	-
PCNB	Decrease active fungi	Initial decrease total bacteria and flagellates
Carbofuran	Nematodes‡	Initial increase active fungi and viable bacteria; initial decrease total bacteria
Cygon	Microarthropods‡	Initial decrease-ciliates

* Same concentrations as used in this study (see Table 1).
† Recovery to control levels by day 4 or 7.
‡ Should decrease target group, but target group not included in study.

(iii) PCNB did not reduce VAM fungal infection, because active arbuscular infection was near detection limits in both control and biocide treatments. Both active and total hyphal lengths were reduced through most of the summer, and, as a result of reduced N mineralization by the fungi themselves, reduced inorganic N in soil and subsequently in plants. Protozoa increased by grazing an initial increase in bacteria, after which fluctuations in protozoan numbers differed from control but basically remained in similar ranges. No other effect of decreased fungal populations on predators or competitors was observed.

(iv) Carbofuran effectively reduced all nematode populations, allowing bacterial and then amoebal and ciliate populations to increase successively, as predicted by the model. A transient N pulse, as expected as a result of the trophic interactions, was observed. Increased plant growth occurred as a result of reduced plant-feeding nematode populations, increased VAM arbuscular infections and improved N availability for growth. A strong indication was given that the C, N and P flow from VAM fungi to fungal-feeding nematodes should be included in our conceptual model.

(v) Cygon is a broad-spectrum biocide affecting plant growth directly and reducing both total and active hyphal lengths. In pre-trials, cygon reduced protozoan numbers but this was not observed in the field experiment.

Bactericide—streptomycin

Probably only that portion of the bacterial population which was sensitive to streptomycin was initially killed and only after the dead cells were decomposed was the reduction observed in total counts. It is likely that nitrifiers were reduced by streptomycin, resulting in the short-duration decrease in NO_3^--N while ammonifiers were stimulated by the presence of streptomycin as a substrate.

The initial decrease in total and active hyphal lengths was probably a direct effect of the bactericide on fungi, as was observed in preliminary experiments (Table 2). Bacteria that are not affected by streptomycin can utilize dead hyphae as a growth substrate, thus even more greatly masking the decrease in a portion of the bacterial population.

Decreased levels of active hyphae occurred at times of increased fungal-feeding nematode populations in June in both depths, and subsequently total hyphal lengths were depressed. In contrast, total amoebae were decreased throughout the summer in the 5–10 cm depth, unlike the 0–5 cm depth where amoebae increased. Therefore, if amoebae were major consumers of hyphae, their depressed populations should have been reflected in increased hyphal lengths. Increased levels of extractable inorganic P were observed only in the 0–5 cm depth, not in the 5–10 cm depth. This may indicate that amoebae were important in mineralizing phosphorus from microbial biomass.

Active flagellates decreased following streptomycin application, as predicted, but most of the decrease could be accounted for as an increase in cystic flagellates. Flagellates encysted, indicating that conditions, probably food source, were not optimal. Perhaps the bacteria affected by streptomycin were those that flagellates exploited, resulting in increased flagellate encystment. Conversely, flagellates may have encysted to escape increased predation by amoebae.

Increased death and predation of the immobilizing organisms, bacteria and fungi leads to the expectation that inorganic N in soil will increase. Initially, however (dates 1 and 2), NO_3^--N was less than that in controls probably because nitrifiers, which are highly sensitive to perturbation (Cairns 1982), were reduced. However, ammonium-N was significantly increased on these two dates. Most likely, this increase was due to N ammonified from streptomycin (see Table 1 for N added in streptomycin), not from decreased bacterial populations.

An increase of 1800 μgN g^{-1} live shoot, as well as an increase of live shoot material, was observed in streptomycin treatments. However, the streptomycin amendment contained only 500 μg N g^{-1} soil, at least half of which could be easily ammonified and contribute to the soil inorganic N pulse. This amendment was enough to account for the increased N levels in plant shoots, but increased soil N may have been due to mineralized bacterial and fungal populations. Changes in N cycling following streptomycin addition probably reflect a fertilizer effect masking any changes due to changed microbial populations.

Increased plant shoot weight was not predicted, although improved N availability probably caused improved growth. This indicates that blue grama was N limited, and increases in available N will increase growth. Also, changes in microbial populations in the soil could conceivably promote plant growth (Ames, Reid & Ingham 1984).

In pre-trials, 1 mg streptomycin g^{-1} soil was utilized, as recommended by Anderson & Domsch (1978) for removal of the total bacterial population. This concentration did not significantly reduce bacteria in microcosm soils (Ingham & Coleman 1984), but 3 mg g^{-1} soil did result in reduced populations. However, this higher concentration did not significantly reduce bacterial numbers in the field trial. These results indicate that measurement of bacterial versus fungal respiration in soil by attempting to remove bacterial respiration by streptomycin treatment (1 mg g^{-1} soil) could give misleading information. Field bacterial populations were not reduced by streptomycin application, and measurement of respiration following streptomycin treatment would have included a large portion of bacterial respiration. In the past, use of this technique for measuring 'fungal respiration' in soil has led to the conclusion that fungi are the dominant microbial group in this grassland soil (Nakas & Klein 1980). This study indicates that their conclusion may have been inappropriate.

Saprophytic fungicide—captan

A single fungicide rarely affects all fungi but tends to reduce certain groups of fungi. The saprophytic fungicide, captan, decreased total hyphae, but the effects on active hyphae were not consistent. A change in fungal species composition following captan application was observed as in earlier studies (Farley & Lockwood 1968, 1969). Bacteria that degrade hyphae increased, probably because some dead hyphae were available as substrate. Fungal-feeding nematodes and mites did not experience a decrease in food supply and did not decrease in numbers or activity.

The increase in bacteria resulted in an increase in bacterial-feeding nematodes, as predicted. It is possible that a product of captan metabolism adversely affected flagellate cysts. The reduced immobilization that would occur with decreased total hyphal length was nullified by change in fungal species and by the increased bacterial growth. Thus, neither increased N levels nor plant growth were observed.

Captan also increased root colonization by VAM fungi in mid- to late summer. Captan removes one portion of the fungal population (de Bertoldi *et al.* 1977), allowing increased growth of remaining fungi (Houseworth & Tweedy 1973). Variable effects of captan (no effect, increases, decreases) on mycorrhizal formation in roots have also been observed (Menge 1982). Therefore, improved plant growth may have resulted from increased VAM fungal infection, although a decrease in fungal plant pathogens is another possible result following captan application.

VAM infection-reducer—PCNB

The effect of reducing VAM on N cycling should be a decrease in plant N and P. These nutrients would then be initially immobilized by increased bacteria and fungi, a portion mineralized when these organisms are grazed and appear as increased/decreased inorganic N and P levels in soil at periodic intervals.

PCNB initially increased total bacterial counts, which then returned to control levels, as was also observed in preliminary trials (Table 2) and by other researchers (Farley & Lockwood 1968, 1969; Wainwright & Pugh 1974), which indicates either reduction in competition from fungi, allowing increased substrate use by bacteria, or that PCNB can be used as a substrate by soil bacteria. This change in bacterial growth may have resulted in the increased protozoan populations and subsequent fluctuations that were similar to, but not synchronous with, control levels.

Beginning in June, when growth conditions became optimal, both active and total hyphal lengths were reduced, a direct effect of PCNB on fungi; and these reductions continued through the growing season. Reduced fungal populations should lead to the same results as expected for captan but no effects on nematode, mite or bacterial populations were observed. Lack of effect of fungal reductions on predators and competing groups could indicate several things. Fungal populations are low in this grassland compared with other ecosystems (see discussion of fungal–predator interactions in Ingham *et al.*, 1986), so that fungi are not important food resources or competitors. This hypothesis is supported by the low numbers of tylenchids (10–20 fungal- and plant-feeding nematodes g^{-1} soil) in this system, which together are only one half to one third the density of the bacterial-feeding nematodes (40–50 g^{-1} soil). This indicates that bacteria are the dominant decomposer group in this soil, not fungi.

PCNB did not appear to decrease active arbuscular mycorrhizal colonization, although it has been reported to decrease mycorrhizal formation in grasses (Brown 1978; Menge, Johnson & Minassian 1979; Menge 1982). Arbuscular fungal colonization (autofluorescence method) was extremely low, below 1% to only 2% of new root length in control treatments, throughout the summer. Reduction of low percentages is difficult to measure accurately.

Neither root length nor shoot biomass was affected by PCNB application, although the percentage of shoot N was decreased on two dates. Increased immobilization by bacteria was probably not responsible for the uptake of the N in place of the plants, as no increase in bacterial numbers was observed. One explanation for reduced N in plants without decreasing any group except the fungi is that fungi themselves were responsible for N mineralization. Reduction in active and total hyphae by PCNB reduced mineralization by fungi and thus reduced inorganic N available to the plant. While fungi did not appear to be the numerically dominant decomposer organism group, fungi may have contributed more to N mineralization directly from organic material than bacteria in this grassland.

Nematicide—carbofuran

Nematicides reduce all types of nematodes—bacterial-, fungal- and plant-feeding—and allow an increase in their particular prey groups, plants, bacteria and fungi, if the predator is important in reducing prey populations.

Carbofuran decreased all three groups of nematodes, as expected, starting with the May sample (June in lower depths). Earthworms, which can be reduced by carbofuran (Martin 1975), are not present in this semi-arid grassland except in rare stream-bed areas.

Stanton, Allen & Campion (1981), working in the same semi-arid grassland, found no increase in shoots following carbofuran treatment, but root biomass did increase, most likely due to reduced numbers of plant-feeding nematodes.

In May or June, increases in bacteria, fungi and plant growth were expected because nematode predation decreased, according to our conceptual model. Bacterial numbers were initially increased (April), an increase also observed in pre-trials (Table 2), probably because carbofuran can be utilized as a carbon source (Fox 1983). In July, bacterial numbers were greater than controls once again (Fig. 3), and this increase was probably the result of decreased predation by nematodes. Increased bacterial numbers did not continue, however, because amoebal and ciliate numbers increased in August and September, grazing the bacterial population to within control levels.

Increased total and active hyphal lengths were expected because of decreased predation by nematodes but were not observed. In fact, slight depressions in total hyphal lengths were noted in August and September. Furthermore, no numerical increase in fungal-feeding mites was observed. This supports results from other biocide treatments, where there was little interconnection observed between fungi and their grazers.

Significant increases in mycorrhizal root colonization (up to 15% in July) occurred in carbofuran treatments. There are several possible explanations for this observation. First, reduction in fungal-feeding nematode populations lessened predation pressure on the VAM fungi and allowed more colonization to occur, indicating that this interaction should be included in the decomposer food web. Second, when plant-feeding nematodes were reduced, fewer roots were destroyed, leaving more sites for initiation of VAM colonization. Third, the changed fungal and bacterial populations that resulted from changed predation pressures removed microbes that compete with or inhibit VAM fungi or the colonization process. Although arbuscular mycorrhizal fungal colonization was 15% in July, it dropped to 4–5% in August. Arbuscular colonization did not remain active for long periods of time. The higher total percentage colonization observed later in the year was likely a cumulative result of many transient colonization events, as also observed by Allen (1983).

Carbofuran treatment resulted in increased live shoot weight through the growing season, and the percentage of N in shoots was increased on one of these dates. Decreased plant-feeding nematode activity undoubtedly contributed to increased plant growth, and the increased VAM fungal colonization may have improved the proportion of N in shoots (Stanton, Allen & Campion 1981). The role of changed microbial populations cannot be discerned, since no changes in soil inorganic N were measured after an initial increase–decrease in NO_3^--N in April and May (Fig. 9a). In addition, although predation by nematodes and thus mineralization of N in microbial biomass by them was decreased, there was no effect on inorganic N, because of a compensatory effect of increased protozoan predation.

Interactions between microbes and predators in the 5–10 cm depth were more similar to control responses. Active fungi were reduced, as were total amoebal numbers and nematodes. Basically, fungal and amoebal variations appeared to be similar to the cyclical patterns observed in the control but were offset by the initial reductive effects of carbofuran (see Table 2). Increased VAM fungal colonization was also observed in the lower depth.

Acaricide—cygon

Arthropod numbers were highly variable, indicating patchy distribution on the grasslands. Any effect of cygon on its target population was difficult to detect because of this variability and low numbers.

Further complications arose because cygon had a direct effect on plant growth. In sterile-plant trials, cygon reduced plant shoot weight, root length and vigour (Ingham & Coleman 1984). Because this effect was more pronounced in enclosed plant growth chambers than in the field experiment, it can be concluded that a volatile factor was toxic to the plants. The carrier for cygon is an aromatic petroleum solvent and possibly could be the toxic agent. Therefore, we cannot recommend the use of cygon for the removal of microarthropods because of its non-target group effects.

Biotic interactions

Biocides can be used to remove or reduce microbial populations in natural situations, and the effect of these removals on system function can be observed. Generally, removal of one predator allowed a second predator to increase in numbers. Reduction of microbes resulted in the increase of tolerant or resistant organisms. Since bacteria and fungi perform many diverse enzymatic functions, attack diverse substrates, and exist in a wide range of physiological states, it is not likely that one biocide (i.e. streptomycin) can remove a significant portion of the total population. However, the importance or role of specific portions of the bacterial or fungal populations could be assessed if the specific group reduced by the biocide is known. Preliminary experimentation must be performed to determine the exact effect.

Despite the perturbations applied to this ecosystem and the occurrence of both long food-chain length and omnivory, both supposedly destabilizing forces in food-chain structure, the trophic structure was not destroyed and was remarkably resilient. Further experiments using these removal techniques could be designed to rigorously test these aspects of trophic structure interactions.

It is important to consider secondary production or predator biomass, as well as primary production, in determining bacterial versus fungal importance or dominance in this ecosystem. Results from several biocide treatments (streptomycin, captan, PCNB, carbofuran) indicated that the conventional concept that fungi are the dominant microbe in this system should be reconsidered. First, hyphal lengths in this system are low compared with those in other systems (see fungal–predator interaction discussion). Second, comparison of the standing crop or total fungal *biomass* with total bacterial biomass gives values of 240 μg fungal biomass g^{-1} soil and 385 μg bacterial biomass g^{-1} soil. However, bacterial-feeding nematodes (200 g^{-1} soil on average) were at least double the number of fungal- and plant-feeding nematodes together (100 g^{-1} soil). Assuming a ratio of 1 fungal- to 4 plant-feeding nematodes (R. E. Ingham personal communication) and feeding rates of 0·19 μg fungal biomass d^{-1} per nematode and 0·38 μg bacterial biomass d^{-1} per nematode, then 4·7 μg of fungal and 76 μg of bacterial biomass, on average during the summer, was consumed by nematodes each day. Consider further that the protozoan biomass consumed, on average (calculation not shown), 40 μg of bacteria d^{-1}, while the few fungal-feeding mites present might have consumed 10 μg fungal biomass d^{-1}. With these considerations, total bacterial biomass would have been 501 μg g^{-1} soil, while total fungal biomass would have been 255 μg g^{-1} soil, indicating that bacteria actually are dominant. Third, reduction in populations which prey on bacteria resulted in significant increases in bacteria and subsequent increases in other groups of bacterial predators. However, reduction in fungal predator numbers was not reflected in increased hyphal lengths (carbofuran treatment), and reduction in hyphal lengths did not affect fungal predator numbers (PCNB treatment). This indicates that the fungal biomass does not support a substantial predator population. Finally, some previous information that supported the hypothesis that fungi are dominant in this system was brought into question when the streptomycin treatments, at both the recommended and threefold-greater concentrations, failed to significantly reduce bacterial populations.

The effect of broader-spectrum biocides that reduce all predators; nematodes and protozoa, and perhaps arthropods, would be an interesting follow-up experiment. Also, determination of whether different ecosystems respond similarly to biocide perturbations would allow assessment of the roles of these groups in each system.

The major conclusions from biotic interactions are as follows.

(i) The decomposer food web was remarkably stable despite some drastic perturbations (biocide application). Long food-chain length and omnivory were not destabilizing but stabilizing forces.

(ii) Bacteria, not fungi, were the numerically dominant microbes in this system, especially when secondary production was considered.

(iii) Fungi were more important than bacteria in mineralizing and releasing N directly from organic material, while bacteria immobilized more N in their biomass, which must then be grazed and mineralized by predators.

(iv) An interaction between VAM fungi and nematodes must be included in the food web model.

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INTERACTIONS OF BACTERIA, FUNGI, AND THEIR NEMATODE GRAZERS: EFFECTS ON NUTRIENT CYCLING AND PLANT GROWTH[1]

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Abstract. The most common system responses attributed to microfloral grazers (protozoa, nematodes, microarthropods) in the literature are increased plant growth, increased N uptake by plants, decreased or increased bacterial populations, increased CO_2 evolution, increased N and P mineralization, and increased substrate utilization. Based on this evidence in the literature, a conceptual model was proposed in which microfloral grazers were considered as separate state variables. To help evaluate the model, the effects of microbivorous nematodes on microbial growth, nutrient cycling, plant growth, and nutrient uptake were examined with reference to activities within and outside of the rhizosphere. Blue grama grass (*Bouteloua gracilis*) was grown in gnotobiotic microcosms containing sandy loam soil low in inorganic N, with or without chitin amendments as a source of organic N. The soil was inoculated with bacteria (*Pseudomonas paucimobilis* or *P. stutzeri*) or fungus (*Fusarium oxysporum*), with half the bacterial microcosms inoculated with bacterial-feeding nematodes (*Pelodera* sp. or *Acrobeloides* sp.) and half the fungal microcosms inoculated with fungal-feeding nematodes (*Aphelenchus avenae*).

Similar results were obtained from both the unamended and the chitin-amended experiments. Bacteria, fungi, and both trophic groups of nematodes were more abundant in the rhizosphere than in nonrhizosphere soil. All treatments containing nematodes and bacteria had higher bacterial densities than similar treatments without nematodes. Plants growing in soil with bacteria and bacterial-feeding nematodes grew faster and initially took up more N than plants in soil with only bacteria, because of increased N mineralization by bacteria, NH_4^+-N excretion by nematodes, and greater initial exploitation of soil by plant roots. Addition of fungal-feeding nematodes did not increase plant growth or N uptake because these nematodes excreted less NH_4^+-N than did bacterial-feeding nematode populations and because the N mineralized by the fungus alone was sufficient for plant growth. Total shoot P was significantly greater in treatments with fungus or *Pelodera* sp. than in the sterile plant control or treatments with plants plus *Pseudomonas stutzeri* until the end of the experiment.

The additional mineralization that occurs due to the activities of microbial grazers may be significant for increasing plant growth only when mineralization by microflora alone is insufficient to meet the plants' requirements. However, while the advantage of increased N mineralization by microbial grazers may be short-term, it may occur in many ecosystems in those short periods of ideal conditions when plant growth can occur. Thus, these results support other claims in the literature that microbial grazers may perform important regulatory functions at critical times in the growth of plants.

Key words: decomposition; fungal grazers; microbial-faunal interactions; nematode nitrogen losses; nutrient cycling; plant nitrogen uptake; rhizosphere.

Introduction

In the study of the mineralization-immobilization phenomena of nutrient-cycling processes, the soil microflora have traditionally been considered responsible for the mineralization of inorganic nutrients from their immobilized forms in soil organic matter (Satchell 1974, Alexander 1977). Theoretical discussions of nutrient cycles generally represent the mineralization process as a flow from a litter or soil organic matter component to a component representing available soil nutrients (Gosz 1981, Van Cleve and Alexander 1981) or, ad-

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ditionally, through a soil microbe component (Melillo 1981). Rarely are the activities of faunal grazers of microflora included in the nutrient-cycling process or separated from the activities of soil microflora (Woodmansee et al. 1981, Coleman et al. 1983). Evidence is accumulating, however, that faunal grazers may be responsible for a significant portion of the mineralization previously attributed to microflora. Since mineralization is a key process in supplying nitrogen and other nutrients for plant growth in terrestrial ecosystems (Alexander 1977, Marion et al. 1981), it is important to understand the roles of all organisms involved in this process, the interactions that may occur between them, and where these interactions occur.

The present study pursues earlier observations, as reviewed by Yeates and Coleman (1982), in which some nematodes, particularly microbivorous types, were considered to have a positive effect on plant growth through enhanced nutrient mineralization. Lee and Inman (1975) concluded that a relatively small grazing component may have a significant effect on subsequent system behavior, particularly nutrient cycling. These grazing control components have been extensively reviewed for protozoa (Stout 1973, 1980), enchytraeids (Standen 1978), and soil microarthropods (Seastedt 1984).

Previous studies of biotic interactions in the rhizosphere have been more descriptive than analytical (e.g., review by Clark 1949, Head 1970, Coleman 1976). It is now important to conduct studies on the distribution and abundance of microbes and the fauna feeding on them, both inside and outside the rhizosphere region of growing plant roots. This paper reports on interactions between microflora and fauna (nematodes) in rhizosphere and nonrhizosphere areas.

The objectives of this study are twofold:

1) To propose and evaluate a conceptual model in which the levels of N and P in microfloral grazer populations are considered as separate state variables in the nutrient-cycling process, as suggested by evidence in the literature.

2) To examine the interactions between bacteria or fungi and the nematodes that feed upon them and how these relationships influence nutrient availability and plant growth.

Effects of microbial grazers on nutrient cycling

It has long been known that microbial grazers may stimulate the activities of microbial populations. Cutler and Crump (1929) reported that amoebae stimulated CO_2 production in sand with mineral amendments. It was found by de Telegdy-Kovats (1932) that decreasing the substrate C:N ratio in the presence of protozoa causes increases in CO_2 production. In sand cultures the presence of amoebae appeared to increase the rate of ammonium production in bacterial cultures growing on peptone (Meiklejohn 1930). This was confirmed by Doyle and Harding (1937), who found that most of the bacterial nitrogen ingested by the ciliate *Glaucoma* sp. was excreted as ammonia by 6 h after ingestion. A similar "regeneration" of phosphorus by paramecia was noted by Buechler and Dilleon (1974). Javornicky and Prokesova (1963) suggested that the presence of protozoa stimulates organic matter decomposition and thus may significantly influence the entire ecosystem energy flow. Mercer and Cairns (1973) reached a similar conclusion for bacterial-feeding nematodes. Johannes (1968) experimentally demonstrated that bacteria do not always directly mineralize nutrients from organic compounds and that nutrients are released at an accelerated rate when the microbial population is grazed. Barsdate et al. (1974) observed increases in gross mineralization of P in bacterial treatments grazed by protozoa as compared to those without grazers. The enhanced P turnover (using labeled phosphorus) was attributed to greater metabolic activity of bacteria in grazed systems.

Bacteria can also act as nutrient sinks in soils. With increasing additions of glucose, more inorganic phosphorus (P_i) was immobilized by bacteria, and, at the end of 160 h, there was no net mineralization of P (Elliott et al. 1979*b*). Coleman et al. (1977) found that almost all soil NH_4^+-N, and 40% of the initial P, were immobilized 21 h after inoculation of bacteria into glucose-amended sterile soils. When either amoebae or bacteriophagic nematodes were introduced to some of the microcosms, nearly all of the immobilized N was remineralized, while less than one-third of the NH_4^+-N was returned in the treatment with bacteria alone. After 24 d, significantly more P_i was remineralized in the bacteria-and-nematode treatment than in either the treatment with bacteria alone or the bacteria-and-amoebae treatment. In a similar study, more N was remineralized as NH_4^+-N in an amoebae-plus-bacteria treatment than in a treatment containing bacteria alone, a treatment with nematodes and bacteria, or one with nematodes, amoebae, and bacteria (Woods et al. 1982). In the same experiment, amoebae-and-bacteria or nematodes-and-amoebae-and-bacteria mineralized the same amount of P_i in unamended soils, while in glucose-amended soils, only the amoebae-plus-bacteria treatment remineralized significant amounts of P_i (Cole et al. 1978). Mineralization of N in chitin-amended soils has also been found to be greater in microcosms containing nematodes and bacteria than in treatments with only bacteria or with bacteria and amoebae (Gould et al. 1981, Trofymow and Coleman 1982).

Increases in the rate of substrate utilization by bacteria in nematode-grazed systems have been demonstrated by measuring substrate disappearance. Abrams and Mitchell (1980) found organic matter loss from sewage sludge to be 1.8–2.5 times greater in the presence of nematodes and bacteria than with bacteria alone. Similarly, more ^{14}C-labeled glucose was respired in bacteria-plus-nematode treatments than with only bacteria, and soil glycol-C in the grazed systems was reduced to 40% of that in the ungrazed system in 10 d (Anderson et al. 1981*a*). In soils of cellulose- and chitin-amended microcosms, significantly more NH_4^+-N appeared and more chitin and cellulose decomposed with microbivorous nematodes present than with only bacteria (Trofymow et al. 1983).

Grazing of bacteria by nematodes has also been shown to affect the allocation of substrate C by the soil biomass. This is suggested by significantly greater CO_2 evolution in systems with bacteria and nematodes than in those with bacteria alone (Anderson and Coleman 1977, Coleman et al. 1977, 1978, Anderson et al. 1978, 1979*a*, 1981*a*, Trofymow et al. 1983).

Very little is known about the effects of fungal-feeding nematodes on nutrient cycling processes in soils. In cellulose-amended soil, N mineralization by *Fusarium oxysporum* was reduced when the fungus was grazed by the nematode *Aphelenchus avenae* (Trofymow and Coleman 1982). However, in a second experiment the nematode increased N mineralization and $^{14}CO_2$ evolution (C of cellulose origin) by *F. oxysporum* in soils amended with cellulose and chitin (Trofymow et al. 1983).

Effects of microbial grazers on microorganisms

The effects of bacterial-feeding nematodes on microbial populations in soils appears to be variable. Boucher and Chamroux (1976) found parallel growth responses between marine nematodes and bacteria in sand microcosms. A similar relationship between soil nematodes and soil bacteria was observed by Banage and Visser (1964) in bush soils of Uganda, and by Freckman and Mankau (1977) in desert soils. Santos et al. (1981), Santos and Whitford (1981), Elkins and Whitford (1982), and Whitford et al. (1982) found that when bacteriophagic nematodes were released from predation pressure by the removal of predatory mites with insecticide, decomposer bacterial populations were reduced and litter decomposition was slowed. In soil microcosms amended with glucose and nitrogen, nematodes reduced bacterial numbers to one-half or one-third of the density in the treatment without nematodes (Anderson et al. 1979*a*). Similar decreases were observed by Coleman et al. (1977), while Anderson et al. (1978) found that the reduction in bacterial numbers due to nematodes was less in microcosms that had not been amended with C and N. In contrast, Abrams and Mitchell (1980) found significantly higher bacterial densities in sewage sludge microcosms when microbivorous nematodes were present. Increased bacterial numbers with bacteriophagic nematodes were also observed by Trofymow and Coleman (1982) in microcosms amended with cellulose, chitin, or both cellulose and chitin.

The ability of mycophagous nematodes to affect growth of soil fungi has been little studied, but appears to be variable and to depend on the species of fungus and perhaps the species of nematode. Mankau and Mankau (1963) examined 18 species of fungi as food sources for *Aphelenchus avenae*. There was a range in the resulting classification from apparently poisonous species (*Pythium ultimum*) to species on which the nematodes reproduced rapidly and overgrazed the fungus, slowing or stopping hyphal growth in five of the nine species tested. Similarly, Wasilewska et al. (1975) found that inhibition of fungal growth due to consumption by *A. avenae* resulted in a 32–52% reduction in dry biomass of *Alternaria tenuis*. The response of fungi to faunal grazing may be dependent on available nutrient concentrations as well as on grazing intensity. Hanlon (1981) observed an increase in fungal respiration of as much as 100% when fungi grown in a high-nutrient regime were grazed by Collembola. However, no change in respiration was observed for grazed fungi grown in low nutrient concentrations. In addition, while moderate densities of Collembola increased fungal respiration, high densities did not, suggesting an apparent optimum grazing intensity, which increased as available nutrients increased.

Effects of microbial grazers on plant growth

Because of high consumption and low assimilation rates, microbial grazers release a considerable amount of nutrients that may then be available as a source of nutrients for plants (Anderson et al. 1981*b*). This may increase the rate of turnover of mineral nutrients and serve a system-regulating function by increasing primary production. The response of plants to nutrient dynamics mediated by faunal grazers has been only briefly investigated. Elliott et al. (1979*a*) grew blue grama seedlings in soil with bacteria and with or without amoebae, under three levels of nitrogen fertilization. At the medium- and high-N levels, there was 50–100% more net mineralization of organic N as NH_4^+-N with amoebae than without, and at all N levels shoot-N concentrations were significantly higher with amoebae. They concluded that bacterial grazing by amoebae accelerates the mineralization of microbially immobilized nutrients, increasing the inorganic N available for uptake by the plant.

THE CONCEPTUAL MODEL AND THE GENERAL EXPERIMENTAL DESIGN

Based on previous work of ourselves and others, we envision the cycling of nutrients (nitrogen and phosphorus) in a soil autotroph-heterotroph system containing bacteria (non-nitrifying) and/or fungi, nematode grazers of bacteria or fungi, and plants to occur as diagrammed in Fig. 1. The state variables are represented by x_1–x_7 and include levels of N and P in each of the following: detritus, plants, inorganic forms (NH_4^+, PO_4^{3-}), fungi, bacteria, fungal-feeding nematodes, and bacterial-feeding nematodes. Flows in the model are represented by F_{ij}, where i represents the state variable the flow is coming from and j represents the state variable the flow is going to. Controls on flows are represented by C_{ij}, where i is the controlling state variable and j is the state variable whose input is being controlled.

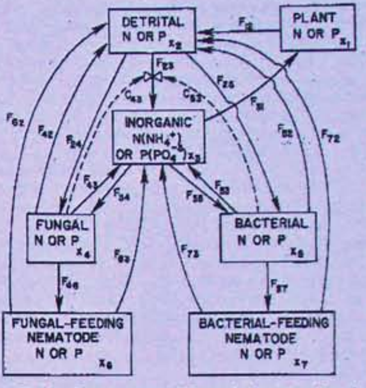

FIG. 1. Conceptual model illustrating important flows in a plant-soil system with bacteria, fungi, and their nematode grazers.

The current study examines the interactions of the biota represented in the model in order to substantiate previous observations under more rigorously controlled conditions and with a more complex assemblage of organisms, including plants. Nitrogen and phosphorus mineralization were examined in two model soil systems, one in which soil was unamended and one in which chitin was used as a representative organic-N substrate. Bacteria, fungi, and nematode grazers of these microflora were chosen from isolates to represent functional groups (Coleman 1976) operating in natural soil systems. Blue grama grass, *Bouteloua gracilis* (H.B.K.) Griffiths, was used as a test plant.

Experimental designs

The design for the unamended experiment consisted of six treatments: a sterile plant control (*p*); plant and bacteria (*pb*), plant, bacteria, and bacteriophagous nematodes (*pbn*$_b$); plant and fungus (*pf*); plant, fungus, and mycophagous nematodes (*pfn*$_f$); and plant, bacteria fungus, bacteriophagous nematodes, and mycophagous nematodes (*pbfn*$_b$*n*$_f$). Each treatment was replicated five times and sampled once after 40 d. Data collected included shoot and root biomass, soil bacterial and nematode numbers, soil NH_4^+-N and bicarbonate-extractable phosphorus (P_i).

The design for the amended experiment consisted of eight treatments: an uninoculated control (*uc*); a sterile plant control (*p*); bacteria and fungus (*bf*); bacteria, fungus, and mycophagous nematodes (*bfn*$_f$); plant and bacteria (*pb*); plant, bacteria, and fungus (*pbf*); plant, bacteria, and bacteriophagous nematodes (*pbn*$_b$); and plant, bacteria, fungus, and mycophagous nematodes (*pbfn*$_f$). Each treatment was replicated five times, with five sample dates: 7, 21, 49, 77, and 105 d after inoculation of microflora. Data collected included shoot and root biomass; rhizosphere and nonrhizosphere counts of bacteria, fungi, and nematodes; and soil NH_4^+-N, soil P_i, and shoot-N and -P concentrations.

Predictions and treatment contrasts

The treatments in the experiments outlined above were used to test the following hypotheses and predictions relating to the model in Fig. 1.

1) In nutrient-limiting soil, fungi (x_4) or bacteria (x_5) provide additional inorganic nutrients (x_3) for plant uptake (F_{31}) by mineralization of organic N and P (F_{43} and F_{53}). Thus, plants (x_1) grown in soil with microflora will grow faster and/or contain more N and P than those grown in sterile soil. (Relevent treatment contrasts: *p* vs. *pb*; *p* vs. *pf*.)

2) Mineralization by fungi (F_{43}) will be greater than that by bacteria (F_{53}). (Treatment contrasts: *pb* vs. *pf*; *pb* vs. *pbf*.)

3) Fungal-feeding nematodes (x_6) or bacterial-feeding nematodes (x_7) increase the amount of inorganic nutrients (x_3) available for plant uptake (F_{31}) by excreting microbial-immobilized N as NH_4^+-N waste (F_{63} and F_{73}) and by increasing microbial activity, which results in a positive feedback control (C_{43} and C_{53}) on decomposition (F_{23}) and further mineralization by fungi (F_{43}) and bacteria (F_{53}). Therefore, plants (x_1) will grow faster and/or contain more N and P when microbial-feeding nematodes are present than when they are not. (Treatment contrasts: *pf* vs. *pfn*$_f$; *pbf* vs. *pbfn*$_f$; *pb* vs. *pbn*$_b$.)

4) Bacterial-feeding nematodes will increase mineralization by bacteria (F_{53}) to a greater extent than fungal-feeding nematodes will increase mineralization by fungi (F_{43}). (Treatment contrasts: *pbn*$_b$ vs. *pfn*$_f$; *pbn*$_b$ vs. *pbfn*$_f$.)

MATERIALS AND METHODS

Isolation and culturing of organisms

All microorganisms used in these experiments were isolated from soil collected from the Pawnee National Grasslands in northeastern Colorado. The fungus used in the unamended experiment was *Mortierella* sp. isolated from soil on rose-bengal agar. The rhizosphere bacterium *Pseudomonas paucimobilis* in the unamended experiment was isolated from the roots of blue grama using the root-washing technique of Louw and Webley (1959), then cultured on nutrient agar. *Mortierella* sp. and *P. paucimobilis* were not used in the amended experiment, because neither species adequately decomposes chitin. Chitin decomposers were isolated from Pawnee soil enriched (to 5% of soil dry mass) with purified ball-milled crustacean chitin, after a 43-d incubation (20°C) (Okafor 1966, Gould et al. 1981). *Pseudomonas stutzeri* and *Fusarium oxysporum* were chosen because they were the most chitinoclastic of the species examined and were palatable to grazers (Gould et al. 1981). In a pre-experimental study, this strain of *F. oxysporum* was found not to be pathogenic to blue grama (R. E. Ingham, *personal observation*). In the amended experiment, treatments pb and pbn_b were inoculated with *P. stutzeri*, while treatments bf, bfn_a, pbf, and $pbfn_a$ were inoculated with *F. oxysporum* and *P. paucimobilis* to duplicate conditions in an earlier chitin-decomposition experiment so that our results would be comparable with those of another study that also included bacteria and fungi (Trofymow et al. 1983).

Aphelenchus avenae (fungal feeder) in this study was obtained from D. Freckman, University of California, Riverside, and *Pelodera* sp. and *Acrobeloides* sp. (bacterial feeders) were isolated from Pawnee soil. *Aphelenchus avenae* was cultured on plates containing 17% potato dextrose agar (in water) and a pure culture of *F. oxysporum*, while *Acrobeloides* sp. and *Pelodera* sp. were grown on agar plates containing a reference soil solution with nutrients (Herzberg et al. 1978) with a pure culture of *P. paucimobilis* or *P. stutzeri*, respectively, as a food source.

Plants were prepared in the following fashion. Seeds of blue grama, *Bouteloua gracilis* (H.B.K.) Griffiths, were surface sterilized for 15 min in 15% aqueous sodium hypochlorite containing a few drops of Tergitol as a surfactant. The seeds were then thrice rinsed in sterile de-ionized water, drained, and placed on nutrient agar for germination. After germination (4 d), the sterile seeds were planted individually into cotton-plugged test-tubes containing 0.5% one-quarter strength Hoagland's agar. The plants remained in these tubes for 10 d and all contaminated seedlings were easily observed and discarded.

Microcosm design

Gnotobiotic plant microcosms were constructed from 600-mL Berzelius beakers with urethane-foam collars and with glass Petri dishes as covers (Ingham and Trofymow 1979, Trofymow et al. 1980). The original design was modified by drilling a 7–8 mm hole in the glass cover and gluing a 2.5-cm length of 5 mm diameter glass tubing into the hole with silicone sealant. To maintain sterility, the exterior end of the glass tubing was fitted with a rubber serum cap for watering the microcosm via syringe.

Treatments without plants ("nonplant microcosms") used foam-plugged 50-mL Erlenmeyer flasks as described in Coleman et al. (1977).

In the unamended experiment we used a sandy loam from the Renohill-Shingle complex (an Ustic Torriorthent) that had been sieved through a 1-mm screen, oven dried, and mixed in a twin-shell mixer for 30 min. A soil lot of 200 g was weighed into each plant microcosm and wetted to field capacity (moisture 15% of soil dry mass). After incubation for 24 h, the soil was autoclaved for 1 h. This procedure was repeated three times. Soil used in the amended experiment was a low-available-N (NH_4^+-N concentration ≈3 mg/g) sandy loam of the Blakeland series (found within the Truckton-Blakeland-Bresser association) (Hays et al. 1982) and was treated similarly to the unamended soil except for the following. A soil lot of 100 g was weighed into each plant microcosm, and a lot of 20 g into each nonplant microcosm. For each gram of soil, all microcosms were amended with 3.38 gm of ball-milled purified crustacean chitin (0.24 mg chitin-N) (Gould et al. 1981). An N-free Hoagland's solution was added after the first autoclaving. The soil was then thoroughly mixed before the second wetting.

Inoculation of microcosms

Treatments requiring bacteria in the unamended study received 1.25×10^5 cells/g of soil, and fungal treatments were inoculated with 1 mL of a concentrated and blended suspension of the fungus. In the amended experiment, bacterial treatments were inoculated with 1.5×10^8 cells/g of soil, and fungal treatments received a concentrated suspension of blended hyphae equalling 97.5 m/g of soil. Bacteria and fungi in both experiments were diluted with dilute mineral salts medium (MSM) before inoculation; uninoculated controls received an equal amount of sterile MSM.

Plants (three seedlings per microcosm) were added on the day of inoculation (unamended) or 7 d after inoculation (amended) of microflora, using sterile technique.

In the unamended experiment, treatments with bacterial-feeders were inoculated with *Acrobeloides* sp. (2–3 eggs, 2–3 juveniles and adults per gram of soil), while treatments containing fungal feeders were inoculated with 7.0 juvenile or adult *A. avenae* per gram of soil. All nematodes were added 10 d after addition of plants and microflora. Nematode treatments in the amended experiment received 8–10 eggs and 3–4 juveniles and adults per gram of soil (*Pelodera* sp.) or 8–10 juveniles and adults per gram of soil (*A. avenae*).

In the unamended study, microcosms were kept in a growth chamber, while for the amended experiment, plant microcosms were maintained in a 54-m² walk-in microbiologically "clean" room, in which conditioned air was recycled through HEPA (high efficiency particulate-free air) absolute filter (>0.3 μm) systems. Illumination (Agro-lite fluorescent lamps) was at an intensity of 400 $\mu E \cdot m^{-2} \cdot s^{-1}$ at the inside of the microcosms. Nonplant microcosms were kept in an incubator at the same diurnal temperature regime as the plant microcosms (30° day/22° night). Soil moisture in

plant microcosms was maintained between 70 and 100% of field capacity by gravimetrically adding sterile de-ionized water. Nonplant microcosms did not require addition of water after the final inoculation.

During the chitin-amended experiment, *P. stutzeri* (b) and *P. stutzeri* plus *Pelodera* sp. (bn_b) treatments were also attempted, but *P. stutzeri* failed to survive in either of the two attempts to inoculate the bacteria into sterile soil.

Sampling of microcosms

Checks for sterility were made on sample dates by spreading ≈1 g of the mixed soil on nutrient agar. These plates were incubated for 1 wk and checked for bacterial or fungal growth.

At sampling dates, plants were carefully removed and roots with adhering rhizosphere soil (soil 2–4 mm from the root surface [Bennett and Lynch 1981, Martens 1982]) were placed in 99 mL of 0.9% NaCl. Shoots were clipped at the base of the crown, dried at 65°, and weighed. From the remaining soil, lots of ≈1 g were taken for soil moisture determination, bacterial plating, and fungal enumeration, when appropriate. Nematodes were extracted from 5 g soil in modified Baermann funnels (Anderson and Coleman 1977). Total hyphal lengths were estimated by taking 1 mL from a dilution of 1 g soil in 9 mL MSM, staining with 0.5 mL phenolic aniline blue, adding 1 mL agar, and observing the hyphal lengths in the agar film with a phase contrast microscope. Lengths of hyphae stained with FDA (fluorescein diacetate) were determined by the method of Ingham and Klein (1982) in agar film, using epifluorescent microscopy.

Rhizosphere analyses

Rhizosphere bacterial numbers were determined, after shaking roots in the dilute saline (APHA et al. 1971), with three replicate platings for each of three dilutions. From each fungal treatment, two 1-mL aliquots were removed for total hyphal and FDA-stained hyphal length analyses.

Roots were then removed, rinsed, dried at 65°, and weighed. Rhizosphere nematodes were obtained by shaking the saline-soil suspension, decanting, and centrifuging for 5 min at 1500 rpm. The centrifuged soil and nematodes were then stained (Anderson et al. 1979*b*) and counted in a gridded petri dish under a dissecting microscope (70×). The amount of rhizosphere soil was then determined gravimetrically.

Chemical analyses

The following chemical analyses were performed on nonrhizosphere or nonplant soil. Rhizosphere soil was generally in insufficient quantity for chemical analysis.

For inorganic-P, 2 g of soil was extracted with 10 mL of 0.5 mol/L $NaHCO_3$ adjusted to pH 8.5 with NaOH (Olsen et al. 1954). After shaking for 30 min and filtering the solution through a Whatman number 40 filter, the extract was analyzed for P_i using a colorimetric technique (Olsen et al. 1954).

Inorganic-N analyses (NH_4^+-N and NO_3^--N) were determined by extracting 4 g of soil with 40 mL of 2.0 mol/L KCl. The solution was shaken for 30 min and filtered through a Whatman number 1 filter. Ammonium-N concentrations were then analyzed on a Technicon Auto Analyzer I by a modification of the methods of Searcy et al. (1967) and Pym and Milham (1976). Nitrate-N levels were determined from the same KCl extract by reducing the NO_3^- to NO_2^- and measuring the NO_2^- concentration, a revision of the technique of Henriksen and Selmer-Olsen (1970).

Plant tissue N and P were determined on plant samples ground in a Wiley mill and digested with H_2SO_4-H_2O_2 (Thomas et al. 1967). Nitrogen concentration was determined colorimetrically by a salicylate assay for NH_4^+-N (Pym and Milham 1976), and an ascorbic acid reduction was used to assay for P (Murphy and Riley 1962).

Statistical analyses include ANOVA and Tukey's honestly significant difference (HSD) mean separation test (Kirk 1968). The ANOVA model used in the unamended experiment consisted of five replicates × six treatments and had 19 degrees of freedom. In the amended study, three ANOVA models were used. The first examined only treatments that contained plants (five replicates × four dates × five biological treatments; 71 df). The second model included only plant treatments inoculated with microflora (five replicates × four dates × two microbes × two grazers; 55 df), and the third model examined all treatments and analyzed nonplant soil, nonrhizosphere soil, and rhizosphere soil separately (five replicates × four dates × three soils × two grazers; 87 df). For all significant differences reported, $P < .05$.

RESULTS

The unamended experiment

Nematode numbers.—In single culture *Acrobeloides* sp. (pbn_b) reached higher numbers per gram of soil than *Aphelenchus avenae* (pfn_a): 1058 ± 186 individuals (SE) and 646 ± 17 individuals, respectively. In concomitant culture ($pbfn_an_b$), however, *Acrobeloides* sp. numbers per gram were significantly lower than in single culture (377 ± 79 individuals), while *A. avenae* were slightly but not significantly ($P > .05$) higher (745 ± 84 individuals).

Shoot and root biomass.—Shoot production (Table 1) was significantly higher in treatments with bacterial-feeding nematodes or with fungus than in the sterile plant control (p) or plant-and-bacteria treatment (pb). In addition, the most biologically complex treatment ($pbfn_an_b$) had more shoot biomass than all other treatments. Root production was significantly higher in the pf treatment than in any other treatment.

Bacterial growth.—Occasional colonies of fungi and

TABLE 1. Biomass of plants and concentrations of P_i and NH_4^+-N in the soil after plants were grown for 40 d in unamended soil with biological assemblages ($\bar{x} \pm 1$ SE).

Assemblage*	Soil concentration (µg/g)		Biomass per plant (mg)	
	P_i†	NH_4^+-N	Shoot	Root
p	17.5 ± 0.4	33.0 ± 1.9	2.1 ± 0.1	2.0 ± 0.3
pb	16.8 ± 0.1	32.2 ± 2.1	2.6 ± 0.5	1.8 ± 0.1
pbn_b	17.5 ± 0.6	45.5 ± 1.4	6.6 ± 1.0	4.2 ± 0.3
pf	17.2 ± 0.6	48.6 ± 2.4	7.5 ± 0.9	9.6 ± 0.7
pfn_f	17.6 ± 0.5	49.1 ± 3.0	8.6 ± 1.1	4.8 ± 0.6
pbfn_bn_f	16.6 ± 0.7	46.4 ± 3.2	13.5 ± 2.7	4.2 ± 0.6
Q_6 value	9.7	10.2	3.0	2.9

* *p* = plant (*Bouteloua gracilis*); *pb* = plant and bacteria (*Pseudomonas paucimobilis*); *pbn_b* = plant, bacteria, and bacterial-feeding nematode (*Acrobeloides* sp.); *pf* = plant and fungus (*Mortierella* sp.); *pfn_f* = plant, fungus, and fungal-feeding nematode (*Aphelenchus avenae*); and *pbfn_bn_f* = plant, bacteria, fungus, bacterial-feeding nematode, and fungal-feeding nematode. The Q_6 value represents the Tukey HSD ($P \leq .05$) for means from the six treatments.

† Bicarbonate-extractable phosphorus.

bacteria appeared on sterility checks for the *pbn_b* and *pfn_f* treatments, respectively. The number of bacterial cells per gram of soil increased from 1.25×10^5 at inoculation to 3.7 ± 0.6, 7.8 ± 0.4, and $5.9 \pm 0.2 \times 10^8$ in the *pb*, *pbn_b*, and *pbfn_bn_f* treatments, respectively. Both treatments that included nematodes had significantly higher bacterial numbers than the treatment with only plants and bacteria, and the highest bacterial densities were in the *pbn_b* treatment.

Soil inorganic nutrients.—There was no significant difference in soil P_i between any pair of treatments (Table 1). All treatments with bacterial-feeding nematodes or fungi contained significantly more NH_4^+-N than the sterile plant control or plant-and-bacteria treatments (Table 1).

The chitin-amended experiment

Nematode numbers.—Nematode population densities were 11 (*A. avenae*) to 18 (*Pelodera* sp.) times greater in rhizosphere soil than in nonrhizosphere soil at the end of the experiment (Tables 2 and 3). Numbers of *Pelodera* sp. increased in the rhizosphere throughout the experiment, while the rhizosphere populations of *A. avenae* initially increased and then declined after day 49. In nonrhizosphere soil, *Pelodera* sp. reached its highest density on day 49 and then declined slightly, while *A. avenae* was most abundant on day 21 and declined considerably after day 49. Abundance of *A. avenae* in soil from the treatment without plants was generally comparable to that in nonrhizosphere soil of the treatment with plants.

Shoot and root biomass.—Shoot biomasses (Fig. 2a) in the *pbn_b*, *pbf*, and *pbfn_f* treatments were higher than those for the *p* and *pb* treatments on days 21, 49, and 77 (with the exception that there was no difference between *pb* and *pbf* values on day 77). On day 105, shoot biomass in the *pb* treatment was not different from that of any other treatment containing microflora. Shoot biomass in the *p* treatment, however, remained less than in any of the other treatments throughout the experiment.

After day 21, root biomass (Fig. 2b) in all treatments with chitin decomposers was always greater than in the treatment without microflora. Among treatments with microflora, root biomass was higher in the *pb* treatment than in the *pbf* or *pbfn_f* treatments on day 77, although it was not so on days 49 and 105.

Bacterial growth.—Within the fungal treatments, data on density of bacteria (*P. paucimobilis*) could be classified in three groups: lowest in the nonplant treatments, slightly higher in nonrhizosphere soil, and highest in the rhizosphere (Fig. 3). In nearly every case, a treatment with *A. avenae* had higher bacterial numbers than the corresponding treatment without nematodes; this resulted in a significant main effect of grazing (Fig. 3). Bacterial numbers changed very little over time in all treatments except *pbfn_f* rhizosphere soil, where bacteria increased significantly during the experiment.

Bacteria (*P. stutzeri*) in the *pb* and *pbn_b* treatments (Fig. 4) increased rapidly between inoculation and day 7. After this time, numbers slowly declined in the *pb* and *pbn_b* nonrhizosphere, while numbers increased in the rhizosphere of both treatments. Bacterial numbers in the *pbn_b* nonrhizosphere were significantly greater on day 21 than those in *pb* nonrhizosphere soil, but were not different later on. In contrast, rhizosphere bacterial numbers were the same on day 21 for both the *pb* and *pbn_b* treatments, but after this date those in the *pbn_b* remained significantly greater than those in the *pb* treatment.

TABLE 2. Numbers of nematodes within the *pbn_b** treatment in the rhizosphere and nonrhizosphere of chitin-amended soil (mean and 95% confidence interval).

Day	No. *Pelodera* per gram dry soil	
	Nonrhizosphere	Rhizosphere
7	13†	13†
21	30.5 ± 16.5	94.1 ± 59.0
49	63.8 ± 29.6	535.5 ± 543.9
77	44.8 ± 24.9	429.6 ± 259.3
105	49.5 ± 36.8	912.2 ± 699.0

* *pbn_b* = plant (*Bouteloua gracilis*), bacteria (*Pseudomonas stutzeri*), and bacterial-feeding nematode (*Pelodera* sp.).

† Values for day 7 represent inoculum level. Replicate sampling to determine confidence intervals was not attempted.

TABLE 3. Numbers of nematodes within the nonplant (*bfn_f**) treatment and in rhizosphere and nonrhizosphere soil within the *pbfn_f*† treatment (mean and 95% confidence interval).

Day	No. *Aphelenchus* per gram dry soil		
	Nonplant	Nonrhizosphere	Rhizosphere
7	9‡	9‡	9‡
21	16.0 ± 6.5	61.0 ± 41.9	154.6 ± 125.0
49	29.2 ± 16.8	42.2 ± 20.6	311.5 ± 145.2
77	29.2 ± 23.1	7.2 ± 2.6	121.5 ± 59.4
105	14.4 ± 14.8	13.1 ± 9.6	142.4 ± 59.8

* *bfn_f* = bacteria (*Pseudomonas paucimobilis*), fungus (*Fusarium oxysporum*), and fungal-feeding nematode (*Aphelenchus avenae*).

† *pbfn_f* = plant (*Bouteloua gracilis*), bacteria, fungus, and fungal-feeding nematode.

‡ Values for day 7 represent inoculum level. Replicate sampling to determine confidence intervals was not attempted.

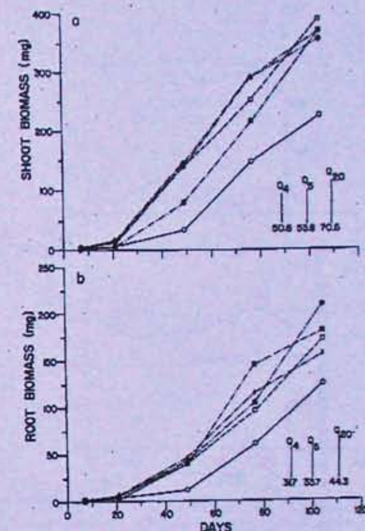

FIG. 2. Shoot biomass (a) and root biomass (b) of *Bouteloua gracilis* grown in soil microcosms with different biological treatments. The Q_4 value represents Tukey's HSD, the difference needed for significance ($P < .05$), between dates for the same treatment; Q_5 represents that for different treatments on the same date; and Q_{20} can be used to compare treatments on different dates. ○——○ Plant (*p*); ■—·—■ Plant + bacteria (*pb*); □---□ Plant + bacteria + fungus (*pbf*); ◆—··—◆ Plant + bacteria + bacterial-feeding nematode (*pbn_b*); ●—···—● Plant + bacteria + fungus + fungal-feeding nematode (*pbfn_f*).

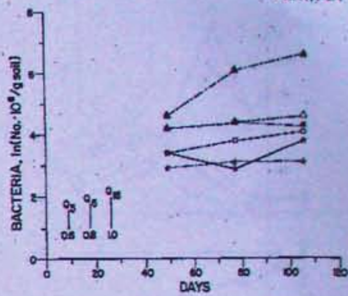

FIG. 3. Natural log (ln) of bacterial numbers in soil microcosms from treatments containing fungi. Q values are Tukey's HSD. Q_3 compares dates for the same treatment, Q_6 different treatments on the same date, and Q_{18} treatments on different dates. ★—·····—★ Bacteria + fungus (*bf*); ☆——☆ Bacteria + fungus + fungal-feeding nematode (*bfn_f*); □-----□ Plant + bacteria + fungus (nonrhizosphere) (*pbf*); △———△ Plant + bacteria + fungus (rhizosphere) (*pbf*); ●-···-● Plant + bacteria + fungus + fungal-feeding nematode (nonrhizosphere) (*pbfn_f*); ▲—·—▲ Plant + bacteria + fungus + fungal-feeding nematode (rhizosphere) (*pbfn_f*).

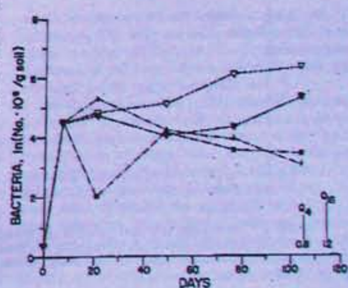

FIG. 4. Natural log (ln) of bacterial numbers in rhizosphere and nonrhizosphere soil of different treatments with bacteria but without fungi. Q values are Tukey's HSD. Q_4 compares dates for the same treatment, and treatments on the same date; Q_{16} compares treatments on different dates. ■—·—■ Plant + bacteria (nonrhizosphere) (*pb*); ▼—————▼ Plant + bacteria (rhizosphere) (*pb*); ◆—··—◆ Plant + bacteria + bacterial-feeding nematode (nonrhizosphere) (*pbn_b*); ▽—·····—▽ Plant + bacteria + bacterial-feeding nematode (rhizosphere) (*pbn_b*).

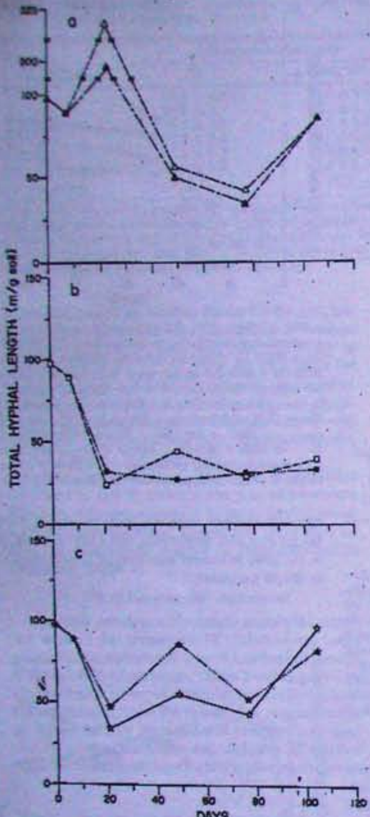

FIG. 5. Total length of fungal hyphae in (a) rhizosphere soil, (b) nonrhizosphere soil, and (c) nonplant soil, from different biological treatments in soil microcosms. Symbols as in Fig. 3.

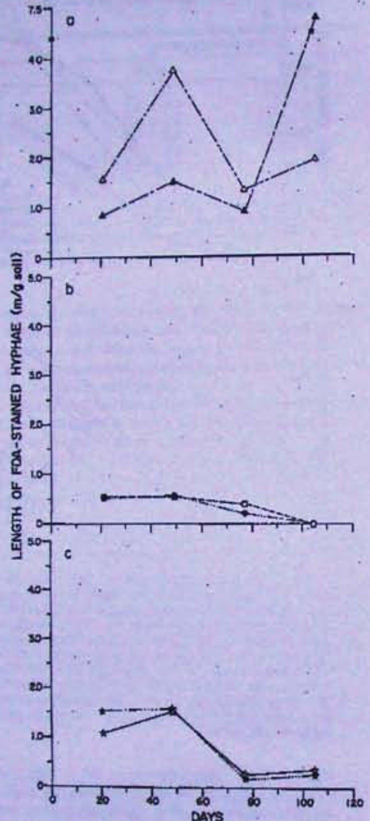

FIG. 6. Length of FDA-stained (metabolically active) hyphae in (a) rhizosphere soil, (b) nonrhizosphere soil, and (c) nonplant soil, from different biological treatments in soil microcosms. Symbols as in Fig. 3.

Bacterial densities within the rhizosphere were nearly comparable between the *pb* and *pbf* treatments and between the *pbn_b* and *pbfn_f* treatments. Treatments with nematodes always contained more bacteria than treatments without nematodes.

Fungal growth.—As with bacterial numbers, three different groups of responses were observed for total (live and dead) hyphal lengths (Fig. 5). Hyphal response in the rhizosphere soils was the most dynamic, increasing after inoculation, decreasing later, and then increasing again (Fig. 5a). Fungal lengths from nonrhizosphere soil of both the *pbf* and *pbfn_f* treatments decreased rapidly after inoculation and then remained at a constant level of ≈30 m/g of soil (Fig. 5b). Fungi in the *bf* and *bfn_f* treatments also decreased after inoculation but returned to the inoculum density by the end of the experiment (Fig. 5c). The amount of hyphae in grazed treatments was generally less than in ungrazed treatments.

Hyphae that stained with FDA (metabolically active hyphae; see Söderström 1977, Ingham and Klein 1982) could also be classified by treatment into three distinct groups (Fig. 6). Initially, stained hyphae in the rhizosphere were most abundant in the *pbf* treatment (Fig. 6a), in which hyphae increased significantly between days 21 and 49, then decreased to the initial level by day 77. Active hyphae in the rhizosphere of the *pbfn_f* treatment were less abundant than in the *pbf* rhizosphere on day 21, but increased with time until they were more abundant than in the *pbf* rhizosphere on the final sample date. In the nonrhizosphere soil (Fig. 6b), both *pbf* and *pbfn_f* treatments showed a decrease in FDA-stained hyphae over time until almost no staining could be detected. Stained hyphae in the *bf* and *bfn_f* treatments (Fig. 6c) were more abundant than in the nonrhizosphere soil until day 77, when stained hyphae decreased to ≈0.1 m/g of soil, a level at which they remained for the rest of the experiment.

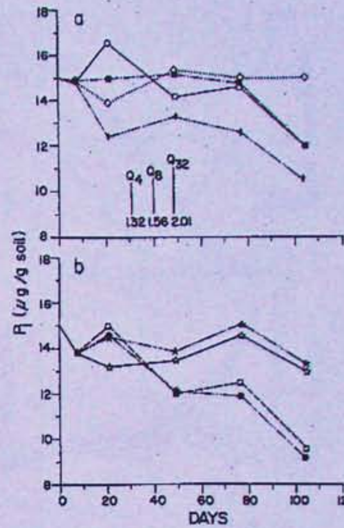

FIG. 7. Mean values of soil P_i in different treatments from soil microcosms (a) without fungi and (b) with *Fusarium oxysporum* and *Pseudomonas paucimobilis*. Q values are Tukey's HSD. Q_4 compares dates for the same treatment, Q_8 different treatments on the same date, and Q_{32} treatments on different dates. ◇---◇ Uninoculated control (*uc*); ★—·····—★ Bacteria + fungus (*bf*); ☆——☆ Bacteria + fungus + fungal-feeding nematode (*bfn_f*); ○——○ Plant (*p*); ■—·—■ Plant + bacteria (*pb*); □ ----- □ Plant + bacteria + fungus (*pbf*); ◆—··—◆ Plant + bacteria + bacterial-feeding nematode (*pbn_b*); ●—···—● Plant + bacteria + fungus + fungal-feeding nematode (*pbfn_f*).

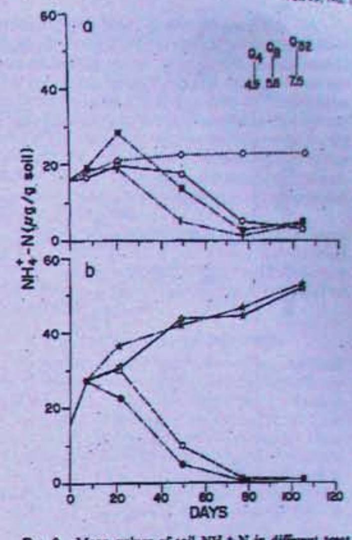

FIG. 8. Mean values of soil NH_4^+-N in different treatments from soil microcosms (a) without fungi or (b) with fungi *Fusarium oxysporum* and *Pseudomonas paucimobilis*. Q values apply to both graphs. Symbols as in Fig. 7.

Soil inorganic nutrients.—Extractable inorganic soil phosphorus (P_i) remained generally constant in the uninoculated control through the course of the experiment (Fig. 7a, b). Values were always less in the *bfn_f* treatment than in the *bf* treatment, and although the difference was never significant on any one date, the main effect of grazing was significant ($P < .01$). All plant treatments immobilized P_i, with the least immobilization in the *p* and *pb* treatments, and the most rapid initial immobilization in *pbn_b*. By the end of the experiment, however, the P_i values were similar for the *pbn_b*, *pbf*, and *pbfn_f* treatments.

Ammonium-N increased slightly between days 9 and 21 in the uninoculated control and then remained constant for the rest of the experiment (Fig. 8a, b). Both the *bf* and *bfn_f* treatments showed significant net mineralization of NH_4^+-N, with no difference between the two treatments. Over time, all plant treatments immobilized significant amounts of NH_4^+-N, although

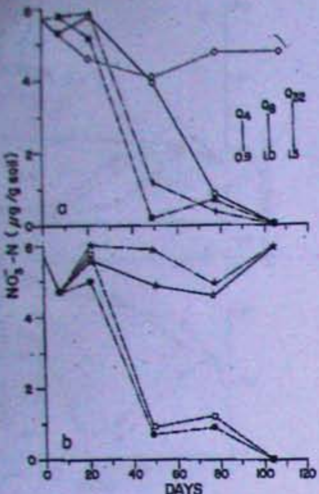

FIG. 9. Mean values of soil NO_3^--N in different treatments from soil microcosm (a) without fungi or (b) with *Fusarium oxysporum* and *Pseudomonas paucimobilis*. Q values apply to both graphs. Symbols as in Fig. 7.

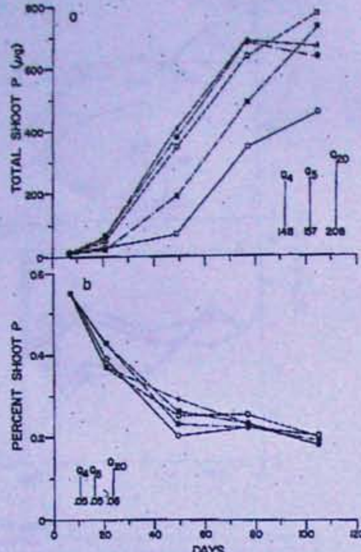

FIG. 10. Total shoot phosphorus (a) and percent shoot phosphorus (b) in *Bouteloua gracilis* grown in soil microcosms with different biological treatments. Symbols as in Fig. 2.

there was some early net mineralization in the *pb* and *pbf* treatments. The most rapid immobilization occurred in the two grazed treatments (*pbn_b* and *pbfn_f*).

Soil NO_3^--N levels were low, and in the uninoculated control decreased between days 0 and 49 and then increased slightly (Fig. 9a, b). Fluctuations also occurred in the *bf* and *bfn_f* treatments, but neither treatment differed significantly from the control or from the initial NO_3^--N value. All plant treatments immobilized all measurable NO_3^--N by the end of the experiment, with the most rapid immobilization occurring within the grazed treatments.

Shoot nitrogen and phosphorus.—Total shoot phosphorus increased throughout the experiment in all treatments except those with nematodes between days 77 and 105 (Fig. 10a). Total shoot phosphorus was significantly greater in the treatments with nematodes and/or fungi than in the plant alone or plant-plus-bacteria treatments until day 105 (except for *pb* vs. *pbf* on day 77). On the final date, the only difference among treatments was that in the *p* treatment there was less shoot phosphorus than in the treatments with microflora. However, there were only small differences in percent phosphorus in the shoots (Fig. 10b).

Total shoot N increased in all treatments between days 7 and 77, but in only the sterile plant treatment did it increase between days 77 and 105 (Fig. 11a). More N was in the shoots of the *pbf*, *pbfn_f*, and *pbn_b* treatments than in the *pb* or *p* treatments until day 77 (except for *pbf* vs. *pb* on day 49). The increases in total shoot N were the result of greater shoot biomass and higher N concentration in the shoots. For example, on day 21 there was 2.5% N in the *p* and *pb* treatments, while in the *pbn_b*, *pbf*, and *pbfn_f* treatments the value ranged from 3.4 to 3.7% (Fig. 11b). On the final sample date there was no significant difference in total shoot N between any pair of treatments.

Nematode consumption of microflora

The amount of bacterial biomass carbon consumed by *Pelodera* sp. was estimated by first determining nematode respiration rates (R) according to the equation $R = 2.52W^{0.74}$, where W is nematode fresh mass in micrograms and R is O_2 consumption in nanolitres per individual per hour. (Schiemer 1982). This esti-

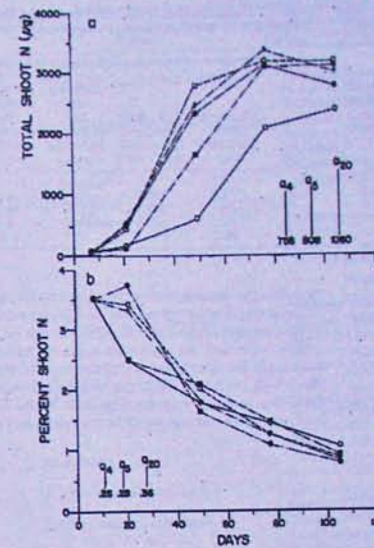

FIG. 11. Total shoot nitrogen (a) and percent shoot nitrogen (b) in *Bouteloua gracilis* grown in soil microcosms with different biological treatments. Symbols as in Fig. 2.

mation assumes a respiratory quotient (RQ) of 0.8 mol CO_2 per mol O_2 (Sohlenius 1979) and a Q_{10} of 2. The proportion of carbon mass consumed (C) and allocated towards production (Pr), respiration (R), or defecation (D) was calculated based on values for *Pelodera* sp. as follows: $C = 0.225Pr + 0.370R + 0.405D$ (Marchant and Nicholas 1972). Percent of bacterial standing crop biomass consumed was determined for each sample date assuming a dry mass of 0.44×10^{-6} μg/cell and assuming bacteria to be 50% carbon (Van Veen and Paul 1979).

Fungal biomass carbon consumed by *A. avenae* was estimated similarly using the equation for respiration rate $R = 2.75W^{0.72}$ (derived from data for *A. avenae* only; Klekowski et al. 1972) and using the values mentioned above for other parameters. Although the production and assimilation efficiencies of a fungal-feeding nematode may be different from those of a bacterial-feeding nematode, there are no reliable literature values, and the values of Marchant and Nicholas (1972) were used as the best approximation available. Amount of cytoplasm consumed was determined based on a value of 55.4% carbon for fungal cytoplasm (Hurst and Wagner 1969). Standing crop of cytoplasm was calculated by multiplying the volume of cytoplasm-filled hyphae by 0.64, since ≈64% of this hyphal volume was cytoplasm and 36% was cell wall, based on our observations of hyphae in agar films. Total cytoplasm was ≈10 times the volume of cytoplasm that stained with FDA. Cytoplasm volume was converted to dry biomass using the conversion factor 0.33 g/cm^{-3} (Van Veen and Paul 1979). Percent of total cytoplasm standing crop biomass consumed per day was determined for each sample date.

The percentage of the bacteria standing crop biomass consumed by *Pelodera* sp. ranged from 3.5 to 26.0%/d (Table 4). The percentage of the total fungal cytoplasm consumed by *A. avenae* ranged from 9.3 to 32.8%/d (Table 5).

Nitrogen losses by nematodes

The amount of N lost by *Pelodera* sp. was based on the allocation $C = Pr + R + D$ with the following assumptions. All N associated with C that is defecated or respired must also be lost, as well as half of the N associated with C that goes towards production, since the average C:N ratio of nematodes (10:1) (Anderson et al. 1983) is twice that of bacteria (5:1) (Woods et al. 1982). Nitrogen losses for *A. avenae* were determined similarly with the following assumptions. All of the N associated with C allocated to production is also allocated to production. However, since the C:N ratio of fungal cytoplasm (11:1) (Hurst and Wagner 1968) is greater than that for nematodes, this amount of N is insufficient for production of nematode biomass. Therefore, additional N must be acquired from that associated with respired C. The additional N necessary is equivalent to 6.4% of the N associated with respired C. The remaining N associated with respired C is excreted. Daily and cumulative N losses were calculated for each day of the experiment for both nematodes. The principal N loss by nematodes is in the form of ammonia (Lee and Atkinson 1977), but at times of luxury consumption of bacteria, some bacteriophagic nematodes may lose up to 50% of their metabolic N as amino-N; this phenomenon is transient (2–3 d) under normal soil conditions (Anderson et al. 1983).

Peak daily N loss from nematodes was reached on day 49 by *Pelodera* sp., when 61.4 μg/microcosm was lost, and on day 22 for *A. avenae*, when 28.0 μg/microcosm was released (Fig. 12a). Cumulative N loss per microcosm at the end of day 105 was 3671 μg for *Pelodera* sp. and 1468 μg for *A. avenae* (Fig. 12b).

DISCUSSION

Plant growth

Addition of similar biotic assemblages to sterile soil resulted in similar plant growth responses in both the unamended and chitin-amended experiments regardless of differences in soil type and species composition.

TABLE 4. Consumption of the bacterium *Pseudomonas stutzeri* by the bacterial-feeding nematode *Pelodera* sp.

Day	Nematode biomass (μg/microcosm)	Consumed bacterial biomass (μg·microcosm⁻¹·d⁻¹)	Standing crop of bacterial biomass (μg/microcosm)	Percent of standing crop consumed
7	31.9	...	3916	...
21	80.6	316.0	9108	3.5
49	177.6	640.0	2992	21.4
77	109.0	427.3	2640	16.2
105	111.1	435.6	1672	26.0

TABLE 5. Consumption of cytoplasm of the fungus *Fusarium oxysporum* by the fungal-feeding nematode *Aphelenchus avenae*.

Day	*A. avenae* biomass (μg/microcosm)	Cytoplasm consumed ($\mu g \cdot microcosm^{-1} \cdot d^{-1}$)	Standing crop total cytoplasm (μg/microcosm)	Percent of total standing crop cytoplasm consumed per day
7	18.8	...	...	...
21	173.9	726.9	2217	32.8
49	144.7	604.8	2070	29.2
77	29.2	122.0	1309	9.3
105	46.2	193.1	718	26.9

The most significant increases in available NH_4^+-N (Table 1), plant growth (Table 1, Fig. 2a), and plant-N (Fig. 11a) occurred when bacterial-feeding nematodes or fungi were present. In the unamended experiment, the rhizosphere bacterium *P. paucimobilis* did not significantly increase shoot growth over the control, whereas addition of the chitin-decomposer *P. stutzeri* (amended experiment) did result in more plant biomass with a higher N content. This resulted from additional inorganic nitrogen made available to the plant through mineralization of chitin by *P. stutzeri*, which supports prediction 1 (see The Conceptual Model: Predictions and Treatment Contrasts).

Bacterial-feeding nematodes stimulated bacterial growth in both studies. Thus, the enhanced shoot growth in the pbn_b treatments of both experiments may have been the result of nematode excretion of N, increased mineralization of N by additional bacteria, or both, as stated in prediction 3. However, in the unamended experiment, bacterial numbers in the *pb* and $pbfn_bn_f$ treatments were not significantly different, yet shoot biomass was 22% greater than in the unamended pfn_f treatment. From this evidence, we suggest that the plant growth responses were caused by the increase in N mineralization from the nematodes *Pelodera* sp. and *Acrobeloides* sp., not by the increase in bacterial numbers. In neither experiment did addition of the fungal-feeding nematode *A. avenae* significantly influence shoot growth; this did not support prediction 3 but was in agreement with prediction 4.

Bacterial populations

Bacterial densities in rhizosphere soil of the amended experiment were nearly always higher than in nonrhizosphere soil from the same treatment (Figs. 3 and 4). Similar results were reported by Starkey (1931), Darbyshire and Greaves (1973), Clarholm (1981), and Ingham and Coleman (1983). The principal mechanism responsible is the addition of soluble or labile organic matter from growing roots, which relieves energy limitations on bacteria and fungi that occur in nonrhizosphere soil (Stotzky and Norman 1963, Lynch and Panting 1980). Nonrhizosphere bacteria populations (*pbf* and $pbfn_b$) tended to be higher than in corresponding treatments without plants (*bf* and bfn_b) (Fig. 3), indicating that the influence of plant roots extended beyond the area defined as rhizosphere in this study.

Nematodes had no significant effect on bacterial numbers in nonrhizosphere soil of the amended study, where both nematode and bacterial populations were lower than in the rhizosphere (Figs. 3, 4; Tables 2, 3). However, in the rhizosphere of the amended study and

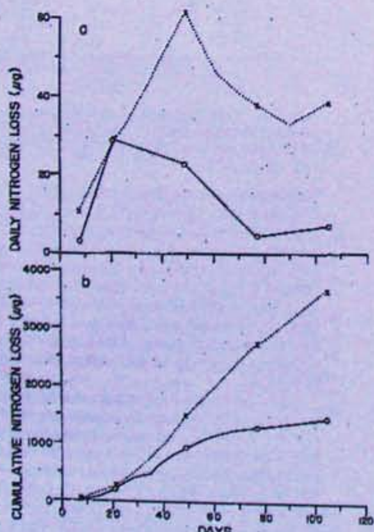

FIG. 12. Daily (a) and cumulative (b) nitrogen losses per microcosm from nematodes grown in soil microcosms with *Bouteloua gracilis*. × ···· × *Pelodera* sp.; O——O *Aphelenchus avenae*.

TABLE 6. System responses attributed to microbial grazers in soil.

Grazer	System responses	Reference(s)
Systems without plants		
Acanthamoeba polyphaga (amoeba, B)*	Decreased bacterial populations Increased CO_2 evolution Increased N mineralization	Coleman et al. (1977)
Mesodiplogaster lheritieri (nematode, B)	Decreased bacterial populations Increased CO_2 evolution Increased N mineralization Increased P mineralization	
M. lheritieri	Increased CO_2 evolution	Anderson and Coleman (1978)
Unamended soil		
A. polyphaga	Decreased bacterial populations Increased CO_2 evolution Increased N mineralization Increased P mineralization	Anderson et al. (1978, 1979*a*) Cole et al. (1978) Coleman et al. (1978) Woods et al. (1982)
M. lheritieri	Decreased bacterial populations	
A. polyphaga and *M. lheritieri*	Decreased bacterial populations Increased CO_2 evolution Increased N mineralization Increased P mineralization	
C- and N-amended soil		
A. polyphaga	Decreased bacterial populations Increased CO_2 evolution Increased N mineralization Increased P mineralization	
M. lheritieri	Decreased bacterial populations Increased CO_2 evolution	
A. polyphaga and *M. lheritieri*	Decreased bacterial populations Increased CO_2 evolution	
Pelodera punctata (nematode, B)	Increased bacterial populations Increased O_2 consumption Increased substrate utilization	Abrams and Mitchell (1980)
M. lheritieri or *Acrobeloides* sp. (nematode, B)	Increased CO_2 evolution Increased substrate utilization Increased N mineralization Decreased P immobilization	Anderson et al. (1981*a*)
Pelodera sp. (nematode, B)	Increased bacterial populations Increased N mineralization	Gould et al. (1981)
Field populations of amoebae	Decreased bacterial populations	Clarholm (1981)
Rhabditis sp. (nematode, B)	Increased CO_2 evolution Increased P mineralization	Anderson et al. (1982)
M. lheritieri	Decreased bacterial populations Increased N mineralization	Anderson et al. (1983)
Pelodera sp. Cellulose-amended soil	Increased bacterial populations Increased CO_2 evolution Increased N mineralization	Trofymow and Coleman (1982) Trofymow et al. (1983)
Pelodera sp. Chitin- and cellulose-amended soil	Increased bacterial populations Increased CO_2 evolution Increased substrate utilization Increased N mineralization	
Field populations of amoebae, ciliates, and flagellates	Decreased CO_2 evolution and decreased N mineralization when densities of amoebae, ciliates, and flagellates were reduced	Coleman et al. (1984)
Field populations of bacterial-feeding nematodes	Decreased bacteria and decreased decomposition when nematodes increased following removal of predatory mites	Santos and Whitford (1981) Santos et al. (1981) Whitford et al. (1982) Elkins and Whitford (1982)
Aphelenchus avenae (nematode, F)	Decreased or killed fungal cultures	Mankau and Mankau (1963)
A. avenae	Decreased fungal biomass	Wasilewska (1975)
Oniscus asellus (collembolan, F) or *Glomeris marginata* (millipede, F)	Low and moderate densities of the microarthropods resulted in increased CO_2 evolution, but high densities re-	Hanlon and Anderson (1979)

TABLE 6. Continued.

Grazer	System responses	Reference(s)
	duced CO_2 evolution. All densities reduced fungal standing crop	
Folsomia candida (collembolan, F)	Increased CO_2 evolution at some densities and some nutrient levels	Hanlon (1981)
A. avenae Cellulose-amended soil	Decreased CO_2 evolution Decreased N mineralization	Trofymow and Coleman (1982) Trofymow et al. (1983)
A. avenae Chitin- and cellulose-amended soil	Increased CO_2 evolution Increased N mineralization	
Systems with plants		
A. polyphaga	Increased N mineralization Increased shoot-N concentration	Elliott et al. (1979*a*)
Acrobeloides nana (nematode, B) and *A. avenae* (present in low numbers)	Decreased bacterial populations Increased loss of N in leachate during last half of experiment attributed to increased N mineralization once nematodes had achieved high population levels Slightly increased biomass of pine seedlings	Bååth et al. (1981)
Tectocepheus velatus (mite, F)	Increased total hyphae and FDA-stained active hyphae	
Field populations of amoebae, ciliates, and flagellates	Increased plant-N uptake Increased plant-N concentration	M. Clarholm (*personal communication*)
Pelodera sp. (nematode, B)	Increased bacterial populations Increased biomass of blue grama grass Increased plant-N concentration	This study
A. avenae (nematode, F)	Increased bacterial populations	

* Taxon and B = bacterial-feeder or F = fungal-feeder included in parentheses.

non-rhizosphere soil of the unamended experiment (Table 1), where the densities of nematodes were high, *Pelodera* sp., *Acrobeloides* sp., and *A. avenae* all significantly increased numbers of bacteria, relative to treatments without nematodes. In both the pbn_r and $pbfn_r$ treatments of the amended experiment, rhizosphere bacterial numbers continued to increase to the end of the experiment. These results suggest that when the microbial populations of field soils are examined without reference to the rhizosphere/nonrhizosphere separation (as is common practice), important microbial events mediated by plant roots or nematodes may be diluted and overlooked.

The mechanism by which bacterial-feeding nematodes increase the bacterial population in some studies and decrease it in others is intriguing. These inconsistencies may be nematode species-specific. While all nematode species may be capable of stimulating bacterial growth, some may also be capable of consuming the additional production before it can be observed as a net increase in numbers. For example, Anderson et al. (1983) observed a net decrease in bacterial numbers with grazing by *Mesodiplogaster lheritieri*, but they calculated that the production of nematode biomass that occurred would have required the consumption of five times as many bacteria as the number observed during the bacterial population decline. Thus, bacterial production was stimulated and the increase was then consumed by the nematodes. In four studies that recorded increased bacterial populations in the presence of a bacterial-feeding nematode, the nematode was a *Pelodera* species (the amended experiment of this study; Abrams and Mitchell 1980, Gould et al. 1981, Trofymow and Coleman 1982; study results are summarized in Table 6). All experiments in which *Mesodiplogaster lheritieri* was added as a bacterial predator resulted in net decreases in bacterial densities (Coleman et al. 1977, Anderson et al. 1979*a*; see Table 6). *Acrobeloides* sp., however, increased bacterial populations in the unamended experiment but reduced them in two other studies (Anderson et al. 1981*a*, 1983; see Table 6). The discrepancy in results may be attributable to differences in nematode density. In the current study, low nematode densities in the nonrhizosphere soil of the amended experiment did not affect bacterial numbers, while higher densities of nematodes in either the rhizosphere soil of the amended experiment or the nonrhizosphere soil of the unamended study resulted in higher bacterial populations.

There are three possible mechanisms for stimulation of bacterial population growth by bacterivorous nematodes. First, up to 60% of the bacteria passing through the gut of a nematode may be defecated alive (Smerda et al. 1971), and bacteria that survive ingestion may obtain some otherwise limiting nutrient, hormone, or growth factor while in the gut, resulting in rapid growth

after being defecated; this phenomenon has been demonstrated for phosphorus in aquatic grazing systems (Porter 1976). Second, the nematode may be important in transporting bacterial cells, either internally or externally on the cuticle, to unexploited, substrate-rich microsites that the microbe would not be able to reach as rapidly by its own form of mobility (Wasilewska et al. 1975, Gould et al. 1981, Anderson et al. 1982). Third, excretion and defecation products of nematodes may provide substrates or inorganic nutrients for bacterial growth that are locally concentrated and readily useable, and this may have a stimulatory effect. For example, nematodes defecate significant amounts of amino acids into the soil (Anderson et al. 1983), and Marchant and Nicholas (1974) noted that bacterial reproduction was stimulated by the release of waste products by *Pelodera* sp.

We believe that the first mechanism, passage of bacteria through the gut, cannot be the only mechanism involved, since *A. avenae* and *Tylenchorhynchus claytoni* (Ingham and Coleman 1983) also increased bacterial numbers even though they are incapable of ingesting bacteria and passing them through the gut. In fact, bacterial numbers in the present study were as high or higher in the presence of *A. avenae* as with *Pelodera* sp. It is likely that both the transport and excretory product mechanisms are responsible for the stimulation of bacterial growth by nematodes.

Bacterial consumption

We calculated that 3.8 μg of bacterial biomass was consumed each day for each microgram of nematode biomass (Table 4). The corresponding rate of consumption of bacterial biomass C is $1.96\ \mu g \cdot d^{-1} \cdot \mu g^{-1}$, which is greater than the rate of $0.73\ \mu g \cdot d^{-1} \cdot \mu g^{-1}$ derived from Marchant and Nicholas (1974) and based on a population of *Pelodera* sp. weighing 13.2 mg, a consumption rate of $1.277\ J \cdot h^{-1} \cdot mg^{-1}$, an energy value of 21.1 J/mg bacteria, and the assumption that 50% of bacterial dry mass is carbon. The nematode species we used was much smaller than that of Marchant and Nicholas (1974) and thus should have a higher consumption rate per unit mass. Since the average dry mass of a *Pelodera* sp. individual in this study was 0.021 μg, the average nematode consumed 1.9×10^5 bacteria/d. This is considerably lower than the rate (72×10^5 bacteria/d) reported for *Plectus parietinus* (Duncan et al. 1974) but similar to the rate for male *Pelodera chitwoodi* of 3.9×10^5 bacteria/d averaged over an 8-d life span (Mercer and Cairns 1974). However, since *P. parietinus* and *P. chitwoodi* are much larger nematodes than the *Pelodera* sp. used in this study, their individual consumption rates would be expected to be greater. The calculated consumption in this study and others underestimates the number of bacterial cells actually ingested because the value for defecation derived by Marchant and Nicholas (1974) is an underestimate. They calculated defecation from the soluble ^{14}C recovered from washes and supernatants after centrifugation. However, a large percentage of cells ingested may be defecated whole or as parts of cells (Smerda et al. 1971). These would have been removed by centrifugation and thus unaccounted for in the measurements of defecation.

Fungal growth

The rapid decline of total hyphal lengths after inoculation (Fig. 5) indicates either that the initial inoculation density was greater than the available carbon substrates could support or that inoculation of hyphae into the soil caused the destruction of some hyphae. Fungi and/or bacteria are capable of rapidly decomposing dead hyphae (Lockwood and Filonow 1981). The increase in total hyphae in the rhizosphere region after plants were added suggests that the fungus was able to utilize carbon substrates produced by plant roots.

The abundance of active hyphae (FDA stained) slowly declined after day 49 in both the nonrhizosphere and nonplant soils (Fig. 6). This was probably due to the utilization of easily metabolized substrates until only chitin and other native nonlabile compounds remained available, as also suggested by a decrease in the rate of N mineralization (Fig. 8b). There was no effect of nematodes on the abundance of active hyphae in either soil zone. As with total counts, active hyphae were more abundant in the nonplant soil than in nonrhizosphere soil. The abundance of active hyphae in the rhizosphere did not decrease with time, and significantly increased in the $pbfn_r$ treatment on the last sample date, suggesting that fungi in the rhizosphere may have been less energy-limited than in nonrhizosphere soil. Active hyphae in the treatment with *A. avenae* were significantly less abundant than in the treatment without nematodes on day 49. However, the significant increase of active hyphae in the $pbfn_r$ treatment on day 105 suggests that nematode grazing of fungi may stimulate fungal growth, as with nematode grazing of bacteria.

Fungal consumption

We calculated that 4.18 μg of fungal cytoplasm biomass, or 2.32 μg of fungal biomass C, was consumed each day for each microgram of *A. avenae* biomass (Table 5). Since the average dry mass of an individual *A. avenae* was 0.029 μg, the average nematode consumed 0.067 μg C, or 0.12 μg cytoplasm, each day. This is within the range of cytoplasm consumption of 0.01–0.17 μg/d for 1-d-old and 5-d-old *A. avenae*, respectively, as calculated from de Soza (1973). These ingestion estimates are more precise than those for bacterial-feeding nematodes, since only soluble compounds are defecated, with no need to account for whole cells or cell fragments that are not assimilated. As *A. avenae* consumption exceeded the amount of FDA-stained cytoplasm, these nematodes also must eat cytoplasm that is not sufficiently metabolically active to stain with FDA.

Nematode populations

In the unamended experiment, *Acrobeloides* sp. and *A. avenae* were grown both in single (pbn_a and pfn_f) and combined ($pbfn_a n_f$) cultures. Although both nematodes reached high population levels when in single culture, *Acrobeloides* sp. populations were 65% lower in the presence of *A. avenae*. Since bacterial populations were not different in the two treatments with *Acrobeloides* sp. (pbn_a and $pbfn_a n_f$) and since the two nematodes do not compete for the same food source, reduction in *Acrobeloides* sp. numbers may have been caused by interference competition with *A. avenae* for some environmental resource, such as habitable pore space.

In the amended study, both *Pelodera* sp. and *Aphelenchus avenae* strongly preferred the rhizosphere (Tables 2 and 3). Although rhizosphere soil was never more than 5% by mass of the total soil in the microcosm, at times 30–40% of the total population of either species was recovered from the rhizosphere. Root-feeding nematodes are commonly known to predominate next to roots (Ingham and Coleman 1983), but this is the first quantitative report that bacterial-feeding and fungal-feeding nematodes also prefer this habitat. Andrew and Nicholas (1976) observed that living *Pseudomonas* spp. attracted bacterial-feeding nematodes, but dead bacteria did not. Similarly, fungi also produce substances that attract nematodes (Balan et al. 1976, Jansson and Nordbring-Hertz 1979). Therefore, the majority of the population is likely to spend most of the time in the rhizosphere, where microbial densities are highest. Bacterial-feeding protozoa have also been observed in greater numbers in rhizosphere soil (Darbyshire and Greaves 1973, Clarholm 1981).

Soil inorganic N and P

In the short-term unamended study, there was net N immobilization in the *p* and *pb* treatments, as the plants took up the limited available N while little or no N was mineralized (Table 1). In the treatments with fungi and/or bacterial-feeding nematodes, however, there was more N mineralized than the plants could take up, even though there was greater and more rapid plant growth in these more biologically complex treatments.

In the amended study, the bfn_f and $pbfn_f$ treatments consistently immobilized more P_i ($P < .01$) than the *bf* and *pbf* treatments (Fig. 7a, b). The increased bacterial populations in the treatment with nematodes most likely immobilized much of the P, with a small portion also being immobilized into nematode biomass. Similarly, the pbn_b treatment immobilized significantly more P_i than the *pb* treatment. While most of the additional immobilization was due to the more rapidly growing plants in the pbn_b treatment, some of the P_i was also taken up by the larger bacterial population in the rhizosphere of the pbn_b treatment. More P_i was immobilized in the pbn_b, *pbf*, and $pbfn_f$ treatments than in the plant or plant-plus-bacteria treatments because of the larger plant biomass attained in treatments with bacterial-feeding nematodes or fungi.

Before the addition of plants (days 0–7), all inoculated treatments mineralized N (Fig. 8a, b), with the fungal treatments mineralizing much more than the treatments with bacteria since *Fusarium oxysporum* is a better chitin decomposer than *Pseudomonas stutzeri* (Gould et al. 1981). The greatest net mineralization of N was in the *bf* and bfn_f treatments. The mineralization rate in these two treatments was initially rapid and then slower after day 21. Therefore, the initial mineralization of N could have been from simple native organic N compounds (proteins, amino acids, etc.), followed by a slower mineralization of N from the added chitin. Between day 7 and day 21 there was net mineralization of N in the *pbf* treatment but net immobilization in the $pbfn_f$ treatment (Fig. 8b). On day 21 there was no difference between these two treatments in shoot, root, or fungal biomass (Figs. 2a, b, 5), so the net immobilization of N in the $pbfn_f$ treatment must have been due to increased uptake of NH_4^+-N by larger bacterial populations in this treatment and incorporation into nematode biomass. After day 21, immobilization of N was rapid in both *pbf* and $pbfn_f$ treatments as plants grew rapidly. Most of the increase in soil NH_4^+-N in the *pb* treatment on day 21 probably resulted from the marked decline in bacterial populations, but the excess was rapidly immobilized again as bacterial populations increased after day 21. The greater immobilization in the pbn_b treatment was due to a larger bacterial population and more rapidly growing plants, which were already significantly larger than those in the *pb* treatment on day 21. The faster initial growth rate of the plants in the treatment with *Pelodera* sp. probably resulted from the greater availability of N as the large population of nematodes grazing on the bacteria excreted NH_4^+-N, which allowed for rapid uptake by the plants (Anderson et al. 1983). In all plant treatments, nearly all available inorganic N was immobilized by the end of the experiment (Figs. 8, 9), suggesting that the plants remained N-limited throughout the experiment and that the mineralization rate of chitin did not exceed the plant's ability to take up N.

Nitrogen release by nematodes

While appreciable N was released by nematodes in the pbn_b treatment, the amount was insufficient to explain all the early increase in plant N as compared with plants from the *pb* treatment. For example, on day 21, 647 μg of N were found in plants from the pbn_b treatment, while *pb* plants contained 175 μg N, a difference of 472 μg. By this time only 269.5 μg N had been released by nematodes. Thus, another mechanism must be proposed for the additional N uptake by the plant. Several factors should be considered. First, the bacterial populations on day 21 were 25 times greater in the pbn_b treatment than in the *pb* treatment (Fig. 4), so chitin decomposition by bacteria was probably much greater in the treatment with nematodes. Second, since both bacteria and nematodes were concentrated in the rhizosphere, much of the N mineralized by either bacteria or nematodes was probably in close proximity to the roots, available for immediate uptake. This more advantageous N regime was probably responsible for the more rapid root growth early in the pbn_b treatment. The greater root biomass was then able to exploit a larger soil volume and reach soil inorganic N not available to roots in the *pb* treatment. This was primarily responsible for the differences between these treatments in NH_4^+-N and NO_3^--N levels, which were noted in the first half of the experiment (Figs. 8a, 9a). Therefore, it seems likely that *Pelodera* sp. had an important positive feedback effect early in the experiment.

Root biomass between the two treatments was no longer different by day 49, yet plants in the pbn_b treatment contained 813 μg more N than those in the *pb* treatment. By this time nematodes had excreted 1491 μg N per microcosm, which may have accounted for much of the additional plant N, although some of the nematode-excreted N was undoubtedly taken up by bacteria.

During the entire experiment, *A. avenae* in the $pbfn_f$ treatment lost 1468 μg of N per microcosm, appreciably less than the 3671 μg excreted by *Pelodera* sp. The fungus alone mineralized 3750 μg of N per microcosm in the nonplant (*bf*) treatment; thus, the amount of N lost by *A. avenae* did not significantly improve the N regime of the plant. Hence, the fungus treatments with and without *A. avenae* did not differ in either shoot biomass or total shoot N.

Evaluation of the Conceptual Model

The conceptual model introduced in Fig. 1 was generally supported by the results of this study and was useful in interpreting the results observed. The model proposes that microbial grazers influence the strength of feedback controls on substrate utilization by fungi (C_{43}) and bacteria (C_{33}). Our results support this, as do those of Anderson et al. (1981*a*), Abrams and Mitchell (1980), and Trofymow et al. (1983) (Table 6). Fungal feeders have been shown to increase (Hanlon 1981) or decrease (Trofymow and Coleman 1982) system respiration. System responses are likely to be dependent on grazing intensity as affected by initial population sizes (Coleman et al. 1984).

The ecological importance of grazer influence on the rate of substrate utilization C_{33} is not only that disappearance of litter would occur at a faster rate with nematodes but also that potentially more nutrients would be mineralized. The availability of these nutrients for plant uptake depends on the amount of organic matter C available for microfloral growth and hence on nutrient immobilization. By comparing the *pb* and pbn_b treatments, relative estimates of mineralization can be made, however. The higher concentration and total amount of N in the shoot tissue in the pbn_b treatment suggest that those plants were drawing from a larger pool of available N than those in the *pb* treatment. By the end of the experiment (105 d), however, there was no difference in plant or soil N between the *pb* and pbn_b treatments, indicating that the presence of nematodes may be of only short-term advantage to the plant. This concept was also proposed by Anderson et al. (1981*b*), who hypothesized that microbial grazers accelerate the rates of substrate utilization and nutrient mineralization but not necessarily the final amounts of substrate decomposed or nutrients released. However, in many ecosystems, particularly those in arid and semiarid climates, ideal conditions for plant growth occur only for short periods. Thus, a short-term advantage may be quite significant. Some of the additional N mineralized in the pbn_b treatment was immobilized into microbial biomass as bacterial populations in the rhizosphere of the pbn_b treatment increased. Thus, in the latter part of the experiment the bacteria may have been outcompeting the plant for the NH_4^+-N mineralized by the nematode. A similar increase in nitrogen concentration in plant shoot tissue in the presence of a protozoan (amoebal) bacterial grazer was also reported by Elliott et al. (1979*a*) and M. Clarholm (*personal communication*) (Table 6).

Our prediction that plants grow faster in the presence of microfloral grazers than in their absence was supported for bacterial-feeding nematodes but not for fungal-feeding nematodes. There was no evidence in this experiment (Fig. 8b) that the system with fungal-feeding nematodes mineralized more N than the one without grazers (*bf* and bfn_f treatments). Even if more N had been mineralized with *A. avenae*, however, there still may have been no plant growth response, because the amount of N mineralized by the fungus alone may have been optimal. An increase in plant growth with the addition of microfloral grazers probably occurs only in a nutrient-limited environment. Elliott et al. (1979*a*) found that addition of bacterial-grazing amoebae resulted in a smaller increase in plant-N uptake when initial NH_4^+-N levels were high (15% increase) than when they were at a medium level (132% increase). Because of greater chitin-N mineralization by *F. oxysporum* than by *P. stutzeri* (Gould et al. 1981), plants in the *pbf* treatment had more N available than those in the *pb* treatment. Thus, plant growth and amount of shoot N in the *pbf* treatment were greater than in the *pb* treatment and equal to values in the treatment with bacterial grazers.

While Bååth et al. (1981) observed that Scots pine seedlings were 17% larger in treatments with microbial-feeding nematodes than in a like treatment without nematodes, this mass difference was not significant and there was no difference in seedling N concentration between the two treatments. However, the pine seedlings had not been inoculated with mycorrhizal fungi and thus were probably more limited by phosphorus than by nitrogen, since seedlings did not respond to nitrogen additions in a similar treatment. Had the seedlings been responsive to additional available N, there may well have been a growth response in the treatment with nematodes. Higher concentrations of N in the leachate from the nematode treatment during the last half of the experiment indicated that the microbial-feeding nematodes caused a higher rate of N mineralization than in the comparable treatment without nematodes. These results show, however, that plants may not respond to the activities of microbivorous fauna under all conditions. We suggest that the additional mineralization from microfloral grazers may be of significant importance to plant growth only when mineralization of a growth-limiting nutrient by microflora alone is insufficient to meet the plant's demand for that element under current growing conditions. The importance of this contribution by microbial grazers may vary from ecosystem to ecosystem, from microsite to microsite, and even from time to time within the same system. However, the effects of microfloral grazers on microflora growth are probably important in all systems at all times that these biota are active.

Influence of microbivorous fauna in ecosystems

An objective of this study was to illustrate that microbivorous soil nematodes have a potentially important role in ecosystems. However, these nematodes are only one of several regulators of ecosystem nutrient cycling and primary production (Anderson et al. 1981*b*, Coleman et al. 1983, Seastedt 1984). Although the biological processes observed in microcosms represent phenomena that may also occur in the field, in a native soil these processes may be mediated by other physical and biological interactions. For instance, while it is suggested here that nematodes regulate primary production, Santos et al. (1981) and Whitford et al. (1982) have noted that predatory mites may regulate nematodes in arid and semiarid ecosystems.

Understanding ecosystem functioning must be an integrative process that considers all biological processes as they interact with one another. Gnotobiotic microcosms are a tool that can be used to examine these interactions with greater resolution than can currently be achieved in the field. We suggest that in the future, use of a "functional group" approach (Coleman 1976) to build complex biotic assemblages for the combined study of soil microflora, microfloral grazers, plant nutrient uptake, and nutrient cycling will yield considerable new information about ecosystem functioning.

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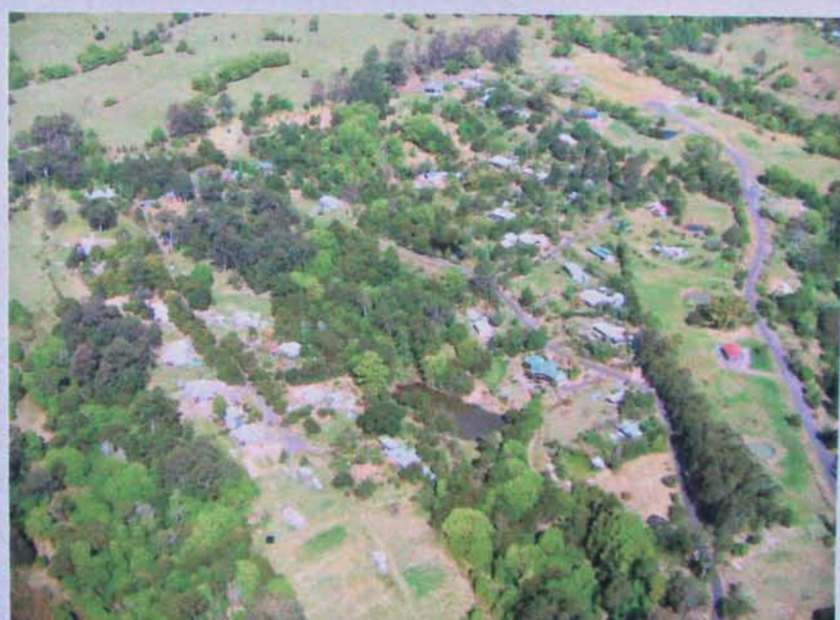
ACCREDITED PERMACULTURE TRAINING™
SUSTAINABLE SETTLEMENTS MODULE

Ecovillage & Sustainable Settlements Design

COURSE NOTES & RESOURCES



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Collated & Facilitated by

Robyn Francis

March 2006
Revised August 2007

NONI [redacted]

This course provides foundation training contributing towards a cluster of units in the Diploma of Permaculture AQTF Qualification

The Ecovillage and Sustainable Settlements Design module provides key underpinning knowledge and skills training for the following units from Diploma of Permaculture:

PIL503A Develop a strategic plan for a permaculture project
PIL506A Design and plan a sustainable settlement
PIL507A Research and interpret requirements for a permaculture project
PIL509A Plan and design structures for permaculture systems
PIL510A Prepare a community and bioregional development strategy
PIL512A Plan community governance and decision-making processes

And supporting knowledge and skills training contributing to:

PIL511A Facilitate participatory planning and learning activities
PIL502A Design an integrated permaculture system
PIL504A Manage a permaculture project
PIL505A Plan the implementation of a permaculture project
RTC5801A Provide specialist advice to clients

Attainment of the Diploma qualification can be gained through:

- Structured internship and/or occupational training placement involving tutorials, master-class workshops, research, case studies, field visits and mentored project work and participating in relevant seminars and conferences as an ongoing assessment process

- Undertaking independent , research, case studies, field visits and project work, workplace experience, and participating in relevant workshops, short course training, seminars and conferences and eventual RPL Assessment.

Please refer to information documents for RPL assessment in APT qualifications available from:
www.permacultureinternational.com.au (downloadable documents)
or email request to robyn@permaculture.com.au

DIPLOMA IN PERMACULTURE COURSE CODE 30342QLD

DIPLOMA OF PERMACULTURE
Is designed for those involved in permaculture design, consultancy and/or management, and community development. It is also designed for those who are seeking to develop management level skills and knowledge through training.

CAREER OPPORTUNITIES
This qualification will provide training in permaculture for those who are working as project managers on permaculture community development projects, and those seeking to become permaculture systems designers and/or consultants, and work as facilitators and consultants for community consultative and planning processes. Client groups include those who have completed basic permaculture studies, those looking to be supervisors on labour market/community development programs including those based in indigenous communities, and those involved in ecovillage and intentional community development. Outcomes include further training options, employment as a project manager or consultant across permaculture, agriculture, horticulture or land management industries.

PREREQUISITES: completion of core units from Cert IV in Permaculture is an essential prerequisite for entering into Diploma studies.

Note: Diploma of Permaculture may require up to 3 semesters

DIPLOMA QUALIFICATION REQUIREMENTS: Complete 10 units of competency

- A minimum of six (6) elective units from Group A below
- An additional four (4) elective units from Group A and/or B below

GROUP A Elective units	
PIL501A Carry out permaculture field research	80
PIL502A Design an integrated permaculture system	120
PIL503A Develop a strategic plan for a permaculture project	60
PIL504A Manage a permaculture project	60
PIL505A Plan the implementation of a permaculture project	60
PIL506A Design and plan a sustainable settlement	120
PIL507A Research and interpret requirements for a permaculture project	120
PIL508A Plan management strategies for overseas development projects	120
PIL509A Plan and design structures for permaculture systems	80
GROUP B Elective units	
PIL510A Prepare a community and bioregional development strategy	120
PIL511A Facilitate participatory planning and learning activities	80
PIL512A Plan community governance and decision-making processes	80
BSBADM504A Plan or review administration systems	80
RTC5203A Plan erosion and sediment control measures	120
RTC5801A Provide specialist advice to clients	60
RTC5912A Market products and services	80
RTE5523A Develop climate risk management strategies	80
RTD5802A Support group and community changes in resource management	
RTC5914A Prepare reports	

Rules A maximum of two (2) units from other permaculture qualifications levels can be substituted for elective units in this qualification At least 8 of the units of competency presented for this qualification must relate specifically to permaculture work procedures, activities or contexts

DURATION: generally 3 semesters to complete Diploma studies

Diploma of Permaculture

Qualification Requirements: Complete 10 units of competency

- A minimum of six (6) elective units from Group A below
- An additional four (4) elective units from Group A and/or B below

** denotes units for which the Sustainable Settlements Module provides specific foundation training for those working toward achieving competency in these areas. Completion of a unit will require further directed &/or self-directed learning, research experience and completion of required assessment projects
* denotes the units for which this course provides a valuable context and enterprise framework and contributes a degree of direct and related knowledge and skills.

GROUP A
PIL501A Carry out permaculture field research

PIL502A Design an integrated permaculture system*
This competency standard covers the process of designing an integrated permaculture system.
It requires the ability to develop a design brief, undertake a site analysis, develop a concept design and produce a final design for an integrated permaculture system. The preparation of an integrated permaculture system design requires detailed knowledge of permaculture design principles and processes, and plant and animal relationships

PIL503A Develop a strategic plan for a permaculture project **
This unit requires the ability to prepare a project brief, vision statement, aims, objects, goals, strategies, benchmarks, data collection methods, strategic planning processes, qualitative & quantitative analysis techniques etc

PIL504A Manage a permaculture project*
This unit covers the process of managing a permaculture project. It requires the ability to acquire project resources, manage project activities, and finalise project and evaluate and report on activities. Managing a permaculture project requires knowledge of permaculture principles and practices, contract law, project management systems, and budgetary framework.

PIL505A Plan the implementation of a permaculture project*
This unit covers the process of planning the implementation of a permaculture project. It requires the ability to evaluate and assess project, determine project tasks and associated timelines, assess resource requirements, develop project budget and document the plan. Planning the implementation of a permaculture project requires knowledge of permaculture principles and practices, data collection methods, qualitative and quantitative analysis techniques, methods for analysing and evaluating information, presenting information and community consultation.

PIL506A Design and plan a sustainable settlement **
Includes site assessment/evaluation (including catchment context: natural, social & services), & ability to develop a social strategy, concept plan and management plan for a sustainable settlement: co-housing, eco-village, housing co-op, land-sharing communities

PIL507A Research and interpret requirements for a permaculture project **
This unit embraces legal & planning frameworks, tenure, cultural, social and economic factors, including consultation models

PIL508A Plan management strategies for overseas development projects*
This unit covers the process of planning management strategies for overseas development projects. It requires the ability to research local conditions and culture, develop strategies and methodologies to facilitate community directed program development, develop strategies for a community health program, and research and evaluate technologies and resource conservation strategies. Planning management strategies for overseas development projects

requires knowledge of permaculture principles and practices, environmental, social, political, economic, health, housing, education/literacy, equity and human rights, food and security issues relevant to overseas projects.

PIL509A Plan and design structures for permaculture systems *
This unit encompasses design for the built environment including roads, buildings, water features, recreational facilities etc, Includes passive solar design & alternative building materials and techniques

GROUP B

PIL510A Prepare a community and bioregional development strategy **
This unit covers preparing a brief, analysing info, consultation with individuals, groups & community, develop strategies and design organisational structures. Includes community economics as well as socio-cultural & natural resource factors

PIL511A Facilitate participatory planning and learning activities **
This unit requires ability to facilitate participatory planning and learning programmes and activities for community groups, education etc. Essential for anyone working with groups. Includes conflict resolution skills and group presentation methodologies.

PIL512A Plan community governance and decision-making processes **
Includes assessing needs & developing options for community governance, and decision making frameworks & processes, negotiation and conflict resolution, and facilitation.

BSBADM504A Plan or review administration systems
This unit covers planning and/or reviewing the requirements for effective administration systems and procedures for implementing, monitoring and reviewing the system

RTC5801A Provide specialist advice to clients*
This competency covers the process of providing specialist advice to clients relevant to agriculture, horticulture, or conservation and land management. It requires the ability to develop and maintain technical knowledge, communicate with clients, and formulate a response to client enquiries and needs. Providing specialist information requires knowledge of environmental sustainability and land use issues, enterprise policy, legislation and consultation methods, techniques and protocols.

RTC5914A Prepare reports
This unit covers the process of preparing comprehensive reports for a rural, horticultural or land management setting. It requires the ability to research material, evaluate information, produce a document, and deliver oral presentation. Preparing reports requires knowledge of information and research sources, report structure and presentation, and public presentation techniques and approaches

RTD5802A Support group and community changes in resource management*
This competency covers the process of supporting changes in resource management processes in a group or community context. It requires the ability to identify changes occurring at group and community levels, identify potential impacts and reactions, and facilitate change in management processes. Supporting group and community changes in resource management requires knowledge of change management theories at individual and group level, meeting procedures, local networks and groups, and community viewpoints and cultures.

RTE5921A Market products and services
This unit covers the functions required to market products and services in an agricultural, horticultural or land management enterprise. It requires the application of skills and knowledge to plan and implement a marketing strategy, and monitor and improve market performance. It also requires the ability to collect, analyse and present data in the internal and external business environment. In addition, it requires an awareness of industry structures and business trends. The work will be carried out independently within own area of responsibility and within enterprise guidelines.

Sustainable Society

* Products that are upgradable, recyclable, have long life span (that go back to the manufacturer)
* Renewable and non polluting energy sources
* Clustering of settlement - people close to the facilities they need and/or are self reliant the further away they are situated
* lease of land and common facilities for living, working, playing
* work & access to resources to be more equitable
  - people 'working' smaller part of life with work sharing (presently the overworked and unemployed!!)
* common heritage dividend equating to minimum income with better flow between cash and non-cash society.
* changing the patterns in institutions by slowing resource throughput to increase quality of life (slowing down the pace)
* concept of governance rather than government
* accepting the emergent quality of evolution, the laws of chaos, the uncertainty principle, and
* getting in touch with what has to be done and doing it with the opportunities that present themselves .....

Characteristics of Eco-villages

1 Human scale

2 Full featured

3 Ecologically sensitive

4 Healthy human development

5 Sustainability principle

A sustainable community includes eco-villages, clusters and networks of eco-villages, and non geographically based "communities" (eg. businesses, themes eg. conservation, permaculture etc)

Human scale in size (urban - neighbourhoods; rural - hamlets and villages)

Cities are not eco-villages - however one made up of eco-villages could be a sustainable community

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What sustainability means to us:

- *Some things are best left alone*
- *If we make a mess, clean it up*
- *If we use something, replenish it*
- *Think of the children*
- *Prevention is better than cure*

What needs to be sustained:

- *Biodiversity*
- *Ecological Integrity*
- *Natural Capital*
- *Social Integrity*
- *Economic Viability*

(Source: SSROC Background and Discussion Paper on Sustainability)

Figure 1

A SYSTEM OF DIVERSITIES

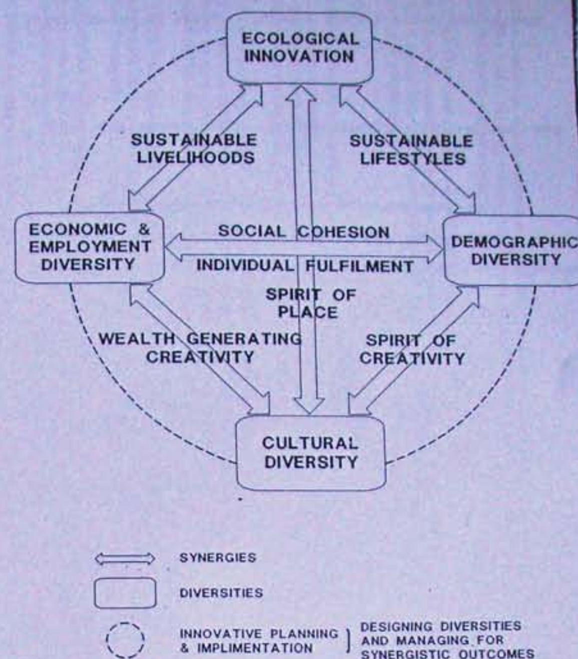
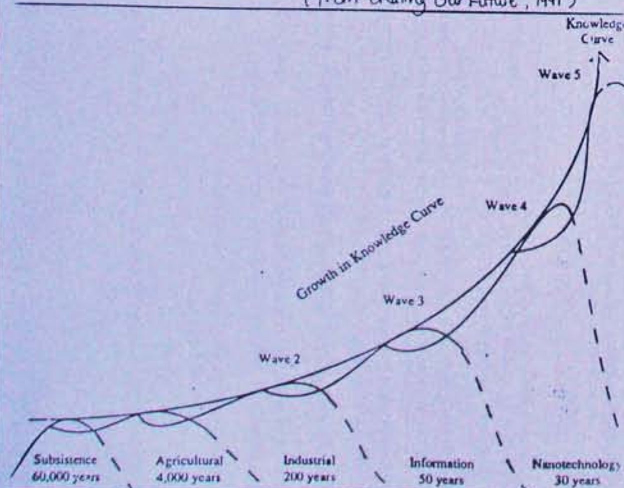
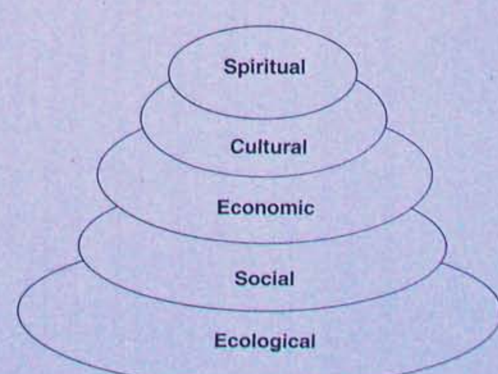


Figure 6 Major Technological Epicycles in Human History
(from Creating Our Future, 1991)

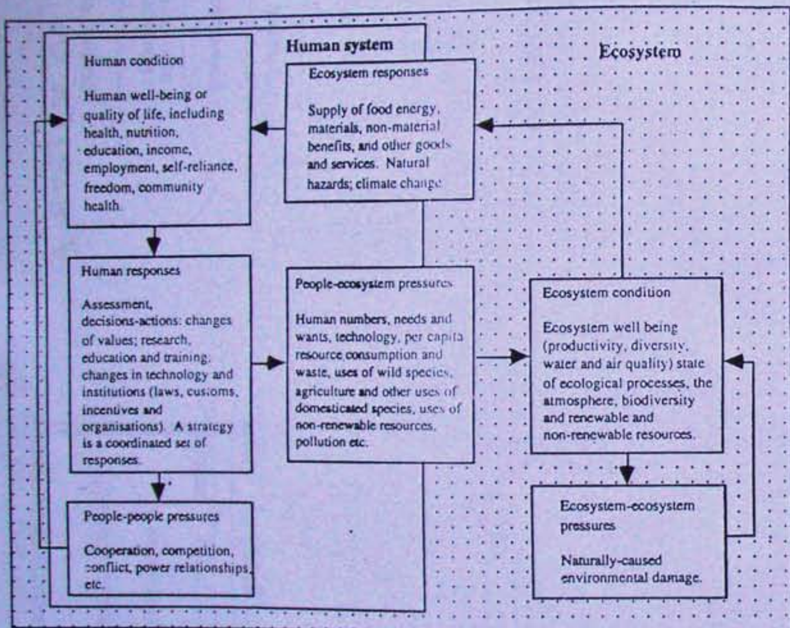


Key Elemental Layers of Sustainability



P Cumming RYE

The relationship between humans and the rest of the ecosystem is at the core of the issue of sustainability. An excellent description of this relationship is provided by Carew-Reid *et al.* (1994) as shown in Figure 2.2.



The relationships between people and the Earth, adapted from (Carew-Reid *et al.* 1994:18).

Essential Steps Involved in CREATING A COMMUNITY &/or ECOVILLAGE

1. Establish Core Group – note Skills Mix, establish key protocols
2. Identify Specialist Input Needs i.e. advisors and consultants e.g. legal, financial, planner, engineers, permaculture
3. Clarify Vision – commence the Strategic Plan
   Establish the brief
4. Research Real Estate Market in Desired Area
5. Research Zoning & Planning Issues, development consent requirements
6. Develop Checklist for Land Selection
   Bioregional/Neighbourhood Context – commence land search
7. Research and visit established Communities
   – learn from their experiences, successes and failures
8. Research Decision Making, Governance Processes
   - develop Conflict Resolution skills
9. Research Tenure & Legal Structures
   + insurance, tax, inheritance & transference implications
10. Establish Core By-Laws & draft residents agreement
11. Learn/research Financing Options
12. Develop a Realistic Budget
    Calculate Potential Development Costs
    Stage Development - Prioritise
13. Meet with Planning Authorities
    Determine Carrying Capacity (planning & natural resource constraints)
14. Develop Master Plan with Professional consultants
    Development Approval Process
15. Finalise budget - Establish buy-in Costs
16. Create Community Agreements, Governance, Conflict Resolution Processes
    Selection Criteria for New Members, Transference: In's & Out's
17. Implement Planning Consent Requirements
    Contingency Planning

... now the hard work really begins when you start building & living on the land

Shaping Our Futures

1 **Dreaming and Visioning**
- finding values and developing concepts

2 **Identifying and exploring Issues**
turning them into challenges
create solutions and options

3 **Understanding our resources**
- S.W.O.T and Mapping

4 **Develop a strategic framework**
- navigating the journey
(principles, goals, actions)

5 **Establishing pathways**
- decisionmaking & co-leadership
- networks and links
- receptive and inclusive approaches

6 **Choosing processes and tools**
- interactive, educative, informative

7 **Developing models and good examples**
- guidelines, performance standards
- technical and creative assistance

8 **Education and awareness**
- forums, mediums of exchange, approaches

9 **Management and Observation**
partnerships & agreements, monitoring & evaluation

10 **Adaptability and Innovation**
creative response, adjusting, finding niches, dreaming

Peter Cuming - Sustainable Futures Planning & Design 1997

Framework: Elements

Vision	Concept(s)
Principles	Policies
Goals	Objectives
Strategies	Actions
Performance Targets	Timelines
Education & Awareness	Evaluation

Process:

Data Collection & Information

Liaison and Networking

Collective Discourse & Broadening Perspectives

Strategic Questioning & Thinking

Identifying Issues - Challenges - Opportunities

Exploring Options & Solutions

Co-operative Visioning & Goal Setting

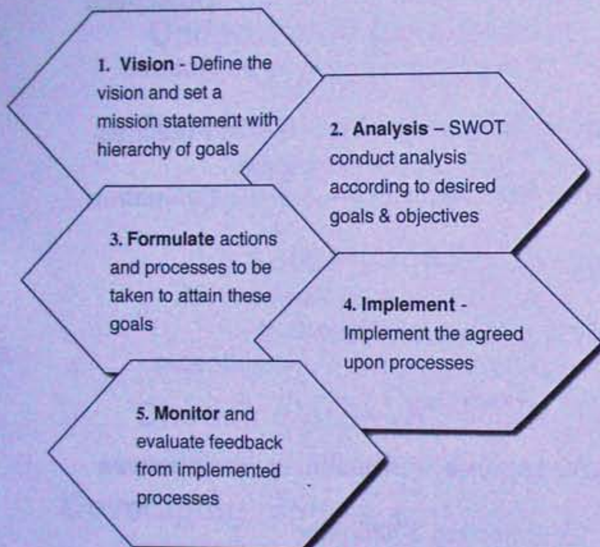
Conflict Management & Resolution

Feedback and Adjusting Focus

Peter Cuming SFPD.
1997.

Strategic Planning

Strategic planning identifies where the organization or project wants to be at some point in the future and how it is going to get there., The "strategic" part of this planning process is the continual attention to current changes in the organization/project and its external environment, and how this effects the future of the project or organization.
Skills in strategic planning are critical to long-term success.
Strategic planning and decision processes should end with objectives and a roadmap of ways to achieve those objectives.



A **VISION STATEMENT** inspires to what can be ~~and is SMART (Specific, Measurable, Achievable, Relevant and Timebound).~~

Performance Measures should be SMART

A **MISSION STATEMENT** provides a path to realize the vision in line with its values.

1 Clarify the project brief and develop a planning framework

- Project **vision** statement, **aims** and **objectives** are defined in the brief.
- Project **benchmarks** and **indicators** and are established in consultation with stakeholders
- Catchment **analysis** contexts, **constraints** and **opportunities** are identified for the project
- **Core values**, **principles** and **guidelines** to ensure ecological sustainability, social responsibility and equity are defined in the project brief
- **Protocols** on cultural respect and sensitivity for the design, implementation and ongoing management are developed in consultation with stakeholders.

<u>**Frameworks**</u> may include:

- **WEB**
- **MATRIX**
- **FLOW CHART**
- **Other planning models**

The framework identifies the key components of the strategic plan and their relationships which directs the planning process.

2 Analyse available information

- Research information is formatted to enable appropriate comparisons
- Key **elements and themes** are identified
- Interconnections and relationships between key elements and themes are mapped
- Legal and planning instruments and guidelines relating to the project from local, state and national governments are determined
- Professional and specialist advisers and consultants required for the project are identified

Elements and themes for an ecovillage may include:

- natural environment, ecology & biodiversity,
- water and hydrology,
- soils,
- energy,
- waste management,
- buildings and structures,
- utilities and infrastructure,
- transport
- town planning,
- landscape,
- landuse systems,
- economic and enterprise systems,
- social factors,
- cultural factors,
- hazard reduction,
- nutrient cycles,
- legal framework and governance,
- information and education,
- sense of place

Situational analysis

When developing strategies, analysis of the project/organization and its environment as it is at the moment and how it may develop in the future, is important. The analysis has to be executed at an internal level as well as an external level to identify all opportunities and threats of the new strategy.

Factors to assess in the external situation analysis may include:

- Markets (customers/prospective members)
- Competition (other options available to above)
- Technology
- Supplier markets
- Labor markets, contractors, consultants
- The economy
- The regulatory environment

SWOT ANALYSIS

A SWOT analysis is most effectively employed to assess a clear objective and ***USED*** for creative generation of possible strategies

Strengths: attributes of the project/organization that are helpful to achieving the objective. *How can we best* ***Use*** *each Strength?*

Weaknesses: attributes of the project/organization that are harmful to achieving the objective. *How can we* ***Stop*** *each Weakness?*

Opportunities: *external* conditions that are helpful to achieving the objective. *How can we* ***Exploit*** *each Opportunity?*

Threats: *external* conditions that are harmful to achieving the objective. *How can we* ***Defend*** *against each Threat?*

The aim of any SWOT analysis is to identify the key internal and external factors that are important to achieving the objective:

- **Internal factors** – The *strengths* and *weaknesses* internal to the organization. e.g. resources, location, financial, creativity, unique product, valuable tangible & intangible assets, capacity & capabilities
- **External factors** – The *opportunities* and *threats* presented by the external environment. e.g. economic conditions, public perceptions & expectations, competitors & competitive actions, public relations, market, environmental conditions, regulatory bodies, catchment context

3 Identify required strategies

- Steps required to implement strategies are logical and capable of implementation
- Strategies are clearly formulated and made available to relevant parties for comment, where appropriate
- Strategies include consultation with all **relevant parties**
- Opportunities and constraints to implementation are clearly recognised and documented

4 Document the strategic plan

- Strategic directions for the permaculture project is supported by available evidence
- Sound operational plans can be implemented based on the strategic plan
- Documentation is clear, concise and accurate
- Strategic plan is distributed to all relevant parties to ensure effective communication of information

5 Review strategic plan against identified desired outcomes

- Mechanism for evaluation of strategic plan is determined
- Timeframes for evaluation are determined
- Feedback from all relevant parties on implementation issues and outcomes is evaluated
- Problems identified are resolved and/or reported to appropriate persons
- Where appropriate, modifications to strategic plan are recommended

Principles and Values

Hierarchy of Sustainability

1 Rate of resource throughput does not impair major cycles of biosphere (eg. Greenhouse gas emissions & climate change)

2 Health and viability of ecological sub systems must be maintained (eg. biodiversity, soils, water quality)

3 Extraction of resources and disposal of wastes should occur at a rate that is within ecological limits

4 Renewable resources should be used at a rate at which they can be replenished by natural processes (eg. forestry)

5 A sustainable strategy for use of non-renewable resources requires development of a depletion policy (eg. fossil fuels, phosphates)

6 Sustainability requires that wastes are disposed of at a rate at which they can be absorbed by receiving systems

7 A society is not sustainable if its members live in poverty and it does not operate on the principles of social justice.

(Cronin, K. 1989: The conceptual meaning of sustainability)

The goal: A just, participatory & sustainable society.

Key Strategy Areas for Sustainability

1 Protection:

of existing ecosystems, agricultural lands, amenity and characteristics that make the region/local area attractive.

2 Repair and Regeneration:

of degraded areas and communities by appropriate development and enhancement projects, including revegetation, stormwater source control and treatment, improving services based on ESD principles.

3 Redesign:

of systems and infrastructure providing services eg. water, transport, sanitation, solid waste, energy production and demand. Focussing on the end use and asking: ".. what is really needed and how can we provide it at least cost and with least impact ? .."

Retrofitting, recycling, waste minimisation, efficiency, re-use, incentives, local materials, demand management rather than supply oriented thinking.

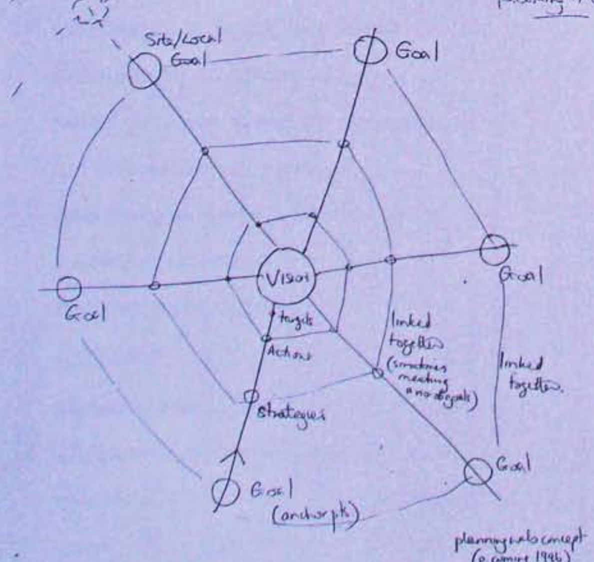
4 Renewal:

of communities urban landscapes, custodianship through involvement in decisionmaking, action and management eg. economic and ecological strategies, social and cultural development

(adapted from White, S. 1996 unpubl)

Perming. 1996

The Planning Web in Action
P. Cuming 1996

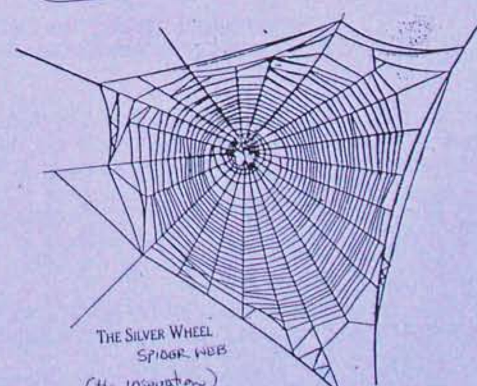


planning web concept (p. Cuming 1996)

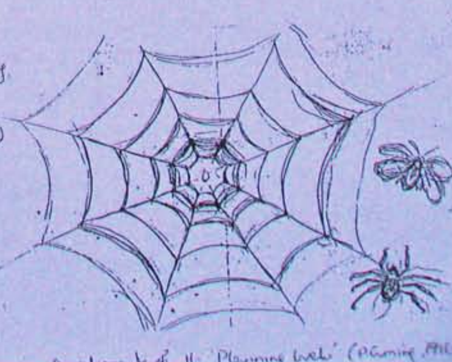
- Guiding principles – used to weave planning web together. They are aspects important to each goal and achieving the Vision eg. sustainability community involvement

- can have as many goals as required, model becomes more complex.

The Planning Web © P. Cuming 1996



Simplifying for developing the model
Cartoon Honor Cuming



Development of the 'Planning Web' (P. Cuming 1996)

Strategic Planning Approach

Framework: Elements

Vision	Concept(s)
Principles	Policies
Goals	Objectives
Strategies	Actions
Performance Targets	Timelines
Education & Awareness	Evaluation

Process:

- Data Collection & Information
- Liaison and Networking
- Collective Discourse & Broadening Perspectives
- Strategic Questioning & Thinking
- Identifying Issues - Challenges - Opportunities
- Exploring Options & Solutions
- Co-operative Visioning & Goal Setting
- Conflict Management & Resolution
- Feedback and Adjusting Focus

Peter Cuming SFPD. 1997.

VISION:

A BROAD STATEMENT OF INTENT TO FOCUS ACTIVITIES, GOALS AND AIMS AND COMMON DIRECTION . A CUSTODIAL COMMITTMENT TO FUTURE GENERATIONS

GOAL:

AN IDEALISED END OR TARGET TOWARD WHICH AN INDIVIDUAL, GROUP OR SOCIETY MAY STRIVE

OBJECTIVE:

AN ATTAINABLE DIRECTION OR COURSE OF ACTION BY WHICH A GOAL OR GOALS MAYBE REALISED

STRATEGIES:

PATTERN OR FRAMEWORK WHICH INTEGRATES ACTIONS TO ACHIEVE OBJECTIVES OR GOALS AND WHICH CAN SET A DIRECTION

ACTIONS: INDIVIDUAL OR SERIES OF PROCESSES AND RESULTS THAT CREATE A DIRECTION

Research Requirements – Planning Framework, Legislation

Requirements impacting on the project need to be identified, researched and evaluated.

1 Select appropriate research strategies

- Research strategies selected are appropriate for the requirements of the project and the available resources – research strategies may include library, internet, interviews, direct sourcing of published and verbal information from agencies and council, professional advise
- A combination of research methods are selected to promote the viability of the outcomes
- The selection of research strategies is negotiated with key people

2 Gather information

- All **relevant information sources** are identified and suitable methods of collecting information are used.
- Materials and aids needed to conduct research are designed and allocated
- **Legislative requirements** impacting on project are assessed and analysed, Legislative requirements may include: Local and State government planning policies, engineering specifications, development control plans, ordinances, restrictions, zoning, development approval requirements and process, community consultation requirements, national codes and legislation, Australian building code, ASIC, international trade.
- **Government departments and agencies** with a potential interest in the project are identified such as: Government departments and agencies such as planning, agriculture, fisheries, national parks and wildlife, soil and water resources, fire and emergency services, environmental protection agencies, housing, health, education, building, business and consumer affairs, state regulated legal structures (associations and cooperatives), land tenure.
- Information is collected in the determined times and methods and recorded and stored according to negotiations with the sources

3 Consult with key people

- A representative range of people and groups with an interest in the issues is identified and consulted
- Information is reviewed, checked for accuracy and the need for further information is identified and followed up

- Liaison is undertaken with council staff such as planners, engineers, community development, enterprise development and elected councillors
- Consultation is undertaken according to agreed practices and protocol of community
- The comments and views of all interests consulted are considered and incorporated where relevant

4 Organise and analyse information

- Information is organised in a form that lends itself to analysis and is suitable for the purpose of the research
- Information is checked with other available research
- Data are confirmed with those who provided it and is reported clearly and comprehensively
- Patterns, observations and explanations are justified by the information and the context
- The conceptual framework of the analysis and the assumptions is clearly explained to those being consulted and in reporting

5 Report the findings of the research

- Complete and accurate details of the research methodology, information and analysis are reported
- Opportunities are provided for the validation of the research findings using a range of feedback from key people and a range of different processes
- The research findings are reported in an accessible and useable style and format
- The results of the research are reported and made available to all key people who have an interest in the issues researched

Goals for Wholistic Designed Settlement (M. Corbett - Village Homes California)

1. Approach self sufficiency in energy through conservation and maximum use of renewable sources.

2. Manage water resources efficiently and carefully, including use of re-use water (e.g. grey water) absorbing and utilising stormwater where needed.

3. Diverse organic agriculture production for local consumption making use of sewage and grey water waste.

4. Maximise land use by including food trees and shrubs, vines and gardens in residential landscaping.

5. Reduce dependance on automobile; encouraging foot and bicycle type traffic; through provision of services close to people and compact design of key settlement areas.
Producing goods and services locally wherever possible with emphasis on recycling/re-use.

7. Provide employment within and close by communities for wide range of people/age groups with meaningful training and participation by youth/children.

8. Provide for low income earners to participate in the community fabric and access services, facilities and goods.

9. Provide for basic human psychological needs that don't require excessive consumption.

10. Provide relevant government and institutional services/facilities as efficiently as possible and in an integrated manner.

11. Planning and design process that allows for :
    1. diverse individual needs
    2. involvement of people in the process
    3. incorporates lessons learnt from evaluation and feedback

12. Respond to changing needs in design process whilst retaining the human scale qualities necessary for sustainable and harmonious human settlement.

Characteristics of Eco-Villages (Context Institute 1994/7)

1. **Human Scale**
   - People are able to know and be known
   - People can influence community's direction
   - Practical evidence : b/w upper limit 500-1000
   - In modern industrial societies often lower even <100

- Ebenezer Howard : Towns (1920) 30,000 (made up of wards of approx. 3,000 with own shops/schools etc)
- Clarence Perry - 2,500/3,000 people for neighbourhood unit.
- Abercrombie 1940's - 2,500/3,000 people

2. **Full Featured**
   - All major functions of normal living (residence/work/leisure social life/commerce are present in balanced proportions
   - Integration of function though not isolated or fully self-sufficient
   - Work within as well as work without
   - Specialised services appropriately located with clusters and networks assisting in the provision of services

3. **Ecologically Sensitive**
   - Respect for other life forms
   - Cyclical use of material resources rather than lineal (use of renewable resources, composting of organic wastes, recycling as much of waste stream as possible, avoidance of toxic and harmful substances

4. **Healthy Human Development**
   - Balanced and integrated development of all aspects of human life (physical, emotional, mental, spiritual)
   - Individual nd community well being
   - Economics, governance,social relationships

5. **Sustainability Principle**
   - Honestly not living off capital accumulated in other parts of society/or anti ecological activities somewhere else, not inclusive of all aspects of life (childhood or old age - "blindspots").

DEFINITION OF RURAL RESIDENTIAL

There are a variety of definitions and perceptions about what constitutes rural residential development and living.

The definition varies from State to State generally with an emphasis on residential estates and smaller hobby farms. For example in the eastern States of Australia:

Queensland: RRD is defined as: subdivision and development of land in one or more lots of 2000m2 or larger without sewerage and primarily for residential purposes. (Queensland Department of Housing, Local Government and Planning, 1993)

Victoria: RRD means (a) subdivision of land into one or more lots having an area of between 0.4ha and 2ha if lots are intended primarily for residential use, or (b) construction of a detached house on a vacant lot which has an area of between 0.4ha - 2ha.
(Victorian Department of Planning & Environment, 1992)

NSW: RRD: Holdings normally in the range of 4000-8000m2 and essentially for rural living with little attention to agricultural production.
(NSW Department of Planning - 1985 Rural Lands Policy for North Coast Region)

RRD: Residential Development which occurs in rural or non urban locations, generally on allotments which are of a larger size than those found in urban areas. Land use is primarily for residential purposes rather than for agricultural pursuits.
(Rural Housing Report, Department of Planning, unpubl.)

These definitions do not include single houses on rural holdings used primarily for agriculture which can also be rented out for residential purposes.

"Rural" expresses more the locational and scenic characteristics of a development area rather than implying agricultural activity. However agricultural use of parts of the land or adjoining lands is often evident with rural residential living.

Rural residential development can include options which provide for a combination of residential and agricultural purposes, and general rural lifestyle.

There is a need to clarify the definition to assist in formulation of strategies and policies for rural settlement and living.

Given that all types of rural development on the North Coast are used for residential purposes as well as other functions it is recommended the definition should include **all housing** in rural areas.

TYPES OF RURAL RESIDENTIAL LIVING

There are presently a number of different types of rural residential development which can be generally based on locational and land use aspirations.See Table 1 on the following page which reflects present literature and the views of people involved in consultation and planning workshops associated with the Study Brief.

The main types that have been identified are:

- rural estates
- hobby farms
- rural retreats
- cluster development
- dispersed households

■ **rural estates** - are generally located in close proximity to urban areas and often take on the form of "larger lot urban" estates, in some cases linked to urban sewerage systems.

They can be "dormitory suburbs" with people commuting to nearby service centres for employment, recreation and other community facilities and services.

Most often associated with areas zoned for rural residential or small lot rural use. People living in these areas normally expect urban type services.

■ **hobby farms** - can be located close to or at distance from urban areas. Rural lifestyle use includes part time agricultural, or horticultural purposes.

■ **rural retreats** - generally larger allotments and located in areas with scenic or environmental qualities, however can be located close to urban centres yet separated by a rural land use and/or topographical features eg. a ridgeline. Residents seek solitude from urban living.

■ **cluster development** - includes Multiple Occupancy, CLOS and Cluster Farming and other forms of communal land ownership. Normally associated with a theme of living, part or full time agricultural pursuit, or environment protection.

■ **dispersed households** - include a wide range of lot sizes and land use aspirations based on location of lot, land attributes and characteristics. Often created by concessional lot sub division from larger farm properties in the past the present use may not necessarily be related to adjacent or nearby agricultural areas.

This category includes family based and other commercial farming enterprises where a single household is situated on the land parcel.

Mixing of types can occur such as cluster development for hobby farms and residential estates. In these situations housing is clustered on smaller lots with the balance of the development area being used for the development theme. eg. horticulture, conservation.

It is considered imperative for future rural planning that the definition of rural residential development include the wide range of rural settlement opportunities based on agricultural and other rural land use such as land and nature conservation and rural-residential options such as hamlets and villages. The latter often involve direct links with rural land use enterprise and custodianship.

The description of types of rural residential development should be broadened to include more specific reference to purpose and role of the settlement option eg. farming hamlet instead of hobby farm, conservation enclave instead of rural retreat etc.

This will enable rural planning to address rural residential development as part of a settlement pattern within the rural landscape interlinked with urban development, other land uses and custodial elements such as agroforestry, open space networks, nature and scenic conservation.

Table 1 below provides a broadened classification of types of rural residential development for the North Coast.

Figure 1 on the following two pages gives examples of the typical forms found on the North Coast for each type of rural residential development.

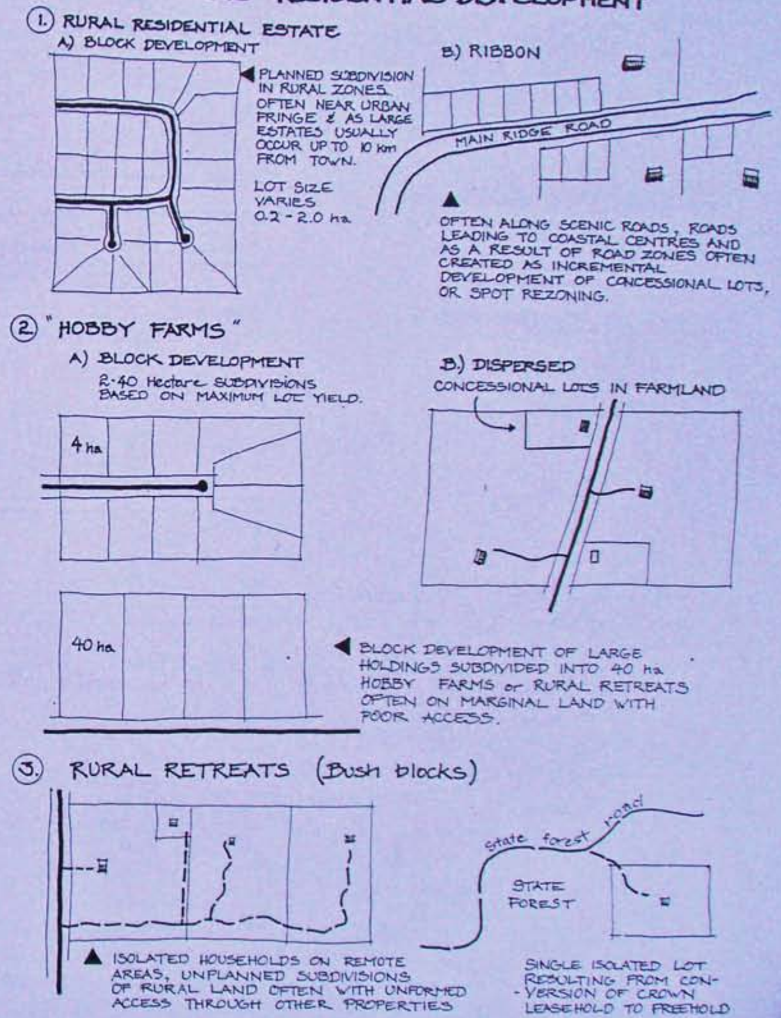
Table 1 A Classification of Rural Residential Types — North Coast NSW

Type	Approx Range of Lot sizes	Existing Emphasis	Land Characteristics	Utility Services normally provided
Rural estates	2000m2 - 2 ha	■ Accommodation ■ Enjoyment of rural environment	■ Estates - range of environs ■ Normally close to urban areas	Sealed roads, reticulated water, electricity, phone improved drainage, can be reticulated sewerage
Hobby farms	2ha - 40ha	■ Accommodation ■ Enjoyment of rural environment ■ Part time agricultural pursuits	■ Small subdivisions and estates. Mix of cleared area and remnant vegetation. ■ Often good soils and dam for water supply.	Sealed or gravel roads electricity, telephone. sometimes reticulated water available
Rural retreats	4000m2 - 40 ha	■ Accommodation ■ Enjoyment of natural/ rural environment ■ Some agricultural pursuits	■ Generally isolated from other residences. ■ Range of topography, ■ Greater emphasis on natural environment	Usually gravel roads, telephone, electricity (optional), usually tank or dam water
Cluster development	generally over 40 ha with small residential lots	■ Cooperative land use and development. ■ Agriculture and/or care of natural environment	■ Varies according to theme of development and group needs. Involvesagricultural land and/or natural vegetation.	Electricity (optional), usually gravel roads, telephone. Can be self contained for utility services
Dispersed Households	Generally large properties over 40 ha	■ Accommodation and lifestyle. Part to full time farming	■ Varies according to use, from prime agric. land to "bush blocks" Can be any distance from urban centres.	Wide range from fully reticulated services to fully self reliant. Dependant on location

Cuming, P. 1993. Table concept based on Table 2 Rural Residential Types of S.E Queensland SEQ 2001 Rural Residential Policy Paper.

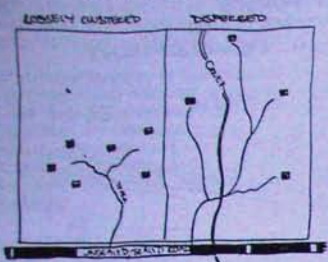
FIGURE 1.

EXAMPLES of FORMS FOR DIFFERENT TYPES OF RURAL RESIDENTIAL DEVELOPMENT



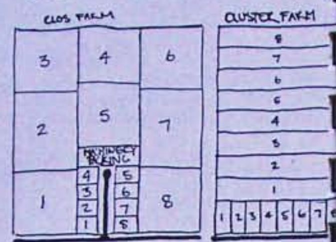
4. CLUSTER

MULTIPLE OCCUPANCY



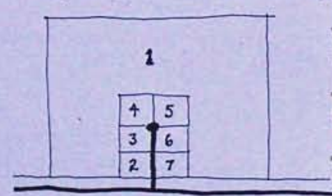
- MULTIPLE OCCUPANCIES, OFTEN LARGE SINGLE PROPERTIES IN 1(a) ZONES
- FREQUENTLY ON MARGINAL LANDS IN ISOLATED LOCATIONS
- RANGE OF HOUSEHOLD NUMBERS (eg 5-50)
- COMMON LAND OWNERSHIP

CLOS FARM   CLUSTER FARM



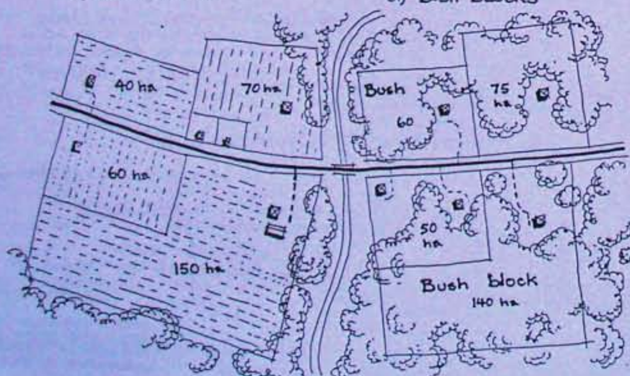
- CLUSTER (CLOS) FARMS WITH SMALL RESIDENTIA[L] LOTS LINKED BY TITLE
- FARMING LOTS BASED ON COMMERCIAL CRO[P] WITH FARM MANAGEMENT CONTRACT.

COMMUNITY TITLES SUBDIVISIO[N]



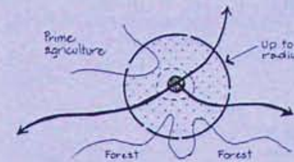
5. DISPERSED HOUSEHOLDS

a) AGRICULTURAL   b.) BUSH BLOCKS



Planning Concepts

RING CONCEPT



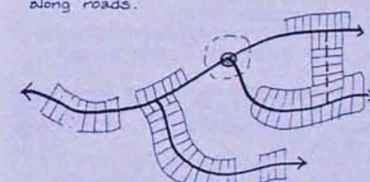
- AREA IDENTIFIED IN A 'RING' AROUND AN EXISTING TOWN OR VILLAGE. NORMALLY UP TO 5 Km.
- CONCENTRATES DEVELOPMENT CLOSE TO SERVICES
- EXPECTATIONS THAT ALL LAND CAN BE DEVELOPED FOR RURAL RESIDENTIAL.
- CAN RESULT IN LOSS OF URBAN DEVELOPMENT OPPORTUNITIES
- CAN CREATE 'RURAL-SPRAWL.'

DOUBLE (DONUT) RING CONCEPT

- SIMILAR TO RING CONCEPT, LEAVING 'BUFFER' FOR URBAN EXPANSION - OPEN SPACE.
- MAINTAINS DEVELOPMENT RELATIVELY CLOSE TO SERVICES
- IF THE BUFFER IS NOT PRESERVED OR URBAN EXPANSION MEETS RURAL RESIDENTIAL, THEN URBAN SPRAWL RESULTS

ROAD CONCEPT

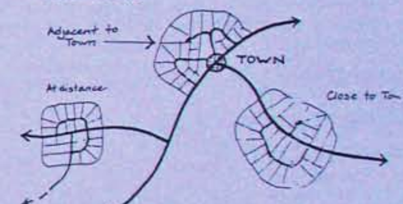
Ribbon development along roads.



- GOOD ACCESS TO TOWN / VILLAGE
- SCENIC IMPACTS ESPECIALLY IF LOCATED ALONG A SCENIC ROAD OR VISIBLE TO ONE
- TRAFFIC HAZARD DUE TO MULTIPLE ACCESS POINTS
- INCREASED CONFLICT WITH ADJACENT LAND USE

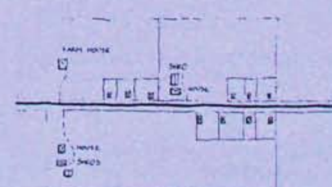
RURAL RESIDENTIAL ZONE

ZONED AREAS



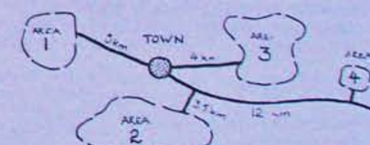
- TENDS TO CREATE SPRAWL & STERILISE FUTURE [illegible]
- SENSE OF COMMUNITY IS LACKING, DORMITORY [illegible]
- INCREASED DEMAND ON SERVICES & FACILITIES
- ACCESS TO TOWN - VARIABLE. DEPENDANCE ON PRIVATE VEHICLES
- LACK OF HEIRARCHICAL SETTLEMENT PATTERN

CONCESSIONAL LOTS



- MAJOR ADMINISTRATION PROBLEMS FOR LOCAL GOVERNMENT
- CONFLICTS WITH ADJACENT TRADITIONAL AGRICULTURE
- PRESSURE TO GO BEYOND ALLOCATED LOT CONCESSIONS
- SCATTER-GUN PATTERN OF DEVELOPMENT RESULTS

PERFORMANCE STANDARDS



CRITERIA (example only)	AREAS 1	2	3	4
1. FLOOD FREE	✓	✓	✓	✓
2. NON - PRIME AGRICULTURE	✓	✓	x	x
3. NOT NEEDED FOR URBAN DEV	✓	✓	✓	✓
4. NOT ENVIRONMENTALLY SIGNIFICANT	✓	✓	✓	✓
5. CLOSE TO TOWN or VILLAGE say 5km	✓	✓	✓	X

Many of the issues relating to rural living apply to rural planning generally and many of the solutions can be achieved, if rural living is not investigated in isolation but as part of an integrated approach to rural planning.

Care must be taken therefore not to address individual issues in isolation. An integrated approach responding to the issues as a whole and to land units in a holistic and hierarchical sense will allow multiple planning objectives to be achieved simultaneously.

For example, small rural holdings that are supplied by a perceived unlimited water supply such as a civic reticulated water system results in increased wastewater to be disposed of. To date issues such as waste water management have been generally addressed in isolation, and for example concentrated on larger disposal trenches rather than turning to the source of the impact such as the water supply. Less demand for a civic water supply, in turn, places less pressure on the need for new regional dams and increased public expenditure.

The range of issues associated with rural planning and therefore rural living is diverse and interconnected. As such it is difficult to place all the issues in exclusive categories.

The following list demonstrates the diversity of issues:

Natural Systems

Water systems
Soil systems
Habitat systems
Atmospheric systems
Scenic Landscape Values

Resource Implications

Agricultural resources
Mineral and quarry resources
Forestry resources
Water and soil resources
Rural character, role and function issues
Urban land needs
Energy demands

Social Issues

Isolation and community living
Demand for utility and social services
Transport - public and private, roadworks
Conflicting values and interests - eg. farming practices, noise, traffic etc.
Local economic development issues
Quality of life and livability of development designs
Land ownership and custodial responsibilities

Servicing implications

Roads and transport
Energy systems such as electricity
Telecommunications
Education
Human services such as health and community services
Emergency services
Water
Wastewater

Administrative Implications

Statutory & strategic planning
Coordination within & between public & private sectors
Ongoing management & maintenance
Monitoring

Issues arising from inappropriate planning

Land fragmentation
Fragmented and dispersed settlement forms
Conflicting uses
Loss of sense of community
Land development speculation
Insensitive design response to land and resources
Pollution, land and resource degradation

To illustrate that each of the above category headings are broad and contain further layers of issues, the category of *water systems* is divided into further aspects as follows:

Water systems

(1) Surface water systems
- human impacts and uses
- riparian vegetation removal
- turbidity generation
- shade removal
- nutrients
- pollution
- volume of runoff water
- increased flooding
- take up of surface water

(2) Groundwater systems
- human impacts and uses
- permeability
- quality
- salinity
- pollution
- recharge

Each major issue has similar layers to be considered. It is not just a case of subdividing land in an incremental manner, a holistic and comprehensive planning and design approach must be used.

Vision for Rural Settlement on the NSW North Coast Region

... Rural Settlement on the North Coast of NSW will provide a range of lifestyle options in harmony with the natural and cultural features and unique character of the Region ...

Rural residential settlement on the North Coast will assist in achieving this Vision by focusing on the following key aspects. They need to be interlinked to promote sustainable rural living.

- **protecting and enhancing the Natural Environment**
- **providing Diversity of Rural Lifestyle Options**
- **retaining and enhancing Rural Character and Identity**
- **satisfying Land Use Capability, Suitability & Compatibility**
- **fostering Efficient Servicing and Self Reliance**
- **encouraging Integrated Settlement Patterns**
- **enhancing Existing Rural Development**
- **promoting Quality of Living**
- **establishing Thresholds to Growth**
- **developing Awareness and Responsibility**

These aspirations relate to the challenge facing rural residential development on the North Coast. They are translated into clear Planning Objectives to guide land and resource development and management.

Recommendations for Regional Policies and Action Plans to meet these Objectives are provided in Chapter 9 of this Report.

Guidelines should be prepared, based on this Report, providing guidance and direction to agencies, groups and individuals involved in rural settlement aspects.

Regional Planning Objectives for Rural Settlement

1 Natural Environment
Ensure rural settlements protect and enhance natural features and ecological values of the region.

2 Diversity of Lifestyle:
Provide a range of sustainable options for rural living as an alternative to urban living.

3 Character and Identity:
Design rural settlements which retain and enhance the character of local areas.

4 Land Use Suitability and Compatibility:
Identify suitable areas capable of rural settlement compatible with adjacent and other land uses.

5 Efficient Servicing and Self Reliance:
Encourage rural settlement located and designed to reduce economic, social and environmental costs of providing services or is self reliant.

6 Integrated Settlement:
Integrate rural settlement and urban patterns in a distinctive hierarchy within the Region.

7 Enhancing Existing Rural Development:
Adapt existing rural settlements where necessary to improve their form and livability.

8 Quality of Life:
Encourage rural communities which promote quality of living throughout the various stages of life.

9 Thresholds to Growth:
Manage demand and supply of rural residential in conjunction with urban development within identified carrying capacity of catchments.

10 Awareness and Responsible Action:
Educate people and foster community involvement in sustainable rural settlement.

These Objectives can be achieved through the co-operative effort of the North Coast community, land development interests, Local Councils and Government agencies.

A concept for sustainable rural residential development is necessary to achieve these planning objectives.

The following Chapters describe the concept and approach, provide examples of where existing forms of development do not meet the requirements, options that can, and ideas for further consideration.

INTENDED RESULT

The intention of the Concept is to establish a land development pattern and management process which addresses the issues of innapropriate existing rural residential forms and location, whilst enabling new forms and development locations which are appropriate to be included and encouraged.

Existing forms and locations identified as causing problems can be reviewed locally to establish ways of overcoming issues and integrating this development into proposed settlement patterns and management systems for the future.

The Concept for Rural Residential Development aims to achieve:

1 **Integration of rural land use and settlement patterns** into an identifiable and compatible mosaic of sustainable land management and usage. Fragmented development, sprawl and extensive ribbon development will be actively discouraged.

2 **A sense of community by clustering development** into identifiable units rather than fragmented and dispersed settlement. Aggregation of land wherever possible prior to development for better design of rural living and land use options involving cluster development.

3 **Provision of a wide range of living options** within a heirarchy of settlement, from individual relatively self reliant rural households through levels of population centres and groups of different size. From small clusters or enclaves, to hamlets and villages, through to higher order urban settlement.

4 **Broadening of lifestyle opportunities** within the hierarchy by encouraging development forms which establish or provide a range of environmental, social and economic living themes and multiple land management and social benefits.

5 **Development forms suitably located and designed** according to land capability, compatible with adjacent and nearby land use and in a manner which is efficient to service or are self reliant.

6 **Fostering of environmental enhancement and landcare ethics** which protect and restore the ecological and cultural values of the Region through direct action and collective community responsibility.

7 **Identification and revitalisation of rural areas and communities** through rural based opportunities including sustainable agriculture and horticulture, agroforestry, nature conservation, ecotourism, arts, crafts and cultural enterprises, and alternative technology industry.

8 **Identification, redevelopment and retrofitting of existing forms** which presently do not meet the aspirations and objectives of the Vision for Rural Settlement on the North Coast.

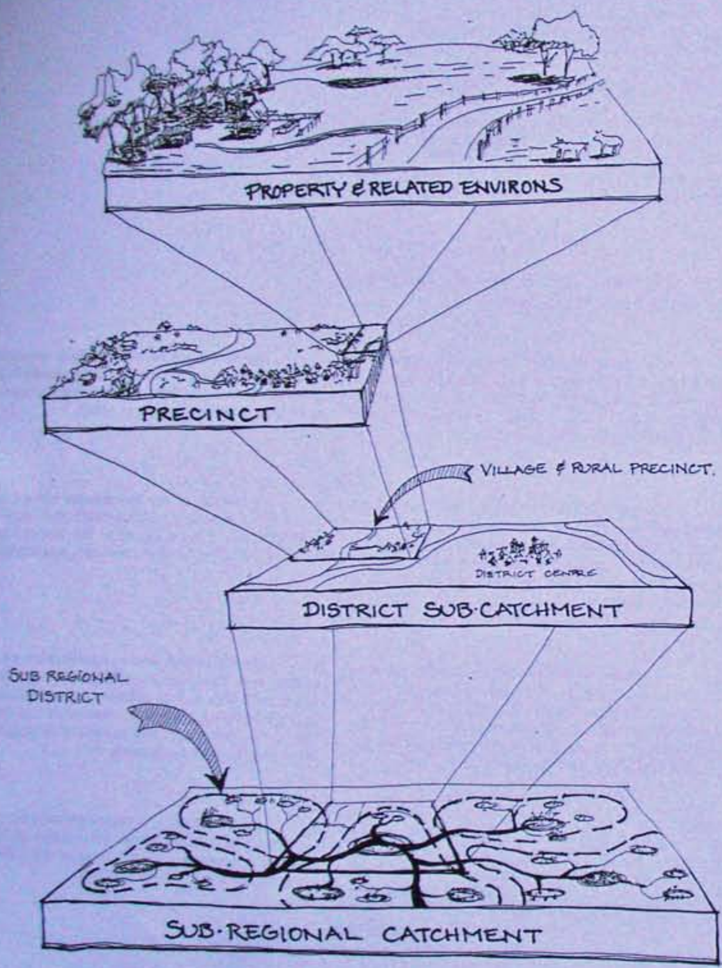
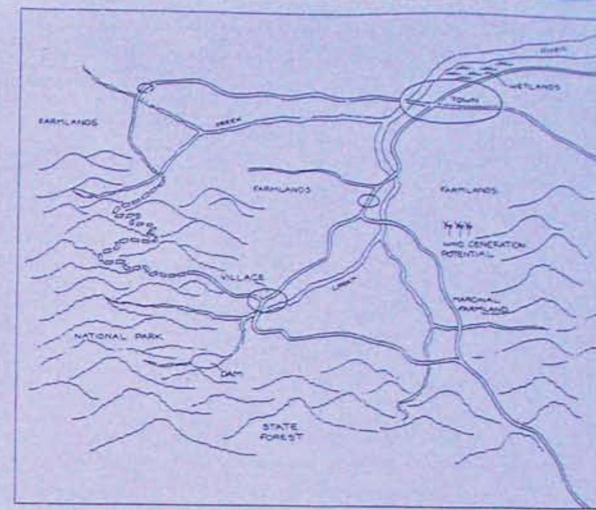


FIG. 7 CATCHMENT PLANNING APPROACH



NATURAL AND LAND USE CATCHMENT:

Figure 8: Natural and land use catchment map

Description: Based on biophysical features which establish an identifiable land management area eg. a river valley, a coastal corridor. Generally at a scale which includes broad land use and suits the management planning exercise.

Example of Key Elements:

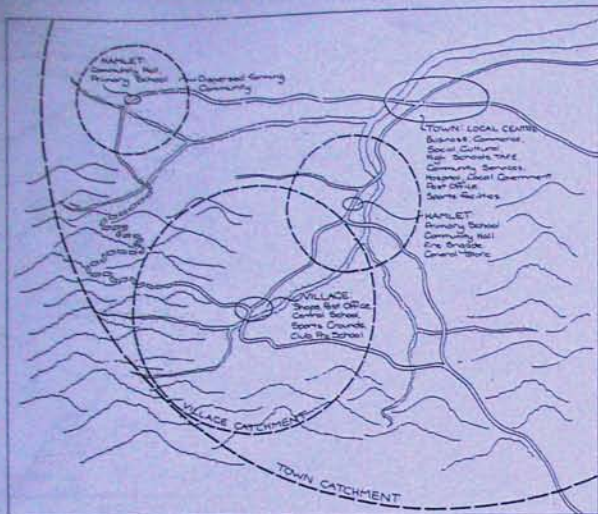
* natural water catchment, flow and dispersal system
* major land features eg. geological and land form
* forests, wetlands, heathlands, and other native flora and fauna systems associated with landform (including strategies for management and regeneration)
* land use and resource management areas and patterns eg. human settlement; agriculture, nature conservation, fisheries, forestry & other extractive industries
* climatic factors and natural hazards (flood s., fires etc)

Methodology: Use of Geographic and Land Information systems, satellite and aerial photography, maps, research data, studies and general knowledge to provide a picture of the Catchment including the key elements. eg. identifying main land use areas, and urban settlement patterns and hierarchy. Interpret the information at appropriate level of planning from sub regional to local precincts with input from government agencies, local government resource management agencies, and wider community.

Establish advantages, constraints and opportunities for rural settlement based on natural and land use features. Integrate with other Catchment Mapping (Social and Servicing)

Intended Results:

* Series of overlay maps or composite map with major interfacing information.
* Possible use of photography, graphics and video technology to assist in presentation.
* Identification of Sub Catchments and possibly Precincts.
* Understanding of interrelationships between the elements to enable a holistic view of the Catchment and Sub Catchments.
* Integrated systems approach to rural planning, development and resource management. Cooperative action between agencies, local government, interest groups and local communities. Forums for Catchment Planning at Sub regional and local community levels.



SOCIAL CATCHMENT:

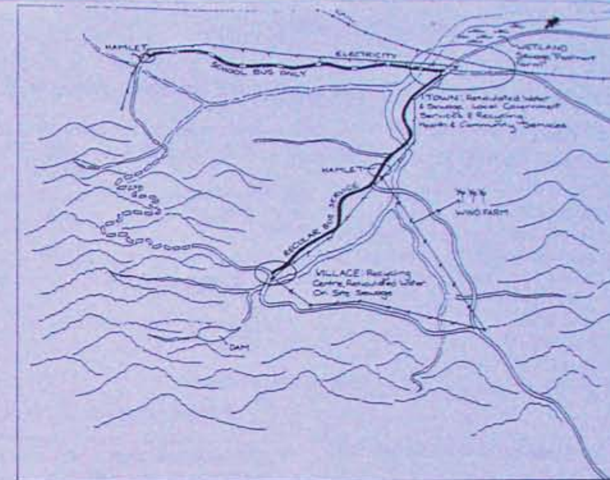
Figure 9: Social catchment map

Description: Identifiable area(s) based on social patterns, how people move around and congregate to satisfy material, social and cultural needs, and an identifiable sense of community. Includes historical context of settlement patterns and land use and relationship of people to their living environment and sense of place.

Example of Key Elements: Human settlement patterns including:
- shopping, commerce and industry, education, enterprise development, employment
- community services and facilities, recreation, entertainment, cultural events
- socio-economic profile and opportunities, human resource potential and experience
- community organisations and established networks.

Methodology: Depending upon level of planning unit from Catchment to Rural Precincts, and level of information required, compile cultural and social servicing maps using:
ABS figures and other survey and research information, social and demographic profiles, information and service networks (agencies, service delivery routes, community event calenders,community group networks, land information systems, cultural values, community economic analysis (including informal market processes).
Prepare a profile and map which identifies the key nodes, and patterns of human activity, needs and services, as well as cultural aspects of a Catchment or planning unit within.

Intended Results:
- A dynamic information system which can be updated over time providing comparative review of development results and impacts for future planning and development.
- Cultural and Social Servicing Maps identifying hierarchies of community identity, patterns of human movement and congregation, access to services and facilities, thresholds and boundaries of servicing social needs.
- Use of graphic, photographic and video based presentation material. Preparation of easy to read information and graphic or mapping presentation style.
- Integrated systems approach to providing services and identifying gaps and thresholds.
- Cooperative action between agencies, local government, interest groups and local communities. Forums for social and economic planning at appropriate Catchment levels.



SERVICES CATCHMENT:

Figure 10: Services catchment map

Description: Identification of network and hierarchy of utility and administrative services, infrastructure, and transport at all levels of Government, private industry and community based organisations.

Example of Key Elements: Existing and proposed utility and administrative services including:
- roads and transport network (including water, rail, air and non vehicular)
- electricity grid and hierarchy
- co-generation and other alternative energy production potential
- strategies for energy resource and water conservation
- solid waste management and recycling
- sewerage and grey water management
- Local government boundaries (including ridings and precincts), State and Federal service and administrative catchment boundaries
- Land ownership and land use zoning information.

Methodology: Depending upon level of planning unit from Catchment to rural precincts, and level of information required, compile servicing maps using:
Relevant LIC information and other administrative units and boundaries to identify responsibilities, overlaps, gaps and thresholds.
Develop utility services network and hierarchy model based on information from service and transport providers including where possible supply and demand trends and thresholds.
Identify sites, areas and strategies for energy conservation and generation.
Investigate and identify means and options to achieve a higher level of self reliance and sustainable resource use.
Establish advantages, constraints and opportunities for rural settlement based on servicing and administration networks. Integrate with other Catchment Mapping (Natural/Land Use and Social.)

Intended Results:
- Servicing administrative & energy opportunities maps including supporting information.
- Identification of present hierarchies and patterns of servicing including thresholds, limits to growth, and rural areas requiring greater degree of self reliance.
- Options and constraints for future development and management including maintenance of systems and networks, and opportunities for self reliance.
- Identification of existing and potential conflicts that can be resolved / avoided.

Sustainable Settlement Design

Summary/Checklist for
Key Elements of the Design Process

Settlements may include:

- Intentional rural land-based communities,
- ecovillage projects,
- hamlets, villages,
- urban residential development,
- co-housing,
- housing cooperative,
- expanded household,
- revitalising existing communities and settlements

1 Evaluate the site for settlement

- **Bio-physical characteristics and features** of the site are identified and recorded
- Land capability is determined and land management options for each land class are identified
- Existing site infrastructure is recorded and mapped
- Areas at risk of soil degradation are identified
- Native vegetation is classified and condition is assessed
- Endangered species are identified as appropriate
- Other **natural resource issues** identified as appropriate to the property
- Suitability of the site in terms of the project strategic plan framework is assessed
- Base plan of site is prepared and site characteristics are recorded

Bio-physical characteristics and features may include:

- Catchment context,
- topography, aspect, slope,
- ecology and natural resources,
- water resources,
- climate & seasonal factors,
- accessibility,
- soil condition and stability,
- drainage,
- land use potential,
- exclusion zones,
- hazard vulnerability,
- carrying capacity,
- neighbouring land use compatibility.

Natural resource issues may relate to

- stock grazing pressure,
- feral animals, pests
- wildlife, habitat, corridors
- weeds, noxious plants
- human impact,
- cultural practices,
- contamination, pollution
- agricultural chemical drift,
- fire, flood, natural disaster
- reintroduction of native animals, legislation,
- management advice,
- heritage agreements and other issues.

2. Research and evaluate other relevant information

- **Community consultation** is undertaken to identify values, expectations and personal goals of the people involved
- Current relevant **legislative and planning requirements** including **land tenure** options impacting on the settlement are researched
- Preliminary information from **consulting team** and experts is obtained including engineering reports and wildlife surveys
- **Environmental information** about the site is obtained

3. Develop a social strategy

- Steps required to implement strategies are logical and capable of implementation
- Strategies are clearly formulated and made available to relevant parties for comment, where appropriate
- Strategies include consultation with all relevant parties
- Opportunities and constraints to social development are clearly recognised and documented

Social Strategy will address factors including:

- Full life-cycle,
- diverse housing and social needs, accessibility,
- safety & security,
- privacy,
- personalisation,
- informal contact,
- community facilities,
- recreation,
- flexible spaces,
- aesthetics,
- sense of place,
- affordability,
- economic viability,
- enterprise and employment opportunities,
- gender factors,
- cultural factors,
- education and information,
- community governance and resource management

4. Develop a concept plan

- Concept plan is prepared to illustrate the location and layout of proposed settlement
- Consultation with existing and potential stakeholders is undertaken to agree on options and approaches for development
- Consistent graphic style is used to present the concept plan
- Information on the plan is

Concept Plan may include:

- Internal zoning,
- placement of lots, housing, building envelopes
- utilities & infrastructure,
- roads and circulation systems,
- drainage and stormwater systems,
- landuse systems,
- passive and active open space,
- public landscapes,
- enterprise and business,
- Community/Public facilities.

relevant and clearly communicates development works to be undertaken.

- Notes and specifications are included on the plan to assist in plan interpretation.
- Concept plan is evaluated against the strategic plan for the project

5. **Develop a management plan for settlement**
   - Guidelines and strategies for implementation and ongoing management are outlined
   - Indicators and benchmarks to measure actual performance are specified
   - Strategies to address **natural resource management issues** are established
   - Plans to repair land degradation are developed
   - Plans to address fire risk and fire management are developed as appropriate or required in accordance with guidelines and legislation

PRINCIPLE 3 THE FIVE KEY PLANNING AND DESIGN ELEMENTS

Rural Residential Development through Strategic and Statutory planning processes will need to encompass and meet the 5 KEY PLANNING AND DESIGN ELEMENTS which together meet the Planning Objectives for Rural Settlement.

Figure13. Integrated Planning & Design Elements

These Elements are interlinked. The strength and health of the Settlement System relies on the principles of the five elements being achieved by rural development types, location and forms.

These Indicators are used at each level of planning and design from Regional to Local decisionmaking, and land use . This includes:

- Regional Planning Strategies
- Sub Regional Catchment Strategies
- Local Government Rural Residential Strategies and Rural Settlement Pattern Concepts.
- Local Environment Plans, Rural Precinct and Property Development Control Plans.
- Property Development Proposals, Development Applications and Development Reviews.

1 PROTECTING THE ENVIRONMENT

Does the rural residential provide for:

- Maintenance of water quality (eg. stormwater control, waste water treatment and disposal)
- Catchment management, riparian zone/watercourses protection, maintenance of freeflow and recharge of groundwater
- Protection of air quality (pollution, dust, noise, smell)
- Protection and enhancement of soils and earth structure
- Management and protection against soil erosion and land slip
- Protection, management and enhancement of biodiversity, natural habitat and vegetation areas
- Connecting wildlife corridors within and between properties
- No or minimal pollution or contamination, and/or cleaning up of an existing unsatsifactory situation
- Management , re-use and recycling, and appropriate disposal of solid waste
- Conservation of energy in construction, and operation of the settlement
- Protection of visual amenty, in particular scenic landscape and cultural values

2 PROVIDING FOR PEOPLE'S NEEDS

Is the rural settlement located, designed and developed in a manner to:

- Provide for human comfort and safety including people with disabilities (for all age groups)
- Provide access to existing services and facilities (schools, shops, social needs, recreation, employment) and/or provide on site facilities and opportunities
- Establish services/facilities to suit scale and location of development
- Reduce or avoid hazards such as bush fire , flood, damage from severe storms etc
- Educate people about and provide for hazards, flood, bushfire, emergency procedures etc.
- Educate people about rural living, self reliance and Landcare
- Reduce longterm living/maintenance costs through design and appropriate technology
- Establish themes for development to create compatible communities or self reliance

3 COMPATIBLE LAND USE & CHARACTER

Is the rural settlement located, designed and have management provisions to:

- Reduce or avoid conflict with surrounding and nearby landuse eg. through appropriate location, access, theme, design, buffers etc.
- Identify and enhance unique character of the area (historic, cultural, natural)
- Protect and or enhance the visual and scenic amenity of the area
- Integrate with or establish a broader and positive social character for the area
- Provide privacy within the development area for residents and for adjacent residents
- Encourage co-operative or compatible living within the development and if relevant with adjacent landholders
- Encourage awareness and education of residents in regard to compatible living
- Promote interaction within the development site and with adjacent and nearby landholders in regard to landcare, community resource management, and emergency procedures for any recognised hazards in the area.

4 EFFICIENT SERVICING & SELF RELIANCE

Is the rural settlement designed, located and does it include provisions for:

- Linking into existing utility and social services without adding unsatisfactory pressure to the system, or as an alternative provides for increased self reliance in utility and social services
- Maximising self reliance in water and wastewater treatment
- Optimising solar aspect and solar access for housing and other commercial options
- Encouraging energy and water conserving technologies
- Environmentally sound solid waste management and recycling
- Reducing motor vehicle dependency and/or encouraging efficient use of vehicles (proximity to village, access to public or private bus service, vehicle pooling opportunities etc)
- Appropriate road location, design, width, natural drainage systems, and efficient and low energy demanding engineering techniques in construction and maintenance of services and facilities
- Efficient fire hazard reduction systems and fire fighting equipment, hydrants etc
- Managing the land area and population in regard to land and resource conservation, weed and feral animal control, hazards eg. floods, bushfires, drought etc.

5 FOSTERING COMMUNITY RESOURCE MANAGEMENT

Does the rural settlement provide for and encourage:

- A legal structure and land tenure system to facilitate community management of appropriate resources
- Individual and community responsibility for community resource management
- A range of opportunities for management input, level of involvement, and potential employment and/or community action in resource management
- Community education eg. land management practice, rural living, conflict resolution
- Involvement in Landcare, Bushfire Brigade and other community initiatives
- Accountability to external authorities re: waste management, water quality, environment protection etc.

EXAMPLE OF CLUSTER PLANNING AND DEVELOPMENT AT PROPERTY LEVEL IN LOCAL PRECINCT CONTEXT:

The following examples are provided of a property being developed within a District Sub-Catchment and Local Rural Precinct, comparing conventional subdivision methods and the cluster approach. A further detailed case study using a development area implementing the cluster approach is provided in Chapter 7 - "Themes". Chapter 7 also provides examples of Cluster Development at property level for a range of rural living themes. Figures 17 - 20 are linked to the adjacent text explaining the area the development site is located in (fig. 17), the landform and land use of the site (fig.18), issuesb arising from a number of conventional subdivision approaches (fig. 19), and an example usingthe cluster approach in resolving the issues (fig. 20)

RESPONSE TO 5 KEY ELEMENTS USING EXAMPLES OF EXISTING FORMS AND A CLUSTER MODEL

Catchment Planning and Settlement Pattern Context:

- The development site is located in a Scenic Rural Precinct which includes major nature conservation (National Park) and forestry areas (State Forest).
- Involves a marginal agricultural area which has been extensively used for grazing. Adjacent property to the south is a grazing property.
- Sealed road access is available to the property boundary. Electricity is only reticulated service.
- An adjacent Village Centre Precinct provides opportunities for wider social interaction and range of services. The public bus service which passes the property connects this village with a local town centre to the north.
- Approximately 2km of undulating country from the village which is suitable for bicycle riding to and from the property.

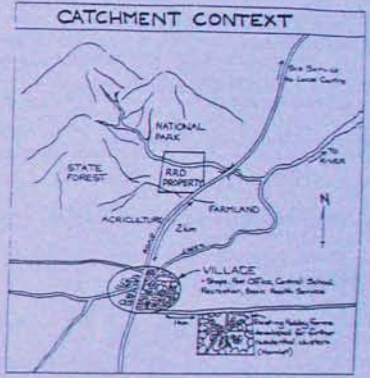


Figure 17 Example of Catchment context

Property Landform and Land Use Map

- The property has a permanent creek coming from adjacent State Forest and National Park areas. It has remnant forest cover on a southern slope adjacent to the State Forest and National Park including viable area of rainforest with regeneration occuring.
- Adjacent land uses include National Park, State Forest, and a farm with issues associated with conservation, buffers, fire management etc
- Range of land management issues in relation to degraded areas, erosion of steep slopes, weed infestation, lack of tree cover etc.
- Property presently being used for minimal grazing with little active land management. Some potential exists for suitable horticulture or animal grazing if the northern slopes are suitably developed and managed.

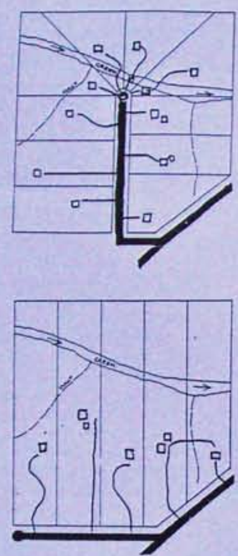
Figure 18 Example of Property context

EXISTING SUBDIVISION APPROACHES

Example of Issues with existing approaches:

- Fragmentation of natural environment. Different management regimes likely for indiividual lots. Possibility of weed problems and damage to conservation values including creek.
- Some lots have difficult building sites including loss of good solar access.
- A number of lots have land degradation issues.
- Potential incompatible uses between lots and with adjacent landuses.
- Loss of efficient servicing opportunities and duplication of services.
- Potential loss of rural character.
- Potential loss of agricultural opportunities
- Council has future responsibility for the road.
- External bodies deal with number of lot owners on issues.

Figure 19 Example of existing subdivision approaches

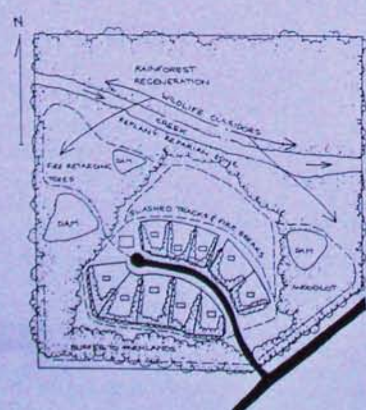


CLUSTER MODEL APPROACH

Example of Resolving issues:

- Natural environment and riparian area are protected including coordinated management action
- All residential lots have good sites and access, and solar access for efficient housing.
- Degraded land has been incorporated into land management plan including erosion control.
- Protection of rural character.
- Potential agricultural development area.
- Efficient external utility service provision with opportunities for water provision using dams.
- Compatible land uses planned including buffers and integration with neighbouring land use and liaison.
- Internal road and range of community facilities are provided and maintained by residents.

Figure 20 Cluster model approach



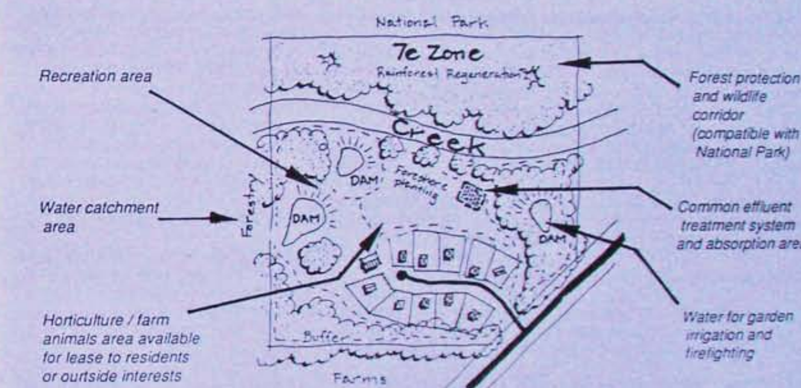
CHAPTER 5 COMMUNITY TITLES

Community Title was introduced in NSW in 1989 to provide a form of land tenure to enable the subdivision of land as a composition of freehold lots with shared community land, an option that the NSW Strata Title could not easily accommodate. Community Title is thus NSW's answer to similar forms of land tenure available in Victoria as Cluster Title, and in Queensland under the Building Units and Group Title's Act.

Community Title as a form of land tenure involves:

- subdivision of freehold lots
- joint ownership of community land and facilities
- legally binding by-laws governing land use and management of common land, services and facilities as well as the management of services on freehold lots such as waste disposal systems
- landscaping and architectural standards regulating the private developments on freehold lots

Using the earlier property example from Chapter 4, figure 25 below shows a Community Title cluster development, the text following describing potential benefits flowing from this form of development.



Cluster development of residential lots and a community management structure provides the following benefits:

- optimal siting of residential lots within landuse context
- better placement of roads and services in landscape
- less infrastructure for roads and services and long term maintenance by residents
- enables managed common effluent treatment
- cohesive fire reduction strategies and maintenance
- common water storage and reticulation system for non-potable use and fire fighting
- open space and recreational land and facilities reduce pressure on wider community
- enables theme development for compatible landuse and lifestyle within development area and with neighbouring areas

COMMUNITY TITLE MANAGEMENT OPTIONS

Community Title is a flexible form of tenure enabling a range of various management structures and methods. These can cater for varying levels of interest in management participation by the individual freehold lot owners.

The ability of people to work together depends upon a range of factors and is better facilitated through the establishment of a common goal or vision (theme) together with a clear framework for decision making and options regarding the individual's level of involvement. These options can include contributions of time (labour), kind (materials, equipment) or funding (levies).

In a situation where people do not wish to be actively involved, the Community Association can employ a part or full time manager to undertake community responsibilities, and/or other people to undertake specific management tasks. Employment and small business opportunities for residents or people in the wider community can occur e.g. general land maintenance, slashing, fencing, road maintenance, tree planting, weed control, lease of agricultural land.

The Community Association provides a single entity for communications with external bodies such as Bushfire Brigades, Local Council, neighbouring landowners and management agencies, as well as for contracting services for sewage treatment, road maintenance etc.

This principle of land management in contrast to other existing land tenure structures used for rural residential development provides the following benefits:

- instead of involving public funding (rates) to maintain resources, private capital is provided by the users with potential to generate employment,

- reduces problems of fragmented land use practices and conflicts (e.g. fire, pollution of water ways, chemical vs organic production and weed control)

- reduces maintenance liability and cost to the individual through a smaller area for private use and shared cost of community land development and management, and potentially eliminates duplication of equipment and infrastructure.

- establishes potential sense of community with broad goals for common land, collective resource and land management, lot owner interaction and support opportunities.

STAGED DEVELOPMENT

NEIGHBOURHOOD AND PRECINCT PLANNING

A community title can be developed either as a single, one stage development or released in stages over a period of time as a number of neighbourhoods and/or precincts. These separate neighbourhoods can provide their own and also share common facilities and land under a range of tiered management structures.

Advantages of staged development include:

- reduction in development costs: with large developments the initial up front capital required to complete capital works, pay all Section 94 contributions, and subsequent high interest rates adds a substantial amount onto the cost of lots
- stages can be released over time according to market demand or can be regulated by local government
- the overall Community Title plan retains the integrity of broader landuse planning and management which could otherwise be compromised by smaller fragmented and piecemeal separate developments
- future development lots can be reserved under the community plan, available for future design and development appropriate to changing community needs and Council policies and strategic planning goals
- precincts and neighbourhoods under the one community plan can be separately zoned e.g. a village/urban residential zoned neighbourhood and a rural residential neighbourhood sharing a common green belt, recreation and community facilities as a buffer between them.

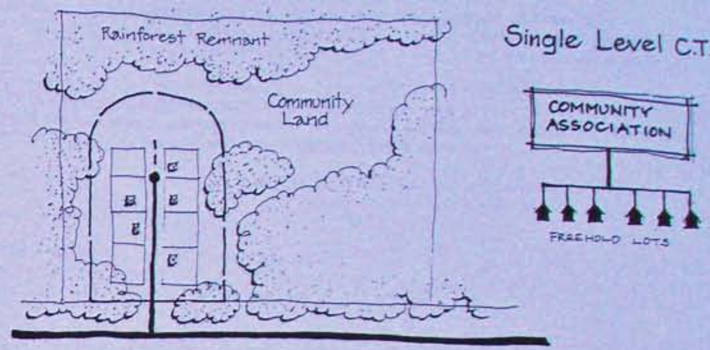
This provides an excellent means to create an urban overlay if required for rural residential land close to an expanding urban centre. This land development approach enables important social, natural, cultural and land use characteristics to be retained in the process of urban expansion and consolidation.
See diagram and commentary on page 45.

Examples of Community Title Development

The following pages provide an example of developing a property using Community Title through various stages, involving a single tier to a more complex management structure, based on the further stages of the development concept. Figures 26 (single tier), 27 (two tier), 28 (three tier) assist in describing the management structures available.

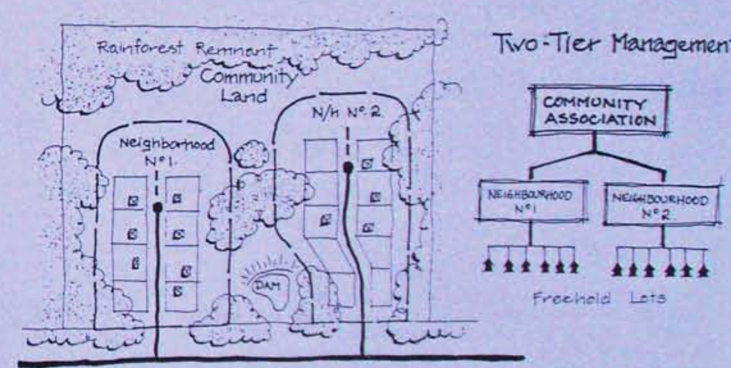
SINGLE TIER COMMUNITY TITLE

Figure 26 Single tier management



TWO TIER COMMUNITY TITLE

Figure 27 Two tier management



- each neighbourhood manages its own Neighbourhood property and facilities
- allows for smaller management groups to care for their immediate surroundings and services
- residents of all neighbourhoods contribute to Community Association for management of Community Property
- Community Property is accessible to and managed by residents of all neighbourhoods
- Neighbourhoods can be released in stages or reserved as future developments lots for future design and development.

THREE TIER MANAGEMENT

In addition to the Community Property and Neighbourhoods, a community title can also involve Precincts which contain their own Neighbourhoods. This design approach provides flexibility in terms of lot size, management areas, theme development and land usage.

In this example shown in **Figure 28** below, Community Title contains two initial rural residential neighbourhoods, followed by later development of a village/urban zone residential precinct containing three neighbourhoods for staged release, and a future development lot which may be zoned for appropriate development for future needs as defined by Council and the development proponent in consultation with the community.

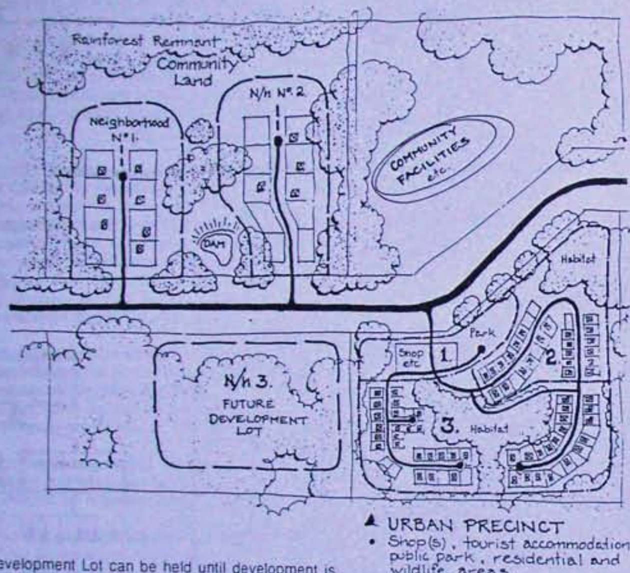
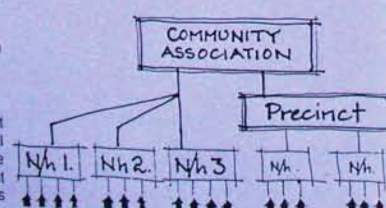


Figure 28
Three Tier Management



The Future Development Lot can be held until development is required. This allows detailed design to be delayed until the parcel is to be developed and so better address specific future housing and landuse needs, or rezoning for urban residential or non-residential use e.g. conference centre, resort, shops, commerce, recreation, light industry.

This could be further residential or a non-residential use within the context of surrounding land use and strategic planning.

The development process results in three tiers of management (see figure 28 oppositewith each neighbourhood of residential lots having a common area to manage, as well as input into the common community land. They can also be the development proponent through the body corporate of the next stages. This arrangement could include the initial development proponent who may have retained ongoing interest in development of the community on this property.

URBAN OVERLAYS :

Urban overlays have been suggested and attempted as a means to enable closer settlement to occur at a later date in an existing or proposed rural residential area such as a rural estate or small lot development. Problems include difficulty to develop on a planned or staged basis, loss of amenity and open space values and in some cases contribution to sprawl.

Community Title provides a mechanism in conjunction with strategic planning and design to establish an open space network in advance including conservation areas, orchards and food production areas, recreation and community space that will remain throughout the development process.

The open space could be fully transferred to Council as development occurs, or partial transfer for public access ways and community facilities only, the balance retained as private open space thereby reducing and focusing Council costs and responsibilities.

In a similar manner community facilities and utility services can be provided by the development proponents and upgraded or enhanced as redevelopment occurs. Management can be transferred to Council or maintained by neighbourhoods or precincts within the development area.

Staging of the development can be controlled by Council as it decides urban consolidation should occur as part of a broader settlement strategy. Lot purchasers would acquire future potential redevelopment interests with their lot. Building envelopes could be used to ensure dwelling sites do not sterilise future development opportunities.

The Example shown in Figures 29 (below) and 30 (p.52) : A rural estate is developed adjacent and to the east of an existing village area which is proposed to be expanded to include the subject estate area in the future. The first stage of consolidation has occured in half of the western neighbourhood. The eastern portion of this neighbourhood will be next to develop, followed at a later date by the eastern neighbourhood.

Figure 29 indicates the location of the proposed rural residential area to be encompassed in the expansion of the village. The diagram on the next page indicates the overlay concept in greater detail.

FIG. 29.

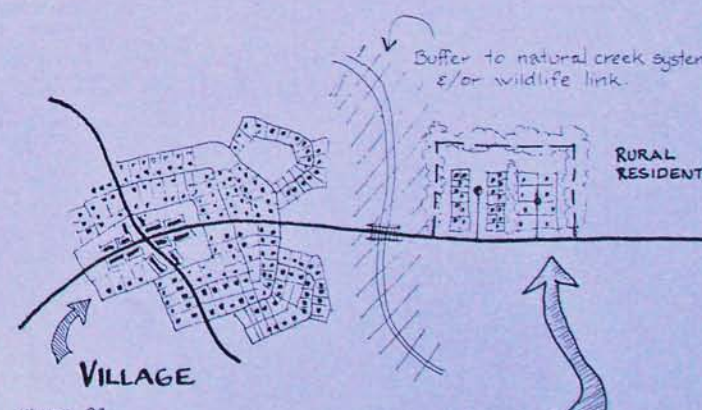


Figure 29.
RURAL RESIDENTIAL with URBAN OVERLAY

FIGURE 32.

THEMES FOR DIFFERENT TYPES

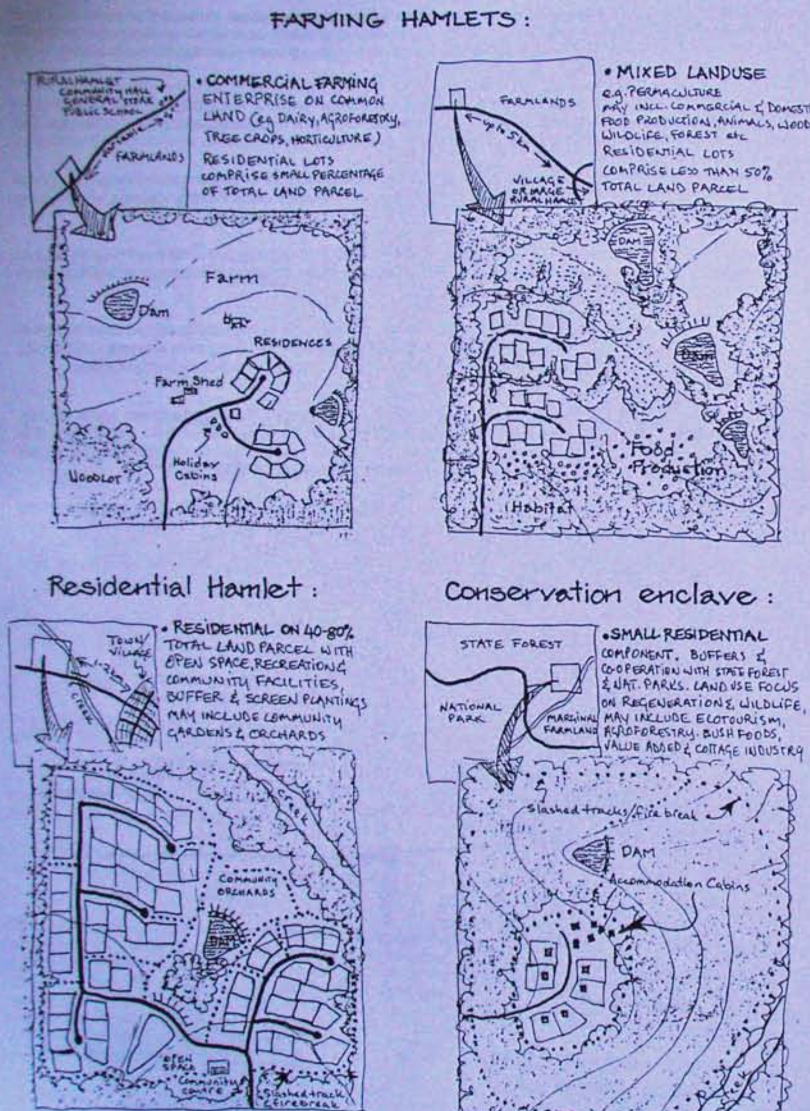


TABLE 3

TREATMENT AND DISPOSAL ALTERNATIVES

ALTERNATIVE DOMESTIC TREATMENT SYSTEMS

Primary systems

Grease trap
Pit
Septic tank
Segregated septic system - (grey water, black water)
Anaerobic Methane digester - Biogas

Secondary and tertiary polishing systems

Fixed media AWTS
Extended aeration AWTS
* Rotating Biological Contactor
Pond/Lagoon - aerobic - facultative - anaerobic
Subsurface wetland
* Surface Flow Wetland
# Silviculture (tree lots)
# Aerobic Mound
* Soil/sand filters - (aerobic, anaerobic)
* RUCK system- (segregated Septic tanks, aerobic filter, anaerobic filter) Laak, 1986
# Rock filter
* Zeolite filter

Phosphorus polishing systems

* Nutrient polishing sand media filter - (bauxite, red mud,iron, organic matter, calcite)
# Harvested pasture or silviculture irrigation areas
# Certain types of permeable soil beds

Nitrogen polishing systems

Subsurface wetland
* Surface flow wetland
* Aerobic/anaerobic filter sequence (RUCK system)
Pond/lagoon
Silviculture/pasture irrigation
* Zeolite filter media
# Intermittent extended aeration (certain configurations)
* Rotating Biological Contactors (certain configurations)

Disinfection

Chlorination - calcium hypochlorite tablet and contact tank
* Iodine - saturator and contact tank
* UV - requires power supply and clear preferably filtered effluent
* Ozone - generated by UV light and clear effluent

Composting systems

Dry Composting
Dry composting/vermiculture
* Wet composting/vermiculture

DISPOSAL SYSTEMS

Conventional single Absorption trench
Dual absorption trenches for greywater/blackwater
Peat bed absorption trench
Transpiration bed
Transpiration/absorption bed
Surface irrigation
"Green Belt" system
"One tree" system
Elevated mound
* Absorption trench with infiltration drains
# Leaky line leach field systems

Note: **Key to notations**

* Was not identified in the region
# Probably present in limited numbers

All others have been identified within the region.

FIGURE 39.

Segregated Absorption System

- Separates grey / black waters.
- Good - Moderate absorptive soils.
- Suits most sites < 20% slope

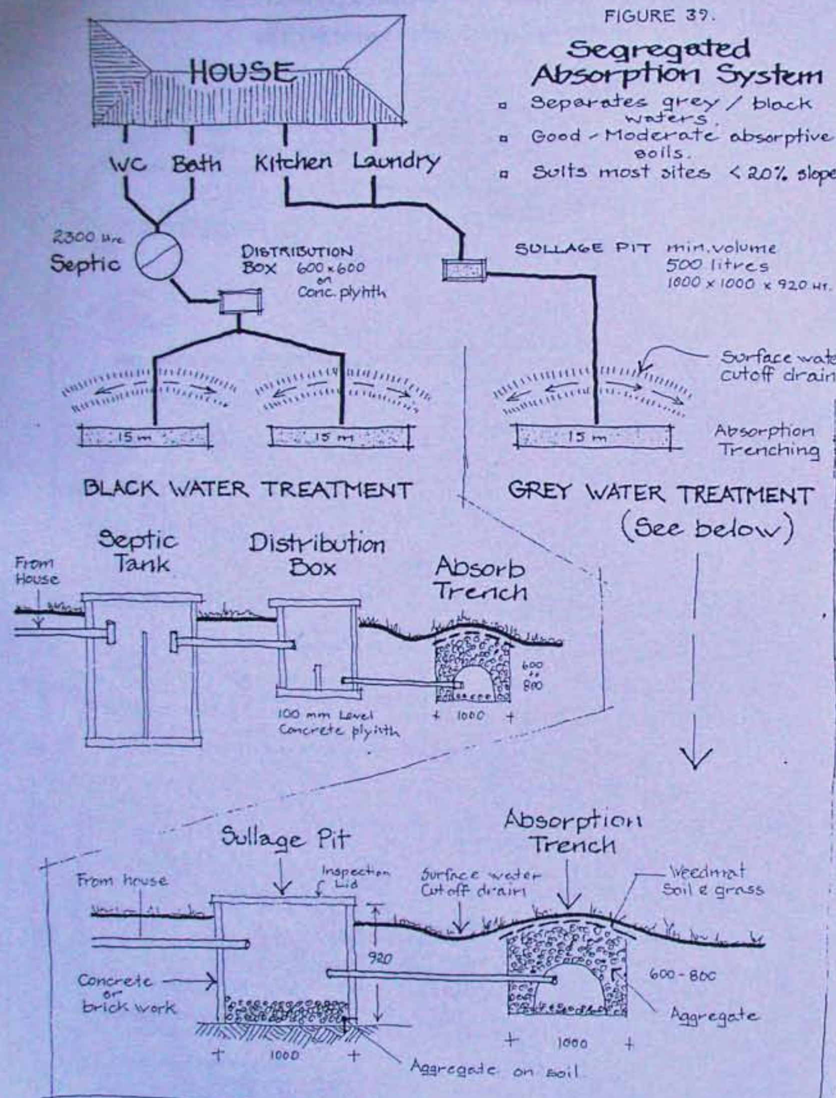


FIGURE 41.

Aerated wastewater treatment plant system

- Suitable for most sites
- Minimum area of irrigation required is 200 sq. metres
- Diversion of surface water is critical.

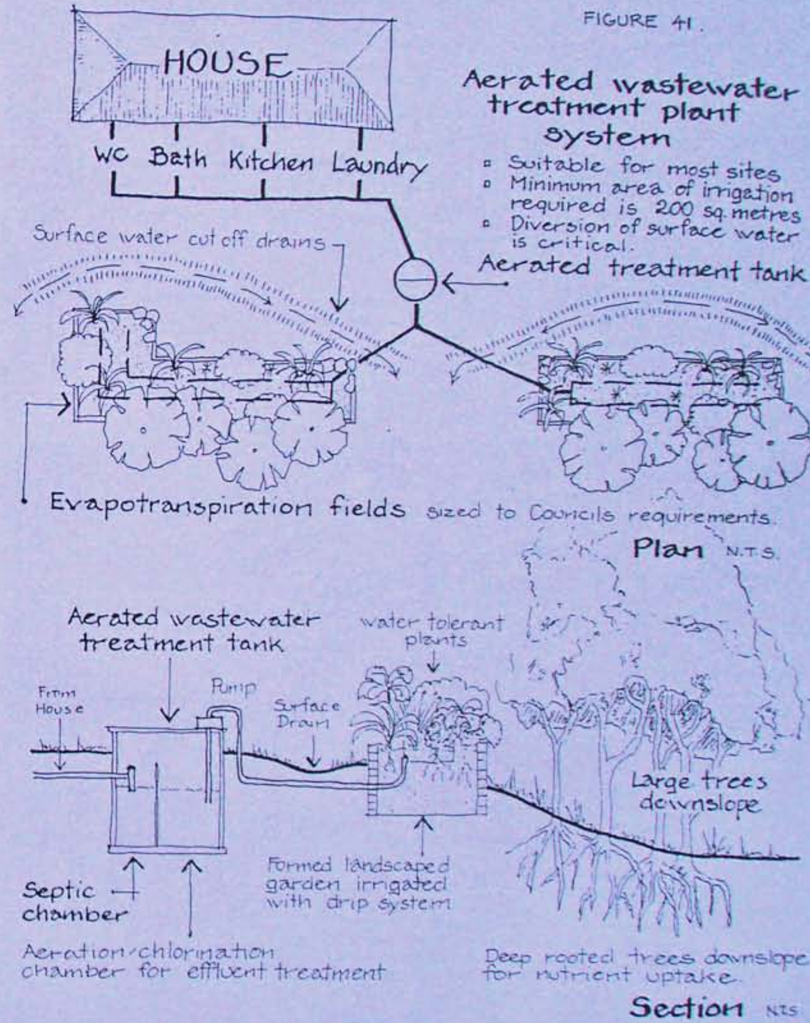
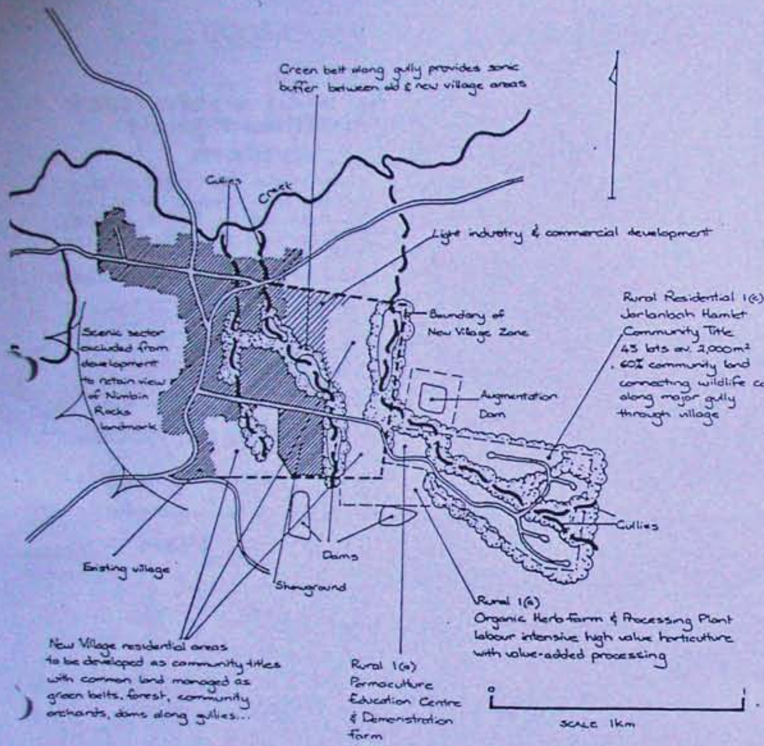
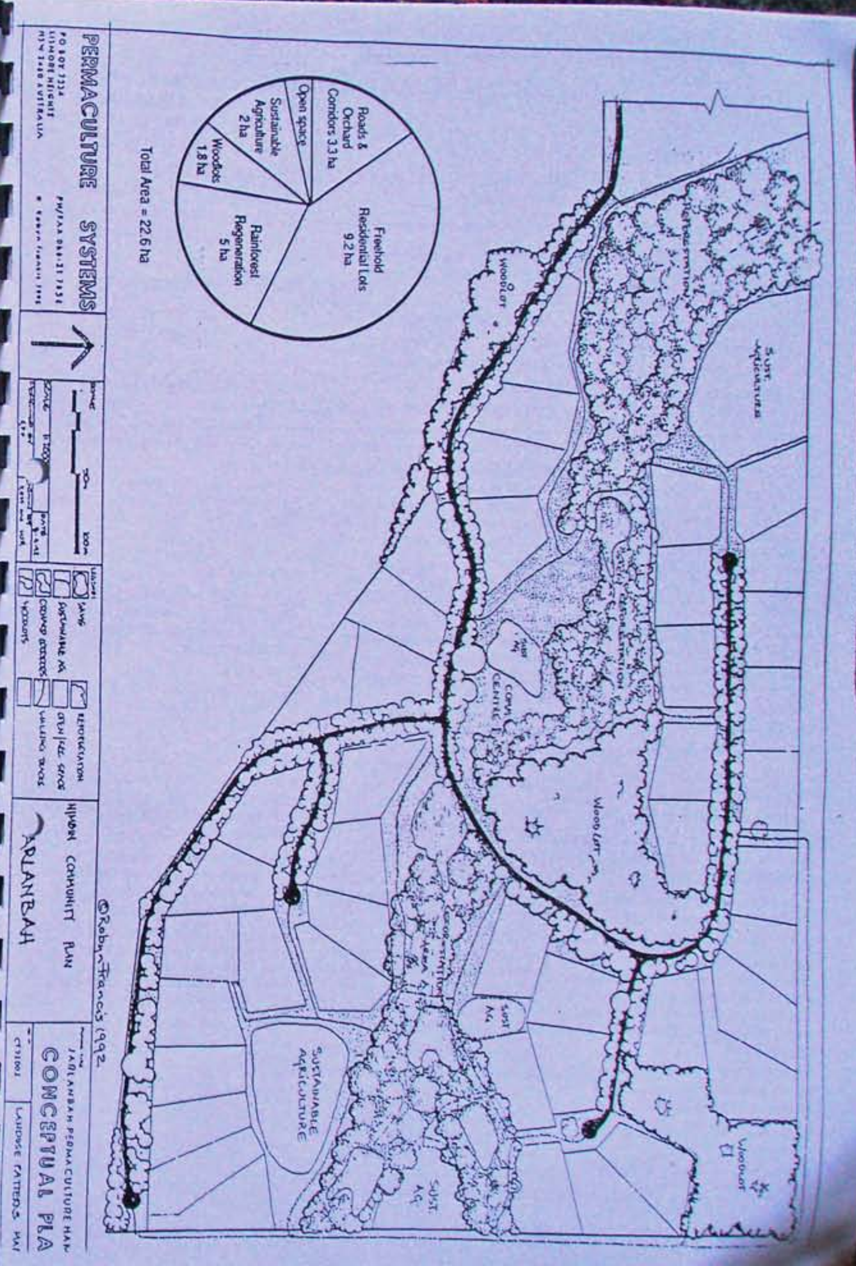


Figure 37
Jarlanbah settlement in context of the local Precinct



- New Village areas incorporate buffer zones as greenbelts along water courses/gullies linked from one property to next through combined community title & Land Care Association management
- Village connects with surrounding land use through greenbelts
- Rural 1(a) land between village & rural residential retained as high input horticulture, value added processing, education and eco-tourist ammenity, providing employment & income generating opportunities for new residents
- Rural Residential 1(c) Jarlanbah Permaculture Hamlet, 1km from Village, small sized lots on 40% of land, appropriate to village proximity. Retaining forest/agricultural use of 60% of land, screens development from village & retains rural character & ammenity



Jarlanbah

Permaculture Hamlet

Information sheet

Tenure: Community Title
Residential lots are freehold title with joint ownership & management of 33 acres common land (neighbourhood property)

43 Residential lots, each approx 2,000 square metres (half acre)

Community Land is divided into landuse and management areas:

- Woodlots
- Re-forestation area
- Sustainable Agriculture areas
- Roads & orchard corridors
- Dams & water system
- Open space & community centre

Services:

Electricity: underground power reticulation is owned by the community. Households can have 240 volt power with 20amp limit or 5 amp tricklefeed.

Water: resident responsibility to collect rain water - community bore reticulated to lots for back-up on 'user pays' basis

Phone lines installed with capacity for 80 connections

Recycling & garbage: Nimbin transferstation

Internal roads are sealed & community owned

Residential lots have been located according to the following criteria:

- for ease of vehicular access from internal roads
- to provide direct foot access to common land: open space, sustainable agriculture areas, reforestation areas, dams and trails.
- on gentle gradients and slopes not exceeding 20 degrees
- for maximum solar access for passive solar house design
- to allow a buffer zone between lots and gully and dams for water catchment protection
- to allow for a fire break between lots and woodlots/ reforestation areas

Landscape Standards:

Landscape designs for allotments should:

a) aim to create a functional and productive ecosystem through the application of permaculture design principles

b) create a microclimate which enhances the energy efficiency of dwellings

c) not restrict the solar rights of neighbours

d) provide for efficient and safe management of rainwater on site to reduce evaporation, decrease runoff and ensure that water run-off on site and leaving the site creates no damage and contains no contaminants

e) consist of no less than 50% edible species and no less than 30% Australian native species within the total landscape plan

f) provide habitats for natural pest predators

g) retain no more than 20% of the total landscape as permanent lawn

h) reduce fire risk through the use of fire retarding plant species

i) not involve the use of any natural or artificial biocides or fertilisers other than those approved as appropriately safe by the Neighbourhood Association

j) ensure efficient nutrient management so that natural fertilisers and manures used and/or created on site do not contribute to nutrient run-off

k) employ water conservation techniques to minimise the use of irrigation water in the landscape

l) no plant species in the landscape of a Lot be allowed to invade a neighbouring lot or Community property and that the proprietor or user of a Lot will be responsible for the removal of any invading plant outside of the Lot

Building Standards

Houses and structures on lots should be designed according to the following criteria so they:

a) integrate built structures with the environment and immediate landscape in terms of aesthetic, climatic, ecological and lifestylefactors

b) create a pleasant indoor microclimate through

- the application of solar design principles
- effective use of passive and active solar technologies and devices
- appropriate placement of verandahs, pergolas and solar screens
- siting and orientation for maximum solar efficiency
- insulation, ventilation and the use of appropriate building materials and thermal mass

c) achieve a high level of energy efficiency and self-reliance through design and the use of solar and energy conserving appliances and technologies that reduce or eliminate the use of and dependence on fossil fuels and grid electricity

d) roofs should be designed for rain-water collection, use non reflective materials and angle north-facing roofs at 33 degrees for maximum solar gain.

e) use materials selected for their environmental and climatic suitability, be generally of earth tones, and where possible use recycled and locally produced materials.

f) should have a minimum of two rainwater storage tanks, one for drinking water, the other for bathroom /laundry, with a minimum total holding capacity of 45,000 litres.

g) conserve domestic water consumption through the use of water conserving fittings and technologies, and recycle greywater for garden irrigation and flush systems

h) use appropriate sewage treatment systems such as dry composting toilets or aeration treatment plants. Septic and similar absorption systems are not appropriate due to the low permeability of the soil.

i) Setbacks: dwellings 5m from Lot boundary; other structures 1m from Lot boundary

PERMACULTURE HAMLET

NIMBIN

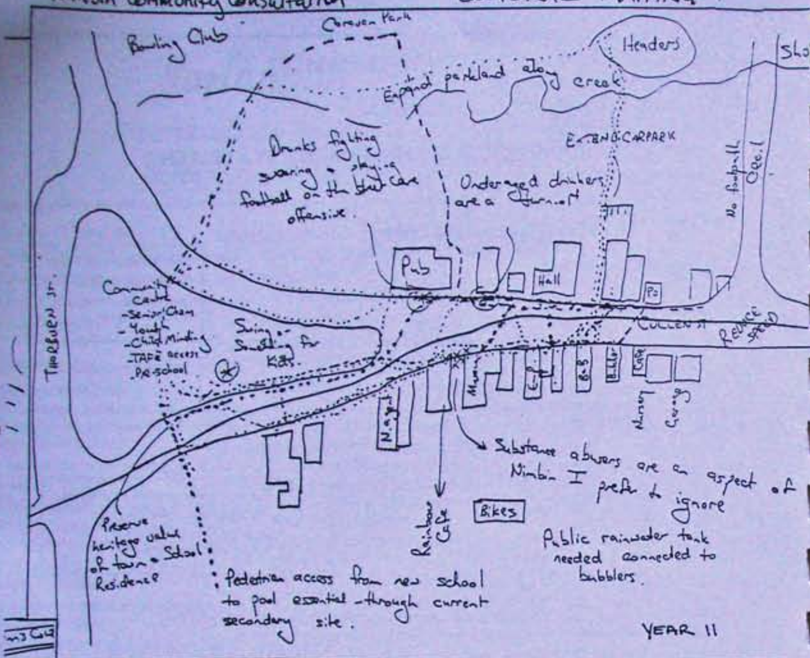
NEIGHBOURHOOD MANAGEMENT STATEMENT

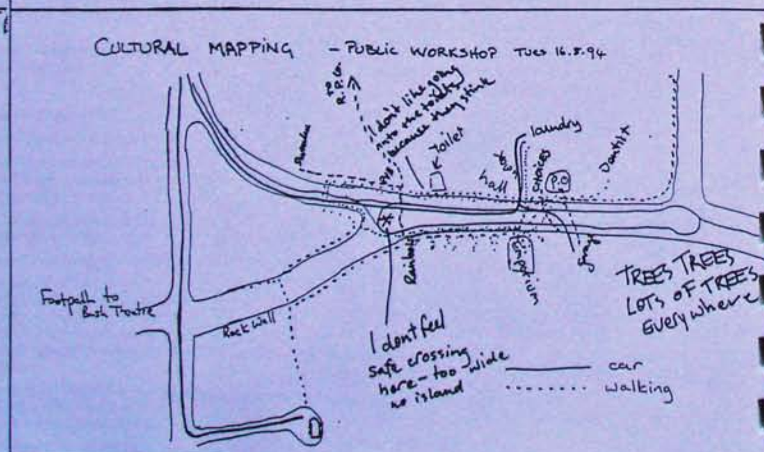
Index

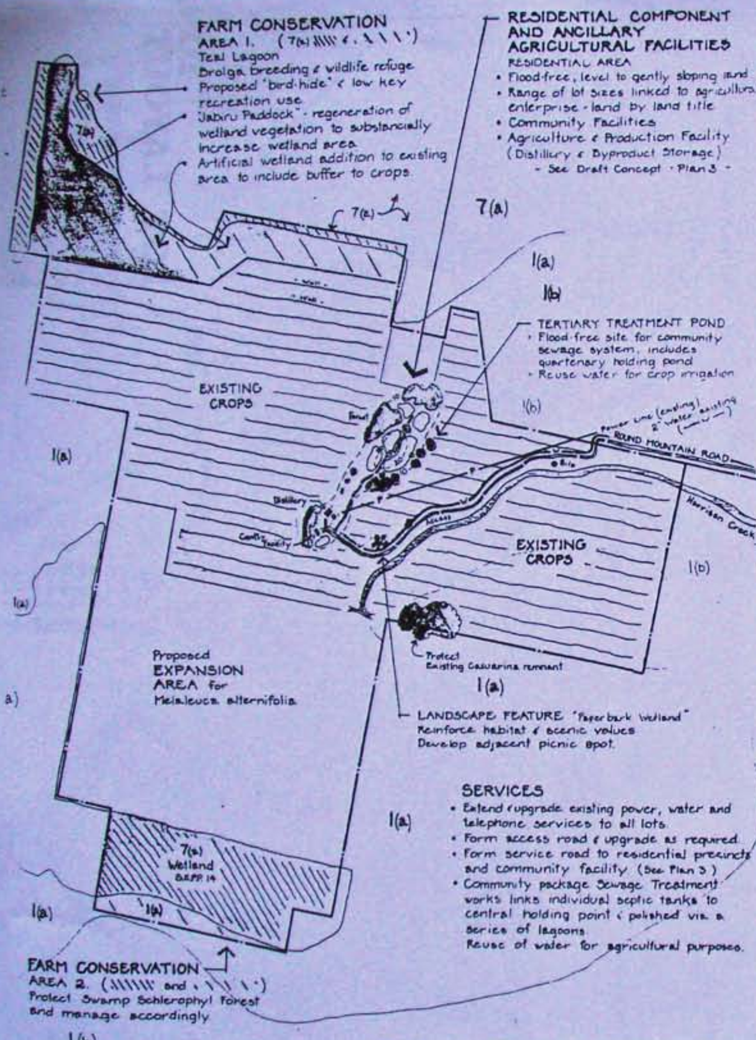
This section can only be amended with unanimous consent of all lot owners (Part 1)

This section can only be altered with approval of all people entitled to use restricted neighbourhood property (Part 2)

Nimbin Community Consultation "CULTURAL MAPPING".







ROUND MOUNTAIN

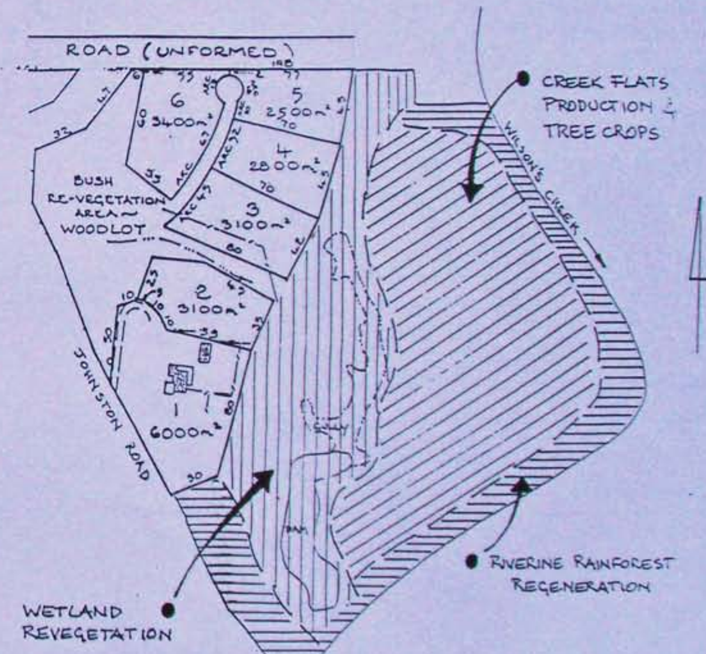
DRAFT CONCEPT

Client: Michael Daley Round Mountain Rd via Laurence

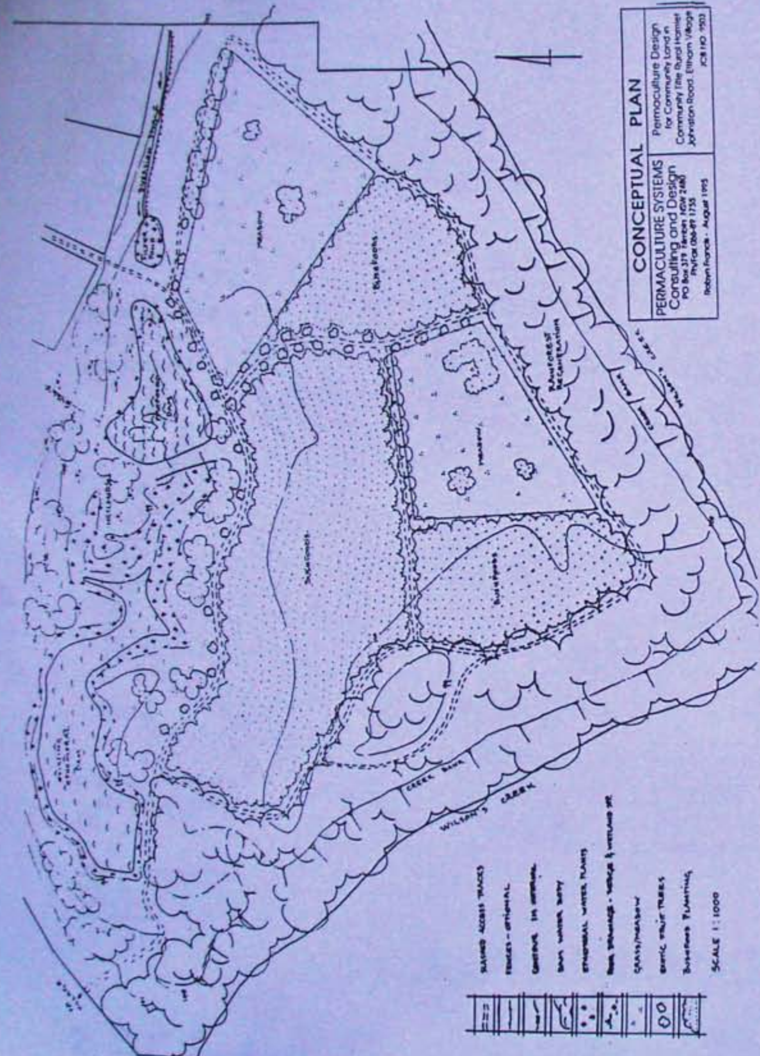
Consultants: SUSTAINABLE FUTURES PLANNING & DESIGN

Planner + Principal Landscape Architect: Peter Cumming, John Webber

2 — 0 500 1000 Metres — NORTH



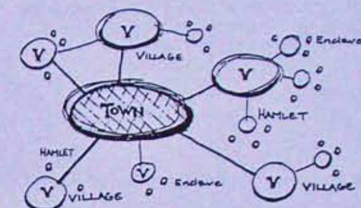
JOHNSTON ROAD
ELTHAM Comm. Title



SUMMARY OF MAIN PRINCIPLES

1 CATCHMENT PLANNING FRAMEWORK

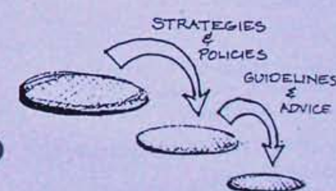
- Understanding the nature of the Catchment.
- Knowing its values, limitations and challenges.
- Recognising layers of sub catchments and rural precincts with their own character.
- Implementing Total Catchment Management principles and developing a Landcare ethic.
- Encouraging cooperative planning and design.



3 KEY PLANNING & DESIGN ELEMENTS

Use of the following criteria for planning, design and development evaluation:

- Protection of the Environment
- Providing for People's needs
- Compatible Land Use and Character
- Efficient Servicing and Self Reliance
- Community Resource Management



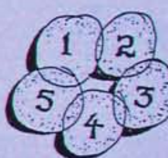
5 PARTICIPATORY SETTLEMENT PLANNING

Establishing and fostering a local and regional community planning focus to assist in:

- Cooperative design of rural settlement patterns
- Discovering and developing living themes
- Researching and testing development ideas
- Using visual and creative material to explain development and settlement concepts
- Gathering and sharing information
- Evaluating planning and settlement results using the 5 key indicators.

2 SETTLEMENT PATTERN DEVELOPMENT

- Interlinked network of differently sized and serviced human settlements.
- Recognising and promoting development forms which create or enhance a sense of community.
- Protecting open space and conservation values, agricultural, extractive industry and sustainable energy production opportunities.
- Identifying and accepting thresholds for growth
- Developing and acknowledging service heirarchies and encouraging self reliance.



4 PLANNING & DEVELOPMENT APPROACH

- Encouraging cluster development at each level of Catchment Planning.
- Providing responsive planning strategies, policies, standards and guidelines to assist in establishing appropriate patterns and forms.
- Using Catchment Planning and Pattern Development to select suitable settlement locations, types and forms.
- Applying Planning and Design Indicators to measure potential and actual performance of planning approaches, locations and forms of development.

Planning & Design Parameters

1. **Planning:**

Vision (key goals)	- Purpose
Objectives	- how to realise vision
Strategies	- Ways to achieve objectives
	e.g. Natural Envmt, Built envmt, servicing, work, managment systems
Action Plans	- Doing it
Priorities!!!!	

2. **Key Design Elements**

(a) Natural Environment

- Biodiversity
  - Existing veg/habitat
  - buffers
  - links
  - expansion etc
- Landform-contours, shape, aspect, fall
- Geology, soils, drainage
- Catchment context
- Water - sources, flow, quality, potential uses, eventual flow
- Climate - winds, dry/wet season, microclimate, rainfall
- Views - scenic, visual amenity, visual pollution

(b) Providing for People's Needs

Hardware/software; On/off-site needs; Work Options on and off site

- Shelter - solar access, privacy, household needs, materials
- Meeting places - covered, uncovered, built & 'natural'
- Property safety
- Vehicle parking /storage
- Access and mobility (see also.transport and servicing)
- Schooling, pre-school, day care, adult/tertiary ed.
- Health services - on & off site
- Specific needs - age groups, disabilities
- Sacred places - ritual/ceremony/retreat
- Recreation aspects - on & off site - active/passive

Hazards

- Flood/flash flooding
- High winds/cyclone/severe storms
- Soil slips/earth movement
- Toxic or contaminated sites
- Farm machinery, activities
- On/off site pollution (air, water, wind borne, noise)
- Waterways
- Electrical storm
- Extreme cold?
- Bushfire
- Traffic, vehicles

(c) **Compatible Land Use & Character**

Sphere of influence of activities, structures etc
(smells, sound, sight/visual impact, feeling of space etc)

- Private vs public space (clear boundaries)
- Scenic views
- Adjoining land use
- Agicultural/other land use
- Development impacts
- Visitor impact
- Architectural guidelines
- Sense of place

(d) **Community Resource Management - On & Off site**

- Common lands - bushfire, emergency requirements, weed control conservation/regeneration, walkways, transport, roads, gardens/orchards, buildings, woodlots etc
- Business enterprises
- Legal & Admin. structures
- Management plans & documents
- Decision making process
- Conflict resolution and mediation process/options
- Financial strategies - maintenance costs
- Landscaping - e.g. Orchards scattered throughout rather than all together?, woodlots for firewood
- Climate control
- Food & fuel
- Habitat
- Privacy: Evergreens for Windbreaks, Vines/ Climbers on Trellis

Community Buildings & Recreation

- Define needs - note proximity to higher settlement orders & facilities
- Shower, toilet, kitchen, laundromat?
- Arts/crafts, workshop, community tool & equipment storage
- Meetings (indoor/outdoor)
- Commerce: Food co-op, cafe, business facilities (fax/photo copier/ Computer/ modem/ printer)
- Social/entertainment: theatre, music, dance, celebration
- Active recreation: handball/basketball, tennis, field sports (cricket/footy), swimming pool or dam, horses (yards, trails etc)

(c) Servicing

Access & Transport - On & Off Site/links
On site & property to outside world

- Pedestrian, vehicle, other paths, roads, trails
- Design/Style - Surface finish/customer technique grades
  Radial vehicle allows pedestrian access to city /town/village centre

Issues

- Traffic on local roads - potential for mini bus
- Flood free access?, Emergency needs (e.g. bushfire access)
- Multiple use - 'Green Street' (traffic gives pedestrians & bicycles R-O-W)

Water

- Potable - drinking and cooling
- Non Potable, fire fighting, garden use
- Landscaping - beauty/visuals
- Economic use - Crop irrigation, aquaculture
- Nature - habitat, wetlands
- Drainage - swales (which way to direct water - purpose or use?)

Power/Electricity
Design impacts (e.g. underground trench v's overhead/bundle cable)
Overall energy equation: Common/grid interactive v's stand alone

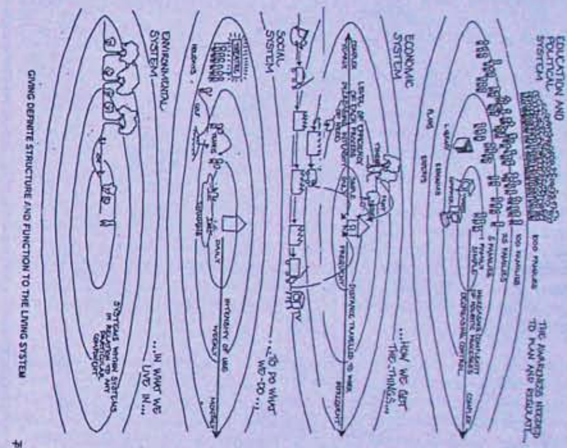
Options

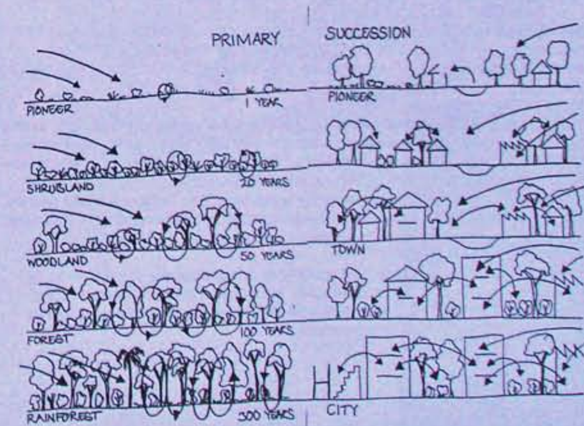
- Wind - need a back up, visual impact/cost of construction
- Solar - cells, stand alone/ community system/ grid interactive
- Biomass - Wood, agricult waste, garbage etc...(solar energy)
  Hydrogen, charcoal, methane, Food,fertilizers,chemicals, by-products
- Wood - Airtight stoves, woodlot - less energy, fast in conversion than other systems (excluding solar)
  issues: carbon monoxide prod., CO2, smoke pollution (cold climates)
- Energy managment systems to demand/use - energy efficient appliances
  Size of wiring and energy system; house and structure designs:
  education e.g. energy.outlets at via readings at each house,
  solar hot water and insulation of buildings

Telecommunications/fibre optic

Sewerage

- septic/bio - biocycle, septic + wetland treatment/green belt etc
- composting: dowmus, clivus multrum, rotaloo, closet deposit
- grey water treatment & management - re-use





Cohousing

Cohousing is a type of collaborative housing in which residents actively participate in the design and operation of their own neighborhoods. Cohousing residents are consciously committed to living as a community. The physical design encourages both social contact and individual space. Private homes contain all the features of conventional homes, but residents also have access to common facilities such as open space, courtyards, a playground and a common house.

The six defining characteristics of cohousing:

1 Participatory process. Future residents participate in the design of the community so that it meets their needs. Some cohousing communities are initiated or driven by a developer. In those cases, if the developer brings the future resident group into the process late in the planning, the residents will have less input into the design. A well-designed, pedestrian-oriented community without significant resident participation in the planning may be "cohousing-inspired," but it is not a cohousing community.

2 Neighborhood design. The physical layout and orientation of the buildings (the site plan) encourage a sense of community. For example, the private residences are clustered on the site, leaving more shared open space. The dwellings typically face each other across a pedestrian street or courtyard, with cars parked on the periphery. Often, the front doorway of every home affords a view of the common house. What far outweighs any specifics, however, is the intention to create a strong sense of community, with design as one of the facilitators.

3 Common facilities. Common facilities are designed for daily use, are an integral part of the community, and are always supplemental to the private residences. The common house typically includes a common kitchen, dining area, sitting area, children's playroom and laundry, and also may contain a workshop, library, exercise room, crafts room and/or one or two guest rooms. Except on very tight urban sites, cohousing communities often have playground equipment, lawns and gardens as well. Since the buildings are clustered, larger sites may retain several or many acres of undeveloped shared open space.

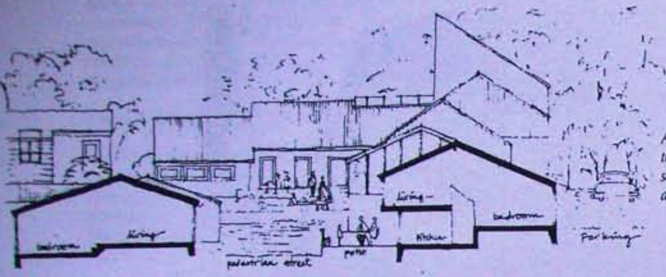
4 Resident management. Residents manage their own cohousing communities, and also perform much of the work required to maintain the property. They participate in the preparation of common meals, and meet regularly to solve problems and develop policies for the community.

5 Non-hierarchical structure and decision-making. Leadership roles naturally exist in cohousing communities, however no one person (or persons) has authority over others. Most groups start with one or two "burning souls." As people join the group, each person takes on one or more roles consistent with his or her skills, abilities or interests. Most cohousing groups make all of their decisions by consensus, and, although many groups have a policy for voting if the group cannot reach consensus after a number of attempts, it is rarely or never necessary to resort to voting.

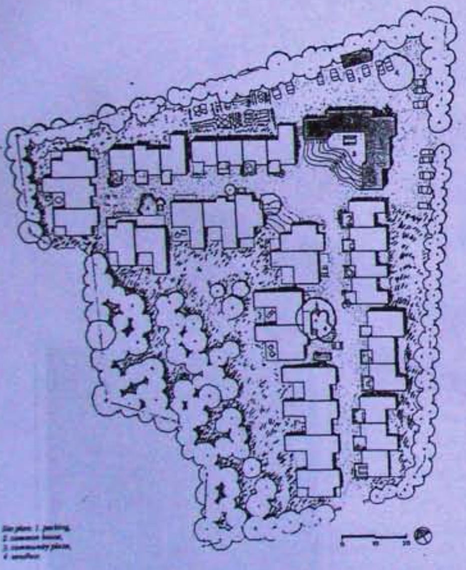
6 No shared community economy. The community is not a source of income for its members. Occasionally, a cohousing community will pay one of its residents to do a specific (usually time-limited) task, but more typically the work will be considered that member's contribution to the shared responsibilities.

http://www.cohousing.org/

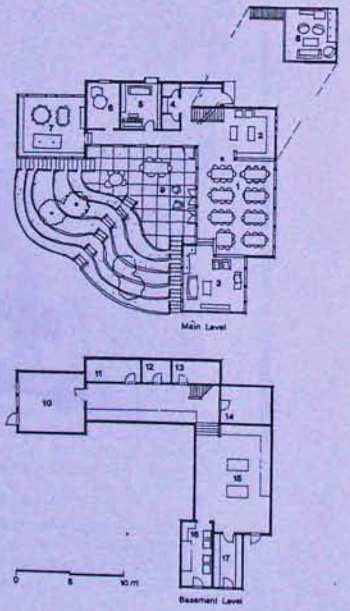
ILLUBUNDA VILLAGE, Sydney www.illabundavillage.com.au/



A section through the site shows the relationship between private, semiprivate, and common areas.



Site plan: 1. parking, 2. common house, 3. community plaza, 4. woodlot



Common house floor plans: 1. dining room, 2. kitchen, 3. TV room, 4. bathrooms, 5. guest room, 6. children's pillow room, 7. children's room, 8. library, 9. terrace, 10. teen room, 11. storage, 12. photography darkroom, 13. freezer, 14. furnace, 15. workshop, 16. laundry, 17. store.

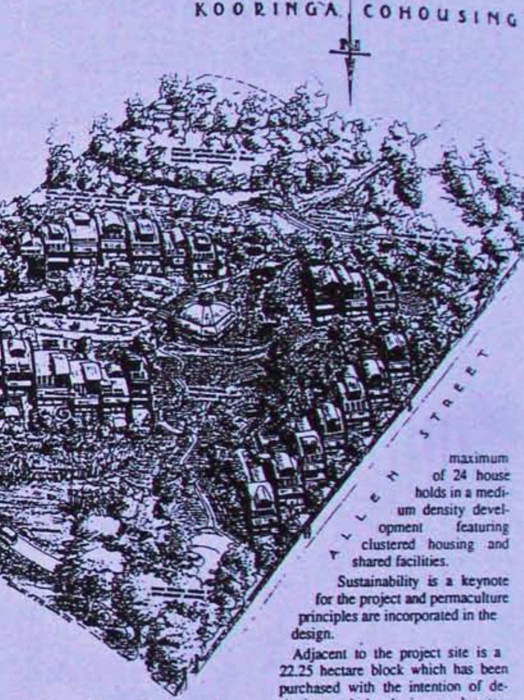
Excerpt from the Permaculture International Journal, #46 page 16, 1993

showing artists impression of Village Layout and Site Plan

vation and the encouragement of cultural activities such as the arts.

Australian Projects

Cascade Cohousing is based near Hobart in Tasmania. Planning began over 18 months ago and the project is now well into its establishment phase. It has State Government backing which makes it one of the first of its type in Australia to gain government support. The site covers an area of 2 acres (0.8 hectares) and will provide housing for 35 people.



Residents will finance and build their houses although Cascade has some caveats on the type of housing and materials that can be used.

The Halifax Project is a large ecopolis and cohousing project in Adelaide, South Australia, which has been initiated and designed by Urban Ecology Australia Inc. and Ecopolis Pty. Ltd. The project involves the creation of an integrated city block with housing, commercial and social facilities. The Halifax Project is being supported by a number of groups including the Australian Conservation foundation (ACF). The ACF, one of the leading Australian environment groups, sees the Urban Ecology project as a model for how to restructure housing and industry towards sustainable development. The design features medium density housing, passive solar design, minimal impact building materials, integrated planning and participatory management.

Kooringa Cohousing

A cohousing development is planned for the outskirts of Burra, a town about two hours drive north of Adelaide, South Australia.

Burra is a conservative farming community; mainly sheep and cereals and the climate is semi-arid temperate. The location provides the advantages of living close to the town and its facilities yet retains a rural outlook.

The project aims to create a diverse community of families and individuals from various economic and cultural backgrounds and to provide affordable, energy-efficient housing.

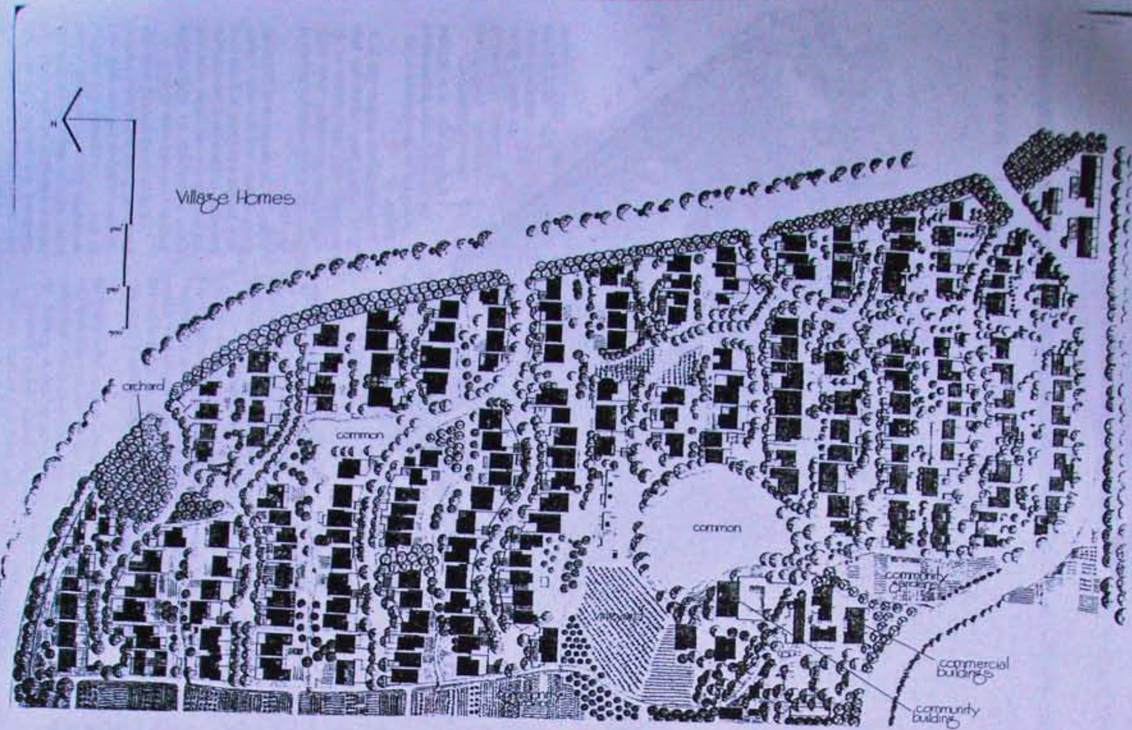
The site is 2.05 hectares and the developers are looking to provide a maximum of 24 households in a medium density development featuring clustered housing and shared facilities.

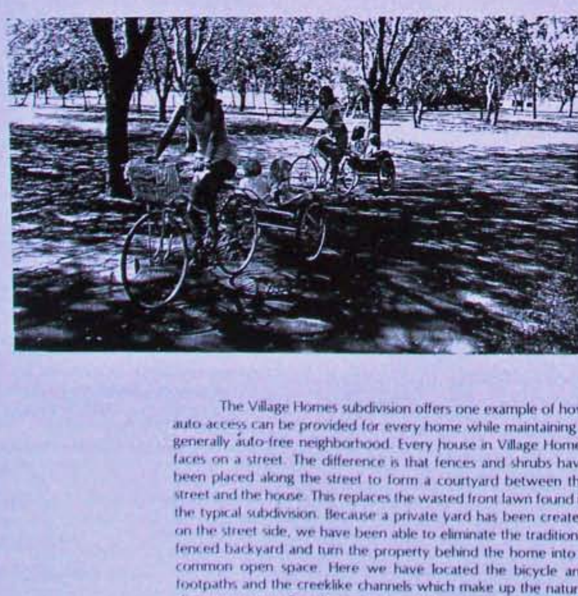
Sustainability is a keynote for the project and permaculture principles are incorporated in the design.

Adjacent to the project site is a 22.25 hectare block which has been purchased with the intention of designing and developing rural enterprises and a demonstration permaculture farm.

One of the designers of Kooringa, Colin Endean and his wife Anthea, have bought a property in Burra itself intending to establish a permaculture institute for dryland South Australia. Colin exemplifies the philosophical basis of Kooringa when he says,

"I tend to see co-housing as an umbrella that gives people permission to experiment and define how they want to live . . . cohousing is a people's movement that says 'we want to live closer together and share facilities because it enhances our own lives'. By enhancing our social lives we also learn to tread more lightly and caringly on the Earth.





The Village Homes subdivision offers one example of how auto access can be provided for every home while maintaining a generally auto-free neighborhood. Every house in Village Homes faces on a street. The difference is that fences and shrubs have been placed along the street to form a courtyard between the street and the house. This replaces the wasted front lawn found in the typical subdivision. Because a private yard has been created on the street side, we have been able to eliminate the traditional fenced backyard and turn the property behind the home into a common open space. Here we have located the bicycle and footpaths and the creeklike channels which make up the natural drainage system. People can be found there cycling and walking as they go to and from their residences or using the space for vegetable gardening or some other activity. Children tend to play there rather than in the streets.

Another important consideration in laying out a neighborhood is that all structures should be able to take maximum advantage of the sun for space and water heating. The Village Homes subdivision provides an example of how to provide north-south orientation while avoiding the somewhat undesirable visual impact of having straight rows of houses all facing south. Streets in Village Homes are curved, allowing the houses to be staggered yet still to universally maintain a southern orientation.

There are a couple of points that seem important to the general layout of a subdivision which is designed to reduce auto traffic. Very small commercial centers should be located adjacent to each neighborhood to reduce the number of trips made to the town center. The variety and number of these should be based on the design of the local neighborhood as it grows and determines what its needs are.

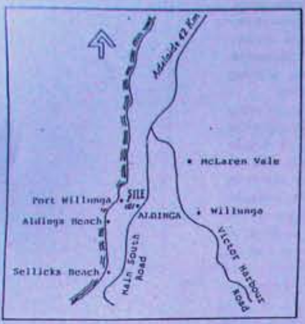
In the Village Homes neighborhood there is a small office complex. There are plans for a small eight-room inn-restaurant, a co-op food store, a medical office, and five small shops which could house such enterprises as a bakery, a tofu shop, potter, sprouting operations, tailor, or other small businesses that could thrive with the amount of business available in such a decentralized location.

The appropriate location of schools can reduce dependence on the automobile. Children in the lower grades should be able to attend schools located in the neighborhood. There are several advantages to this. Not only can young children walk safely through the neighborhood to school, but schools would also be convenient so parents could play a larger role in the early years of their children's education. This should create a very comfortable situation for both children and parents.

In lieu of the normal sidewalks on the street, 6-foot-wide paths can be used between groups of houses. These widths in Village Homes seem to work well. These narrower paths can lead into 8- and 10-foot-wide collector paths, designed to carry more traffic.

In the more centralized locations of a town, heavily used arterial paths should probably be 12 to 24 feet wide. As traffic gets to be heavy at intersections, stop signs may be required, or possibly a traffic circle. In very heavy traffic areas, pedestrian walks and bicycle paths will have to be completely separated.

Street widths can be drastically reduced in a development which encourages pedestrians and cyclists because of the reduction in the use of autos. In the last 30 years, street-width standards in the United States have become ridiculously large, resulting in wasted land, to say nothing of the expense involved in development and maintenance.

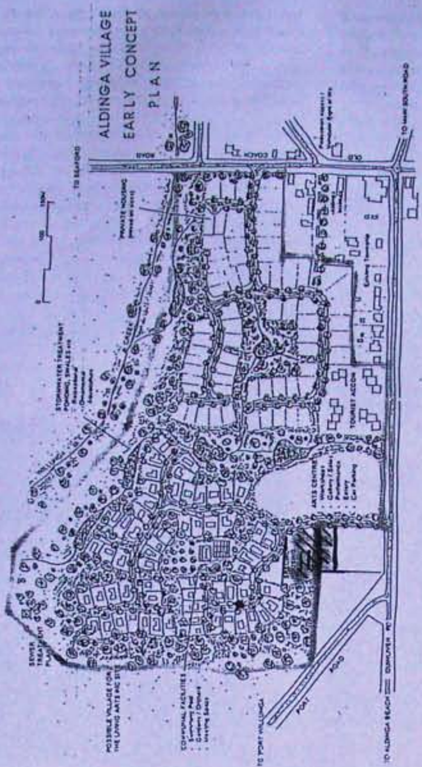


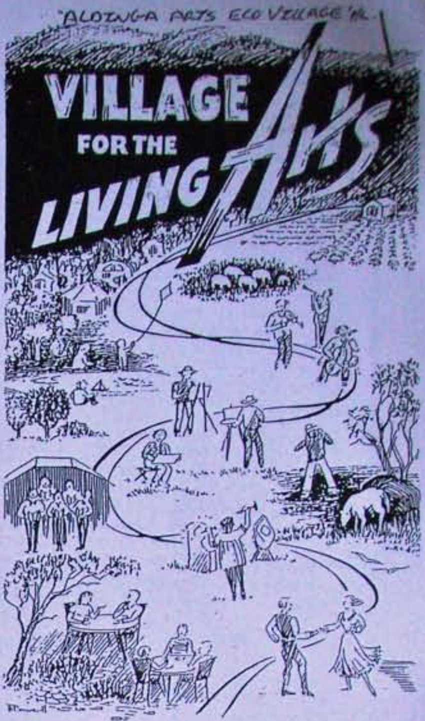
Progress: The site at Aldinga is owned by the State Government which has carried out a feasibility study on the village proposal and, on that basis, the Village for the Living Arts now has an option on the land.

We are seeking people to participate in this momentous opportunity to be part of the first purpose-designed and built artists' village in Australia - a village for the people by the people. Now is the time to become involved so your ideas can be included.

To join the project and become a member of the Village for the Living Arts Inc, there is a fee of $100 a year. This entitles you to select a block of land and participate in the management structure and planning.

Contacts:
Village for the Living Arts Inc, GPO Box 813, Adelaide, SA 5001.
President Barbara Powell-Weise, (08) 83811400.
Secretary Richard Askew, (08) 8388 8514.





The Vision: An oasis in a threatened environment - an ecologically sensitive village designed for and by creative people as a centre for the arts within a market garden and rural creek setting on the beautiful Fleurieu Peninsula.

Concept evolved to meet the needs of visual and performing artists who wish to continue their work in a place of beauty conducive to creativity.

* Village designed to be a total work of art where land and nature are active powers in a dialogue with man.

* Buildings aesthetically designed using environmentally sympathetic local materials and new methods to keep costs down.

* People can design their own homes, large or small, within the village aesthetic concept, to meet the needs of their own particular artform.

* Community areas include a gallery, performance space, workshops, studios and an outlet shop.

* All residents will own shares in the community areas.

* Permaculture farmlands to surround houses with "edible landscale" instead of fencing.

* Emphasis on natural farming as a means of healing the earth.

* Wetlands to purify and reuse grey water; underground storage tanks on each site for rainwater storage.

* Latest energy technology.

* A sense of community.

* No outside person or company will own the village.

* Serviced apartments at a later date to cater for older residents as homes become too large.

Village for the Living Arts Inc: We are a group of creative people committed to establishing a village where we can work in environmentally balanced and beautiful surroundings. The village will be unique in Australia, a valuable contribution to the arts, the community and tourism in South Australia. We have formed an incorporated body to pilot the project to reality.

Location: A site has been selected at historic Aldinga township on the southern side of Port Willunga creek - a gently rolling landscape celebrated by artists for many years for its unique and striking qualities. There is a short walk to Port Willunga Beach along the creek which Willunga Council is developing as a linear park. There is easy access to local shops and medical services. To the east is a magnificent rural area rich in vines, orchards, plant nurseries, restaurants and wineries.

Proposal: A development of up to 80 dwellings of various types is proposed with residents owning their individual land and homes, thus respecting privacy while providing the opportunity for stimulation and companionship in a creative atmosphere. As the village is a lifelong concept; we plan to provide, when necessary, transitional living from large to smaller dwellings, enabling residents to remain in the environment.

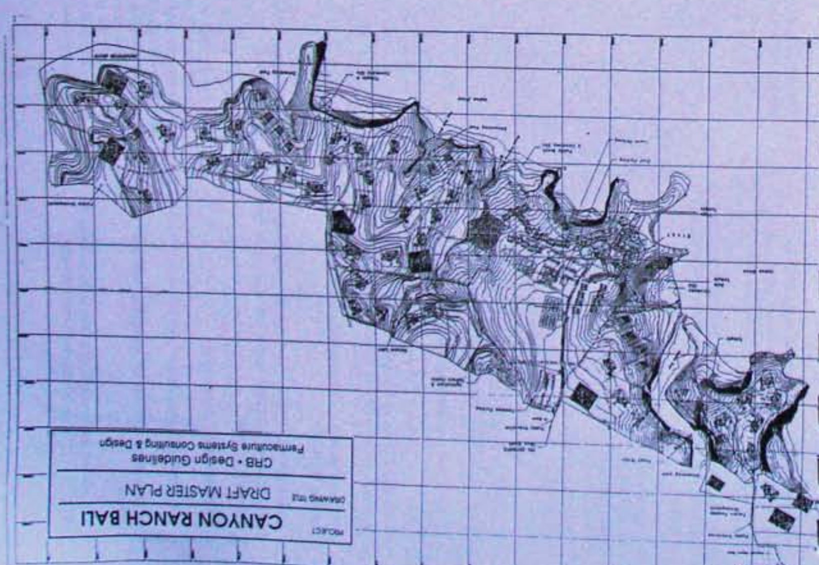
Shared Facilities: These will be owned by the residents and will initially comprise a substantial art and craft gallery and teaching rooms/studios. An art shop, performance space, pottery workshops, a sculpture court, catering facilities and a bio-dynamic farm are also envisioned.

Tourism Related Activity: Residents and the community can best be served by providing for display and sale works of art and craft of the highest possible standard. In addition, teaching programs by invited professional artists in art, craft and music will cater for the public as well as residents. Accommodation for country, interstate and overseas visitors could be provided with units or facilities in private homes. Music and performing arts will enable residents, friends and the wider community to get together for appropriate festivals, anniversaries, etc. in surroundings conducive to quality performances. There is potential for this aspect to be co-ordinated with Adelaide Festival of Arts programming.

Legal Structure: Ownership of land will be by community title. You will own your land and house completely and have a share in the overall management of the village area.

Canyon Ranch: Antap Bali
Development Guidelines

Contents



CANYON RANCH: ANTAP BALI DEVELOPMENT GUIDELINES

Section A
ENERGY

A1.1 ENERGY OVERVIEW

Energy is an essential resource for economic development and human well being, yet it's use contributes to some of the largest environmental crises currently facing the planet.

Energy is a key factor in determining the ecological sustainability and integrity of a development. The primary areas of consideration in energy auditing are

- i. generation / production
- ii distribution
- iii Conversion
- iv consumption - energy usage

Key considerations

- Size of the development - potential energy consumption levels to support lifestyle and comfort expectations of staff, residents and visitors
- Local/ global pollution implications of fossil fuel generation & combustion: Greenhouse, acid rain (SO_2) etc.
- Energy transfer equation - energy source Vs electricity generated - leakage through reticulation grid - energy used
- Reliability and consistency of supply
- Back-up and emergency supply

AI.2 ENERGY AUDIT

A full energy audit to be prepared. Audit to include

- options for generation and technologies utilising renewable resources
- cost analysis of cumulative long term savings of energy conservation devices and strategies vs installation costs (pay-back period)

A1.3 SOURCES OF ENERGY

Non-renewable (imported energy):
- Grid electricity
- Liquid petroleum products
- Natural gas

Renewable (site generation):
- Wind
- Hydro
- Solar

Co-generation - to be identified

A2 AIMS

- Minimise energy consumed on site through appropriate design, technology and demand reduction strategies
- Utilise renewable on-site energy sources and design reticulation system to facilitate future augmentation of on-site generation to reduce grid consumption and fossil fuel dependency
- Ensure a reliable and consistent supply by integrating on-site /renewable electricity generation & co-generation with grid supply
- Give priority to the most energy efficient and least polluting options when selecting technologies and appliances
- Exploit co-generation options and opportunities for integrated systems

A Pattern Language - Alexander c et al 1977 - Oxford Uni Press

Transport:
When people use cars they occupy almost 100 times as much space as a pedestrian. Given many vehicles have one occupant, overall effect is to spread people out and keep them apart. The car's geometry may be breaking down society.
Benefits - immediacy, flexibility, door to door, privacy, accessibility

Life Cycle - The Stages

Need ceremony to encourage movement from one age to another. To grow up!

- Erikson - 8 phases

The Age Phases	Setting	Rites of Passage
1. Trust - Infant	Home,garden nursery	Birthplace- home
2. Autonomy - Young child	Home, common	Walking/ birthdays
3. Initiative - child	Play space, own space, n/hood animals	Venture into town forest
4. Industry - youngster	Home, school, adventure play club, city	Puberty rites, paying your way
5. Identity - youth	Cottage, teenagers town	Work, building, attraction
6. Intimacy - young adult	Household, small groups, family network	Building, social wealth birth of child
7. Generativity - adult	Work, community, room of one's own	Change in work
8. Integrity, older person	Settled, work, home, family, independant	Death, funeral, gravesites

Modes of Activity
- Importance of learning/teaching b/w age groups
- Opportunities to solve conflicts at each phase of life
- Design and buildings can hinder or help provide for the lifestyle process
  - Balanced lifestyle is principle guide for evolution of a community
    - Need full range of age groups, people at different phases
    - Need settings for each phase, cross-overs from one to the other phase, settings for inteaction between stages
    - Need sacred ground which is accessed via a "holy" journey
    - Teenage cottages - studios connected to houses
    - Elderly cottages

Design for the Full Human Lifecycle – Cradle to Grave

we need to consciously develop our awareness of the needs of the full human life cycle in order to plan systems that will be socially as well as environmentally sustainable.

Integrated social design considers the changing needs of growing children, youth, work pressures, child raising, working from home and the realities of aging, of health and physical disabilities

Planning has monocultured housing and human activities: commercial, industrial, mono-suburbs for specific ages and socio-economic groups, retirement villages. Many intentional communities have formed with groups from a similar age group, few have planned for future generations.

Humans are social animals – As a social ecosystem the diversity of human needs and nature is as critical as biodiversity of other species and their relationship with each other and their environment

Rural isolation - the tyranny of distance forces people back to town

- Lack of access to basic social support systems, day-care,
- lack of social contact with other women and children,
- high schoolers and teenagers isolated
- long commutes to town (work, shopping, health care etc)

Designing for human lifespan requires a multi-level approach which applies to and integrates

- individual house and home garden design
- design and planning of hamlets, villages
- bioregional infrastructure and services.

Strategies for integrated social design may include:

- Functional meeting places to bring people together, such as

Village green/ plaza/square with small business premises, in/outdoor cafe, outdoor & covered informal meeting areas, children's playground

easy pedestrian access from housing areas to village green – especially for elderly, single parent residents.

community centre with laundry facilities, kitchen, outdoor B-B-Q eating/meeting areas and children's play area. Picnic and campfire areas on prime locations near dams which are good for swimming and with open space for games and outdoor community events.

- patterning of foot, bicycle and motor vehicle movement.

network of foot/cycle ways connecting residential with recreational and community areas.

foot/cycleways designed to provide more direct access to key village social facilities than road network.

Pedestrian routes provide seating, opportunities for interaction, 'events' (vistas, views, changes in landscape, community art)

motor vehicle movement restricted and slowed for safety

people have more opportunities for casual social interaction as pedestrians than in an environment designed for motor vehicles.

- range of living environments many include

half acre rural residential (peri-urban) allotments in hamlets

suburban eighth and quarter-acre lots;

Compact housing of sixth to eighth acre allotments with shared landscape, gardens

Medium density townhouse and co-housing (e.g strata titled with shared facilities) expanded-houses (e.g. for singles)

elderly people – independent & requiring care.

Affordable rental accommodation

• diversity of living options incl rental accommodation fosters diversity of age and social groups

allows for people to change residence as personal housing needs change – avoid social dislocation of having to move away from a neighbourhood and one's friends.

• The relationship of community space activities and housing options e.g.

Medium density,co-housing and expanded house areas near community gardens and orchard & community facilities and/or village sgreen

elderly residents easily access to key social areas.

• To ensure individual privacy within an environment which provides a range of opportunities for social interaction.

• To maintain a realistic balance between residential areas, functional, recreational and productive community space and areas for wildlife and native forest and to place these various aspects in relationship with each other so that they are all readily accessible.

Brainstorm other strategies that can be included in a social plan…

Social Planning

Social Planning Research and Design Considerations for Public Open Space Spaces in urban and medium density environments – extracts from Wendy Sarkissian Lecture "Questions Social Planners Ask about Sites"
http://www.sarkissian.com.au

Public Open Space

- What is it?
- Who are the unintended users?
- How expensive and/or complicated is it to manage:
  - Security and surveillance?
  - Maintenance?
  - Management?
  - Vandalism and graffiti?

Crime, Vandalism and Management Context

- Rates Trends
- Hot spots, attractors and generators of crime
- Movement predictors
- Displacement
- Drug fashions and market
- Typical problems and issues

Externalities

- Traffic
- Parking
- Noise
- Light pollution
- Others?

How does it Work?

- Evidence of use and congruence between users' needs and the physical environment
- Congruence or "fit"
- The *potential* environment vs The *effective* environment (Herbert Gans)

People adopt and adapt places/settings/environments to make them their own.

Wendy Sarkissian's

15 Questions:

how does the design/development address the following…

1. Privacy
2. Personalisation
3. Climate
4. Wayfinding and orientation
5. Children's play
6. Young people
7. Adult socialising
8. Seating
9. Views
10. Older people and people with a disability
11. Comfort
12. Building interiors
13. Gardening
14. Balconies, terraces, porches, patios
15. The neighbourhood

Privacy

- Hierarchy of open spaces
- Privacy
- Territory

OBSERVATIONS: e.g. looks tight, not always clear definitions, where is the shared or common space?
QUESTION: has this been taken into account sufficiently.

Childrens Play

RESEARCH:

- Under 5
- Middle childhood
- Older children and teens
- Grandparents with children
- Children with a disability

Young People

- Often moved on and unwelcome in the public realm
- Need places to hang out

Adult socialising

OBSERVATIONS:
Taken different times of day, weekdays, seasons, public holidays
Need night--time and bad weather observations
QUESTIONS:
DO people come alone, in pairs, in groups?
Gender and age?

Seating

Two types of seating or furniture arrangements
Sociopetal:

- brings people together
- enables conversations and

Sociofugal:

- keeps people apart
- hinders interaction

Views

- Of Nature
- Prospect
- Refuge
- The "passing parade"
- Solitude
- Places people take their problems (the
- natural world)
- Views for safety (scanning)

Comfort

- Sun
- Wind (esp. at high levels)
- Acoustics
- Thermal comfort
- Building performance

Building Interiors

- Furnishability
- Personalisation at dwelling entry
- Personalisation inside dwelling
- Home office
- Children, Grandchildren
- Periods of illness
- Shared housing
- Cultural preferences
- Frontstage and backstage

The Neighbourhood

- Support for homeworkers
- Support for shift workers & people working long hours
- Dangerous at night? Crime?
- Inappropriate and threatening behaviour
- Gender and age issues
- Traffic
- Traffic noise

Public places should be:

•• **Accessible:** to everyone (including children, people with a disability and older people)

•• **Clear**: Conveys clear, appropriate and user--friendly messages

•• **Beautiful**: enhance the health and emotional well--being being of its users

•• **Safe** : Provide a feeling of security and safety

•• **Culturally appropriate**

•• **For all**: Encourage use by different users, without any one group's activities disrupting the others enjoyment

•• **Comfortable,** in regard to sun, shade, winds wind, etc

•• **Ownership**: Encourages community ownership and caring through involvement in design, and/or maintenance

From *People Places*, 1998.

Plazas/ Village Green

Critical success factors:

- *clarity of intended uses*
- *no spaces should be provided unless their use or uses can at least be suggested*

NB smaller, compact and appropriately furnished open spaces contribute much more to user satisfaction than large, unfurnished areas with ill--defined uses

Functional Elements in design

- Activity generators
- Territorial boundaries
- Natural surveillance
- Movement predictors
- Concealment and entrapment spaces
- Access control
- Natural ladders
- Target hardening
- Fencing and buffers
- Landscaping to:
  - define territory
  - reduce opportunities for concealment and entrapment
- Lighting
-
-
-

Governance and Decision Making Processes

1. Assess current or assess requirements for future community governance and decision making processes,

1.1 Responsibilities and duties of **community individuals and groups** are identified. These may include intentional residential and land-sharing communities, housing cooperatives, community organisations, community supported agriculture groups, community enterprise groups

1.2 Proposed or existing community governance and decision making processes are defined

1.3 Information on proposed or existing governance issues and arrangements is collated

> **Community governance and decision making processes** includes
> - governance of community resources, enterprise and activities,
> - meeting facilitation, negotiation, mediation and conflict resolution procedures, decision making methodologies,
> - consensus processes,
> - protocols, and codes of conduct
> - record-keeping and accountability processes

2. Develop options for community governance and decision making processes

2.1 Opportunities and constraints for development of community governance and decision making processes of options are identified

2.2 **Consultation** undertaken with community on options for community governance and decision making processes

Consultation processes include facilitation, discussion, mediation, conflict resolution, problem solving, analysis and evaluation methodologies, forum, active listening, consensus building, trust building, and participatory planning activities

2.3 Options are evaluated in consultation with community through detailing advantages and disadvantages for each

3 Report on preferred options for implementation

3.1 Preferred options selected for implementation based on comparative advantages

3.2 Options for community governance and decision making processes are based on sufficient, valid and reliable information and analysis.

3.3 Options for community governance and decision making processes are consistent with **community/group values**, policies, guidelines and procedures.

> **Community/group values** may include:
> - vision,
> - aims, objectives,
> - by-laws,
> - philosophy, ethics,
> - cultural and lifestyle factors,
> - equity,
> - individual/member rights and responsibilities

3.4 Options for community governance and decision making processes can be implemented and provide for decision-making to be made in time for appropriate action to be taken.

Twelve Conflict Resolution Skills

The following is a brief summary of the standard package of twelve skills or "tools" which form the core framework of the Conflict Resolution Network program.

1. The Win/Win Approach:

In conflict we aim to design solutions that work for both parties. The first step is to understand the underlying need for each side. Frequently this is for security and recognition. Where a Win/Lose assumption is the cause of a limited view or limited options we take a new look at conflict and co-operation, and the possibilities for mutual gain. What is my real need here? What is theirs? Do I want it to work for both of us?

2. The Creative Response:

Each conflict is an opportunity for interaction and communication, which might never have occurred before. Individuals and organisations are encouraged to move beyond blame and shame, right and wrong and into the possibilities which present economic and social realities. Where there is a severe negative approach and limited sense of possibility we need a creative response. We can start by seeing conflicts as opportunities. Though conflicts are frequently seen as crises, they may also be regarded as an invitation for change. What opportunities can this situation bring? Rather than "how it's supposed to be", can I see possibilities in "what is"?

3. Empathy:

Seeing the other person's point of view. Especially where there is ignorance of, or difficulty hearing, the "other" point of view and different values. Recognising the motivations behind apparently uncaring behaviour of other people.

Each individual or organisation needs to ask:-

* What is it like to be in their shoes?
* What are they trying to say?
* Have I really heard them?
* Do they know I'm listening?
* Have we really understood their dilemmas?
* Do they know we are aware of the difficulties they encounter?

4. Appropriate Assertiveness:

Where passive, fearful, resentful responses are present, or where aggressive judgements are being presented it is helpful to know your needs and rights and how to state them clearly. What do I need to change? How will I tell them this without blaming or attacking? How will we tell them of our needs without eliciting a defensive response? Is this a statement about how I feel, rather than what is right or wrong? How can we be soft on the people and hard on the problem?

5. Co-operative Power:

Mutual co-operation builds root-level security and trust. In the nuclear age, power play between nations becomes more and more inappropriate. The appropriate response in our times is a new dynamic co-operation. This response is applicable to individuals and organisations where disempowering "rackets" are being played out, or where power is being suppressed. The difference is between power over someone else and power with someone else. We can face the problem together when we are soft on the personalities and hard on the problem. Am I using power inappropriately? Are they? Instead of opposing each other, can we co-operate?

6. Managing Emotions:

We cannot overestimate the importance of managing emotions when handling one's own anger and frustration. Where emotions are causing a block to action, either exploded or suppressed. Expressions of unbridled emotion, such as hostile rhetoric, are particularly damaging. What am I feeling? Will telling them how I feel help the situation? What do I want to change? Have I removed the desire to punish from my response? What can I do to handle my feelings?

7. Willingness to Resolve:

This fundamental prerequisite needs to be examined. If this willingness can be created, solutions will be found. If it is impossible to create this willingness, chances are there is a secondary gain in continuing this conflict. Where this is evidenced by disproportionate "knee-jerk" reactions, extreme attractions or dislikes are present. Should the secondary gain be addressed in some more appropriate manner? Do I want to resolve the conflict? There is a need for understanding the role that resentment plays in preventing successful negotiation. Is the resentment being caused by:

* something in my past that still hurts?
* something I haven't admitted to needing?
* something I dislike in them, because I won't accept it in myself?

8. Mapping the Conflict:

Drawing up a map of the conflict which includes looking at the underlying needs, values, objectives and visions of the participants. This is useful when confused, there is lots to be considered, or there is difficulty finding common ground. It is an excellent tool as preparation for negotiation. The questions we ask are: What's the issue, problem or conflict? How many parties are there to this conflict? What are the needs anxieties and fears of each? This mapping will reveal areas of common interest and highlight difficulties to be addressed.

9. Designing Options:

Options are developed without immediate judgement because what may at first seem impossible may seed good ideas. Creating a smorgasbord of choices from which conflict participants can choose action more appropriate for both parties. When solution-hunting begins and where "bottom lines" are emerging. What are all the possibilities? Don't judge them yet. Which options give us both more of what we want? Be creative, mix and match.

10. Negotiation Skills:

Individuals, organisations and nations need to set clear goals when negotiating, with due regard to fair play and justice for all parties. The benefits each party can give to the other should be explored. Objections should not be ignored; they need to be included in the design. There should be careful attention to preparing clear contracts. A well written contract defines the perimeters and minimises future disagreements. Mutual satisfaction is the basis of good contracting. Creating suitable environments for working together towards resolution; synthesising different interests; working towards new balances, agreements and contracts. The secret is getting together to work it out. What do I wish to achieve? How can we make this a fair deal - both people winning? What can they give me? What can I give them? Am I ignoring objections? Can I include them? What points would I want covered in an agreement? Would something help them save face? Is saving face important to me? Do I need something?

11. Mediation:

Understanding the special role of the mediator and the importance of neutrality. When groups have to act together for planning, problem-solving and decision-making. Particularly when getting together is difficult or hostile. Conflicting parties need to ask: Can we resolve this ourselves or do we need the help of a trusted third-party? Who could take on this role? Is mediation the best role for me in this? If so, how could I set up and explain my role to both parties? When an individual is offering to mediate, it is necessary to ensure that both sides are fairly represented and that the right environment is created for parties to open up, understand each other and create their own solutions. What might help this?

12. Broadening Perspectives:

In conflicts it is vital to see the whole picture and not just see one party's point of view. Recognising your view as one point of view and understanding the other's point of view as also valid and necessary as part of the whole. When people are considering only the impact on themselves or their own work group or neglecting long term consequences. Am I seeing the whole picture, not just my own point of view? What are the effects of this beyond the immediate issue on other people or groups? Where might this lead in the future?

SUMMARY: THE PROCESS OF CONSENSUS

Definition: Consensus is a process for making decisions, which seeks to resolve conflicts peacefully, and cooperatively develop decisions, which all participants can support.

For consensus to function, five basic elements are necessary:

1. Willingness/desire to share power
2. Conscious and informed commitment to the process of Consensus
3. A common vision/goal
4. Solid agendas
5. Effective facilitation

Basic Belief: Each person has an important part of "the truth" to share.

Values: Respect, trust, cooperation, non-violence, good will, sincerity, diversity, inclusiveness, responsibility shared by the actions of the group.

Three steps in the Process of Making Decisions:
Introduction
Discussion
Decision Making

Essential Functions:
Facilitator
Guardian of the Archives
Guardian of the Time
Next Agenda Planners
Patrons of Agenda Items

Optional Functions:
Writers
Guardians of the Door
Set up and Clean up Team
Vibes Watcher
Guardians of the Peace

PROCEDURES:

There is never voting in the process of consensus. Before taking a decision, an idea or proposal is introduced, it is discussed and, if necessary, modifications are made. For important proposals the introduction, discussion and decision-making may not be made in a single meeting. If consensus is not reached, a proposal may not be put into effect. The intention is to resolve any concern or conflict relating to a proposal in a peaceful manner so that all participants can support a decision.

Decision making Options:
Block — Stand Aside — Give Consent

DRAFT LANDSCAPE CONCEPTS

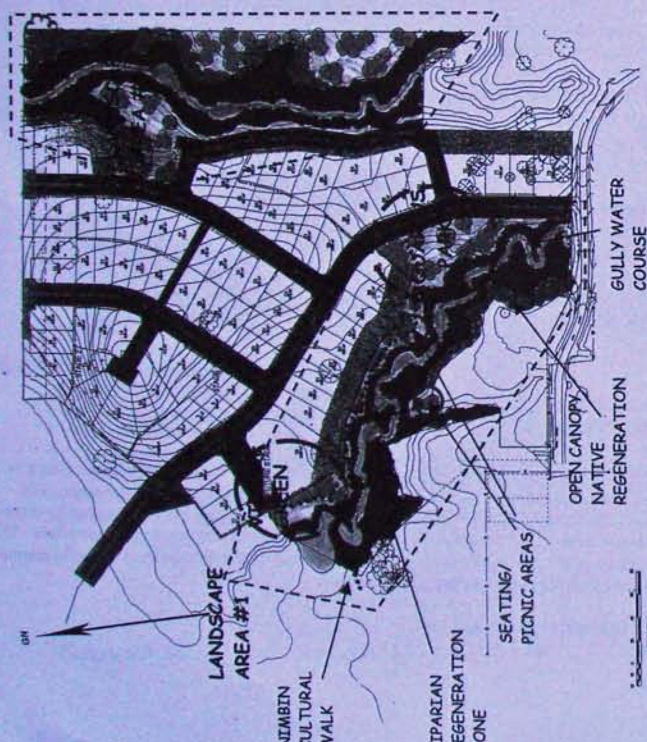
NIMBIN ECOVILLAGE

NIMIN ECOVILLAGE P/L
PROPOSED SUBDIVISION
LOT 641 DP1063413
NIMBIN

NOTE: BASE PLAN "REVISED LOT LAYOUT, STAGING & AREAS" - PREPARED BY ASPECT NORTH

LANDSCAPE CONCEPT
Prepared by
ROBYN FRANCIS
PERMACULTURE EDUCATION
PO BOX 379 NIMBIN NSW 2480
December 2005

Disclaimer: These landscape concepts were prepared for Tareeda Properties. Concepts indicated in this plan are subject to final design considerations, staging of development, council approval and to other relevant authorities and legislation.



NIMBIN - Sense of Place
Designing our Future
Community design for Nimbin village centre

Permaculture Systems Design & Consulting, PO Box 379 Nimbin 2480 Ph/Fax 89 1755

Please complete the questionaire and hand it in to the Permaculture Systems team during the community consultation workshops, Public meetings, Public Display at the Hall foyer (Monday 22nd to Thursday 25th 9am-4.30pm), or post to Permaculture Systems, PO Box 379 Nimbin.
Feel free to submit further ideas and details on extra paper.
Thanks for your input

Community Consultation Questionaire:

1) What does Nimbin mean to you?__________

2) What do you like best about Nimbin? __________

3) What do you dislike about Nimbin? __________

4) What opportunities do you think Nimbin has missed? __________

5) What are your 3 major concerns for Nimbin's future?

i. __________
ii. __________
iii. __________

6) How do you think the village centre could better serve the needs of the community?

7) If you had 3 wished for Nimbin what would they be?

i) __________
ii) __________
iii) __________

8) Please number from 1 to 7 the things you think are most important in order of priority

- ❑ Traffic calming
- ❑ More car parks
- ❑ Trees along roads to town
- ❑ People places in main street
- ❑ People places away from main street
- ❑ Proposed road & parking west of shops
- ❑ Footways linking Centre with other village areas
- ❑ Permanent 'flea-market' area
- ❑ Trees & landscaping
- ❑ Better lighting
- ❑ Bicycle ways & parking
- ❑ New parks
- ❑ Alsop Park

Comments: ______________________

9) Would you like to see Nimbin become less economically dependent on Lismore? Yes / No

Comment: ______________________

10) What kind of employment, business and enterprise opportunities do you think would be appropriate for Nimbin? ______________________

11) Nimbin is unique - how can this be expressed in the landscape of the village centre and new village areas? ______________________

12) Would you like to see a theme for the landscaping and future planning of Nimbin?

13) Which of the following themes/ concepts do you think are most suited to Nimbin's future direction ?

- ❑ Rainforest
- ❑ Bushfoods
- ❑ Tidy Town
- ❑ Eco-village
- ❑ Permaculture
- ❑ Historic
- ❑ Arts & Culture
- ❑ Bundjalung heritage
- ❑ Rustic/rural

Other suggestions: ______________________

Information about yourself:

i) Age: ❑ under 20, ❑ 20-35, ❑ 36-50, ❑ 51-65, ❑ over 65

ii) How long have you lived in/near Nimbin? ______________________

iii) Do you live: ❑ in the village, ❑ within 5km, ❑ 5-10km, ❑ over 10km

iv) What do you do in Nimbin? ❑ work, ❑ shopping, ❑ laundry, ❑ socialising, ❑ entertainment, ❑ other: ______________________

v) How often do you come to Nimbin? ❑ every day, ❑ Mon-Fri, ❑ weekends ❑ more than once a week, ❑ less than once a week, ❑ Other______

Lismore water

LISMORE WATER – A BUSINESS UNIT OF LISMORE CITY COUNCIL

lismore city council

PROTOCOLS for the Nimbin Water Supply Committee (NWSC)

September, 2001

	NWSC OPERATING PROTOCOLS		REPORTING & SUPPORT PROTOCOLS
12	Members of the public are invited to attend as observers and to make a presentation to the NWSC as individuals or on behalf of an organization.	12	Should a member of the general community wish to have a matter raised at a NWSC meeting then the process to follow is to request a member of the NWSC to raise the matter at the meeting. The members on the NWSC are there to represent the community and the community should use the members as a means of two-way communication between the NWSC and the general community.
13	Working Groups may be set up to address specific issues and achieve specific tasks. In general, these Working Groups are not to make decisions on behalf of the NWSC. One exception to this is the Communication Strategy Working Group.		
14	Members of the NWSC have the option to designate an alternative member to attend the meeting under extenuating circumstances in the member's absence. There shall be only one person designated as an alternative for each member. This system of alternative members may be used to represent hitherto under-represented groups. Alternative members should live, or be actively involved, in the community of Nimbin and have a direct interest and involvement in water issues. The primary member must keep these alternative members up-to-date on the workings of the NWSC. To make this easier, alternative members should be individuals who are in regular contact with the primary member, e.g. member of the household, close friend. Carol Davis / Janaka Weeraratne at Lismore City Council are to be notified in writing seven (7) days prior to the meeting as to the choice of this alternative member. Any changes to the choice of this alternative member should also be notified in writing.		

Bullying Techniques

- Spreading gossip, false or malicious rumours about a person to cause damage to that person,s reputation.
- Humiliating a person in front of others
- Being the victim of loud and abusive, threatening, or derogatory language…..usually in front of others,
- Undermining work performance by deliberately withholding information vital for effective work performance.
- Bullies try to achieve the victim,s isolation

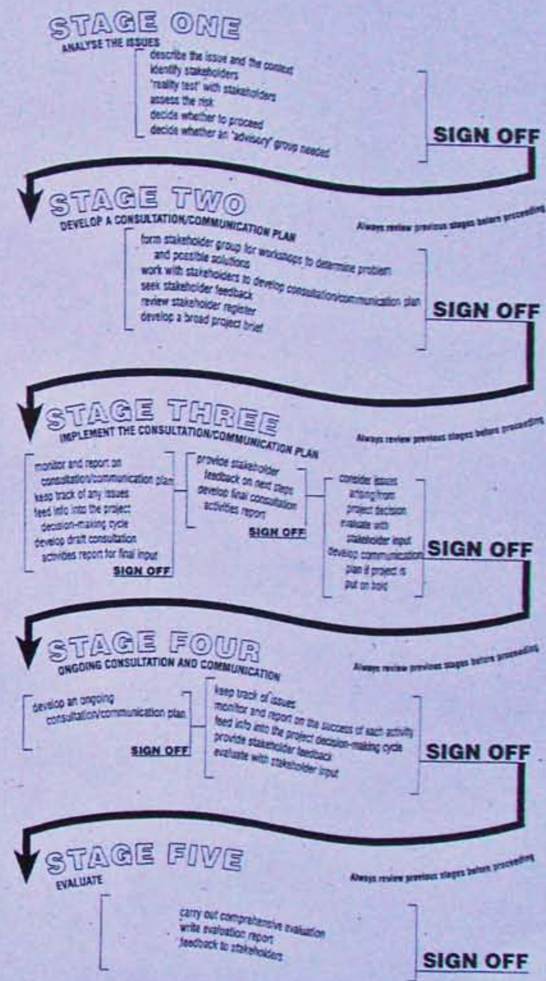
Physical Effects

- Stress headaches and illnesses
- Stomach disorders and skin rashes
- Anxiety and depression and self blame.
- Disempowerment
- Anger and irritability.
- Loss of concentration.
- Loss of self esteem & lowered self confidence.
- Panic attacks
- * Sleep disturbance

Dealing with It

1. Identify clearly who is responsible…target the leader…. separate bully from supporters
2. Take notes where and when it happened .
3. Talk to people about it….keeping quiet increases the sense of isolation which the bully is trying to achieve .
4. Refrain from retaliateing.
5. Complain formally.S

THE CONSULTATION PROJECT CYCLE



intro

Links:

Global Ecovillage Network (GEN)
http://gen.ecovillage.org/

Cohousing Assn of US
http://www.cohousing.org/

ABC Radio documentary series with interviews, resources and case studies of intentional communities in Australia
www.abc.net.au/rn/utopias