LNE94-045 Publication

SCAS Teaching Series No. T97-1
Department of Soil, Crop and Atmospheric Sciences
Cornell University, Ithaca, NY 14853 USA
September 1997

CONCEPTS OF SUSTAINABILITY AND THE PASTURE ECOSYSTEM

Lori J. Unruh and Gary W. Fick

SUMMARY

The pasture ecosystem provides useful examples of ecological principles that characterize environmental sustainability. Five of those principles are defined in this document and then described as they occur in a dairy pasture in the northeastern USA. These principles can be used as a starting point for understanding the ecological basis of agricultural sustainability.

Sustainability as a word captures the whole concept of preparation for the future. Our challenge is to change the word into understanding that will allow us to evaluate present systems and design better ones. Applied to agriculture, the concept of sustainability can be illustrated by a three-legged stool (Fig. 1). Our food supply (the seat) comes almost entirely from agriculture, which in turn is supported by three components (the legs) that are interrelated in agriculture. First is the **ecological** component made up of the laws of nature. For agriculture to be sustained, people must also be able to make a living in farming, and thus there is an **economic** component. Finally, agriculture also exists and changes in the context of the values and institutions of a society or culture, and thus there is a **social** component as well. Our goal here is to take a closer look at the ecological component, identifying fundamental principles that can serve us as we evaluate and design food systems for sustainability.

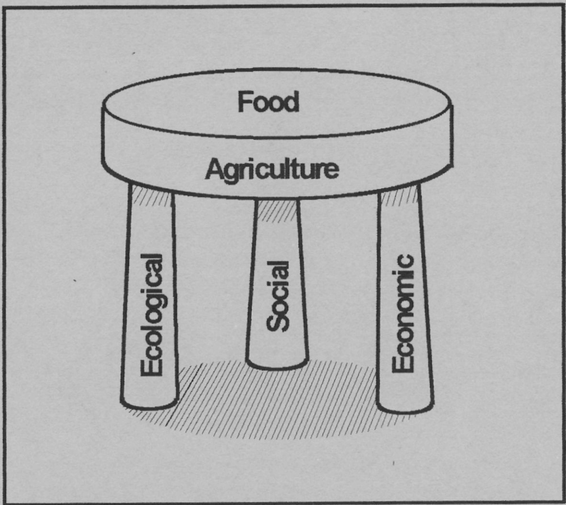

Figure 1. The three-legged-stool model of agricultural sustainability.

We have chosen the dairy pasture as the reference point for our study. First of all, the dairy pasture is a familiar agro-ecosystem in the Great Lakes region of North America. Even city dwellers who may have never stopped on a farm can probably identify a dairy pasture as they drive down the highway. A dairy pasture is also an important source of food. Worldwide, milk ranks in the top ten as a source of food dry matter, making it the most important of all animal products in the food system. The family dairy farm based on pastures is also one of the most sustainable agriculture systems known. Its archeological history in western Europe goes back over 2500 years, and it has been a successful transplant into northeastern North America and several other temperate regions in the world. The dairy pasture is a relatively complex agroecosystem. Complexity may contribute to sustainability, and it certainly makes the dairy pasture a good place to look for ecological principles that undergird sustainable agriculture.

Before we look at the pasture ecosystem in detail, we need to know what we are looking for. Many scientists interested in agricultural sustainability have argued that the most sustainable ecosystems are natural ecosystems, those designed by nature. With this in mind, we should be looking for ways in which the pasture ecosystem is like a natural ecosystem. Phrased as questions, we should be asking the following:

- How is a natural ecosystem designed?
- Where can we see the natural pattern in a pasture?

There are at least five ecological principles that can be observed in pastures and that answer the questions above.

THE FOOD PRINCIPLE

With a little thought, almost everyone would agree that milk is the food for humans that comes from a dairy pasture. But ecologists see food in everything that is or has been alive. Here is the first ecological principle: ***everything in an ecosystem that is organic is food.*** Not only do the cows eat the grass to make the milk which becomes food for humans, but other creatures are also eating the body wastes (dung and urine) that come from the cows. Energy is flowing through the ecosystem from producer to consumer or decomposer organisms in a pattern that is called a food web (Fig. 2).

To help us think about the relationships in a food web, we will base our comparisons on an area of land called an acre. An acre (43,560 ft^2) is about the size of the playing area of a football field. (The playing area is actually 1.1 acres). At the start of the energy flow pattern is

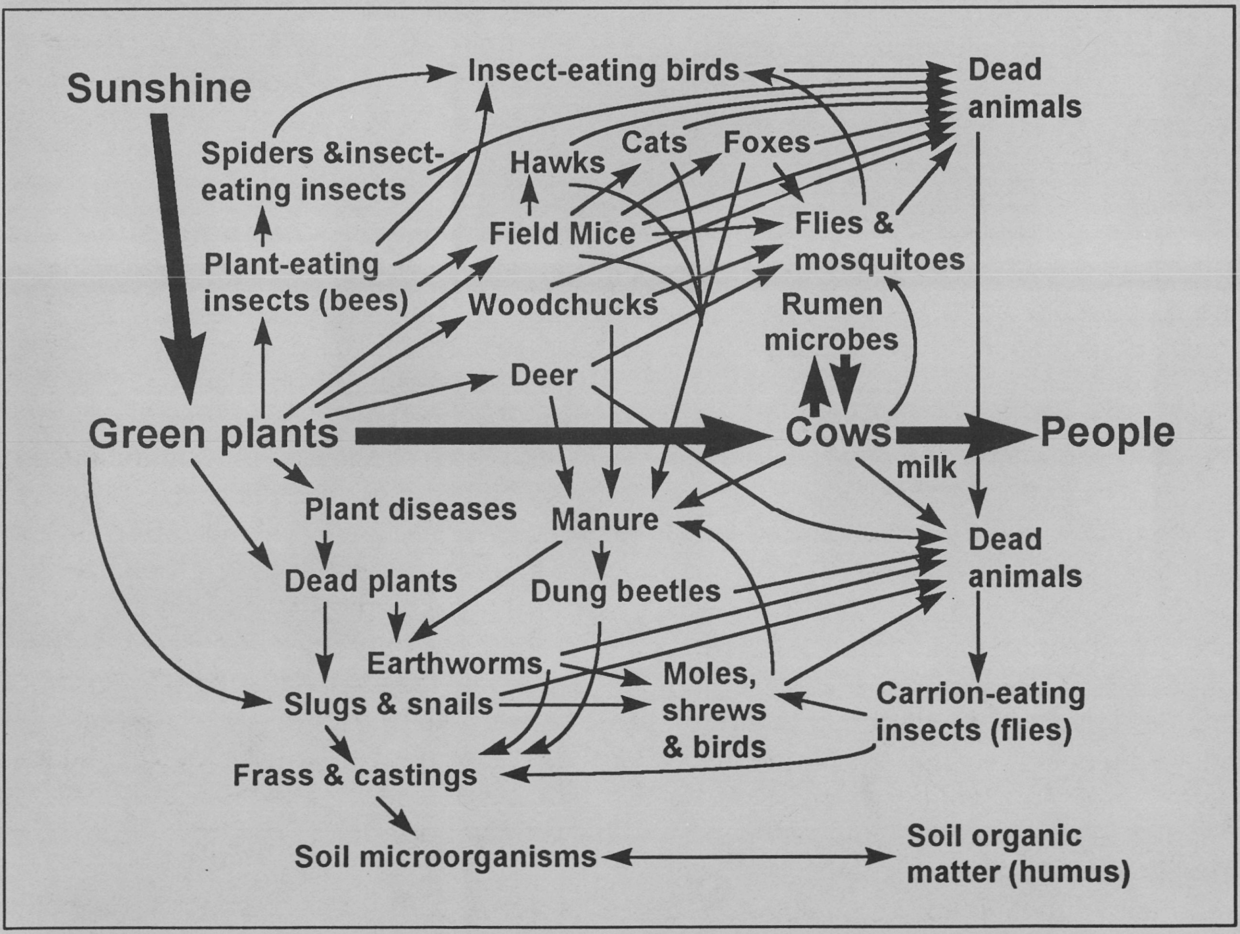

Figure 2. A simplified food web for a dairy pasture in the Great Lakes region. The heavier lines show the main pathway of energy flow to food for people.

sunshine. Sunlight energy not only warms the earth and drives our weather systems, but some of it also is intercepted by green plants. Most of the intercepted energy is used to evaporate water through the plants, thus providing natural air conditioning that protects living enzymes in green leaves. Photosynthetic enzymes in those leaves capture a portion of the sunlight energy as carbohydrates, proteins, and fats used by the plant for growth and maintenance. During the growing season when temperatures are warm enough (from April to November in New York State), sufficient sunlight energy is captured by plants to grow from 5,000 to perhaps 20,000 pounds of new plant organic matter on an area of 1 acre. Some of this is in the obvious green leaves, stems, and flowers, but up to half of it may be underground in the plant roots.

The dairy cow out on the pasture is the most obvious consumer of the nutrients in the green leaves. Thus energy flows from the plant to the cow. The typical New York dairy farm has about 2 acres for every cow, and a typical cow might weigh about 1200 to 1500 pounds. That cow can produce from 14,000 to 25,000 pounds of milk in a year. (The higher production level requires a diet with more nutrient intake than the cow can get from pasture alone.) When the water in the animal body and milk is accounted for, an acre of pasture supports about 500 pounds of dry matter in cows that produce about 1000 pounds of dry matter in milk. That is enough milk to supply all the dairy products consumed by about 15 Americans during 1 year.

The interesting thing about energy flow is that the amount of energy available is reduced at every step. Thus, your food supply depends on how close you eat to the source (sunshine captured by plants). Somewhere between 20 and 30% of the energy in the pasture plants is converted to energy in milk. If people could eat grass instead of drinking milk, the food supply would be increased. The problem of course is that people cannot live on grass. Thus the cow is increasing the food supply by converting something we cannot use for food into something that we can use. If we could grow wheat or soybeans on the same land, a strict vegetarian diet would provide more food for humans. However, we need to consider some additional ecological principles presented below before we come to any conclusions.

Another question that we are ready to address is why is so much energy lost in each step. The answer is that each organism is using up energy to stay alive and reproduce. Perhaps 30 to 45% of the energy captured by green plants goes into plant respiration. An animal has an even higher energy demand to stay alive. On average, only about 10% of the energy is passed in each step in a food web. In ecological terms, the 20 to 30% transfer through milk is very high. One important reason for this is that we do not have to kill the cow to get the milk. A dairy cow has a very long food producing life compared to animals that are eaten when young.

A cow also has a special digestive system that illustrates another common feature of the food and energy transfer

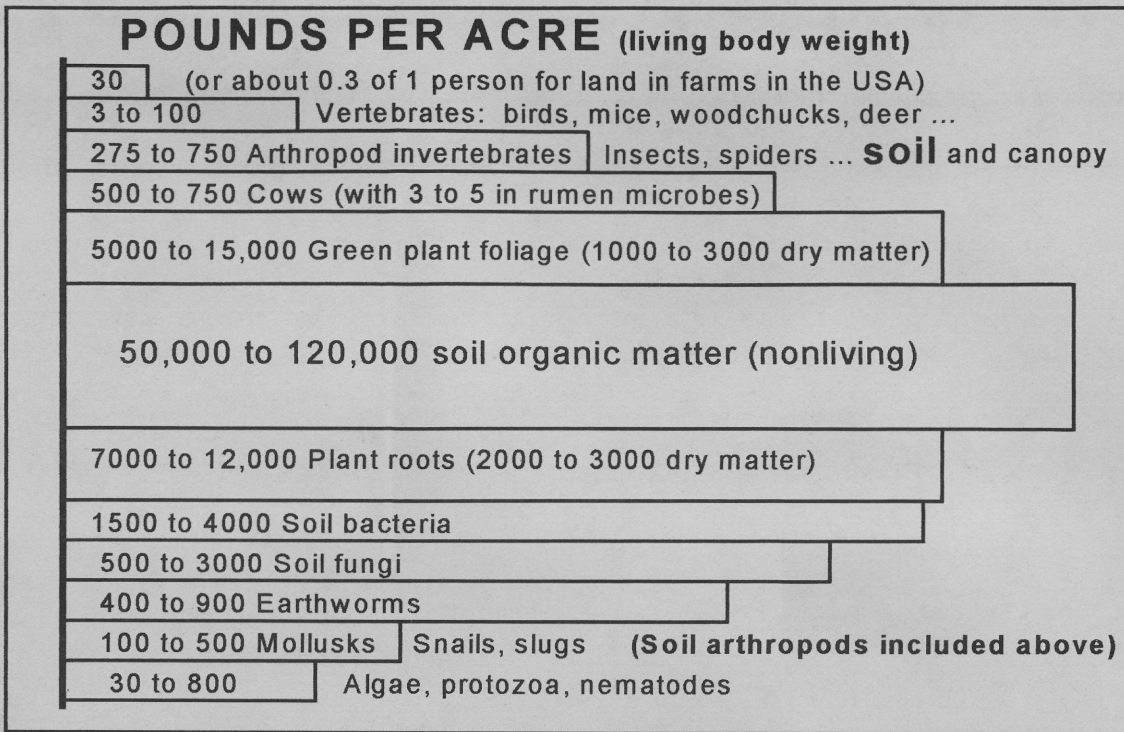

Figure 3. The approximate biomass of different kinds of organisms supported by a typical dairy pasture with a fertile soil.

process. The first compartment of a cow's stomach is called the rumen. Microorganisms in the rumen (bacteria, protozoans, and fungi) live off the food that the cow eats. In turn, they themselves are digested by the cow to provide vitamins and amino acids not in the original diet. The cow's body may also contain parasites that live off the cow without providing any benefits in return. Blood-sucking flies and mosquitoes also get their food energy from the cow, and eventually the cow may be sold, slaughtered, and made into bologna or hamburger for human food.

The energy-flow pattern in a dairy pasture has many other avenues than the one that brings milk to our tables (Fig. 2). In addition to cows, snails, insects, field mice, woodchucks, and deer may be grazing the plants found in the pasture. Birds and foxes may be dining on some of these creatures in turn. Bumblebees may be collecting flower pollen as food for their larvae and some species of mice may be feeding on the larvae in the bee nests. Barnyard cats may be searching the pasture for mice, and barn swallows may be eating the flies and mosquitoes that feed on the cows.

All living organic matter eventually dies, and the energy flow continues through the process of decomposition. Cow dung, which might be carrying the eggs of cattle parasites, is collected and consumed by beetles or other dung-feeding organisms. Slugs and snails eat dead as well as living plant material. The larval maggots of flies live on the decomposing bodies of animals that die in the pasture. Partially decomposed organic matter becomes the food of earthworms, fungi, and a whole host of soil microorganisms. Eventually, all the food energy in organic matter is used up and the raw materials of plant growth are returned to the soil and air from which they came.

A working food web is made up of large numbers of many kinds of organisms. Fig. 3 is a summary of what is known about the biomass of organisms that make up the food web in a dairy pasture.

THE NO-WASTE PRINCIPLE

Ecosystems depend on a continuing supply of sunlight energy because the energy captured as food gets used up (changed in form) as it flows through the food web. There is no such supply of new matter to hold the energy in the chemical bonds of life. Thus, there is a second ecological principle to go with the first: ***in an ecosystem, nothing is wasted.*** Sometimes we restate the first principle by saying that energy flows, and the second by saying that matter circulates.

Major ecological cycles have been described for water, carbon, nitrogen, phosphorus, and the other nutrients that are essential for life. On a global scale, these cycles are not broken, but when we think about a dairy pasture, we see that exports and imports can occur on a local scale. These changes can have serious consequences for the sustainability of agriculture, and we need to think about what the consequences are and how they might be managed.

The water cycle involves the processes of evaporation, which moves water from the liquid phase in oceans, lakes, streams, and soil into the vapor phase in the atmosphere. Cloud formation and precipitation bring the water back to earth's surface. Water is essential for life, be it soil water for plants and soil organisms or drinking water for larger animals including humans. Water is taken up by plant roots in the soil and evaporated through leaves in a process called transpiration. Thus plants will dry out the soil if there is not regular replenishment of water, usually by precipitation. Plants that grow in a pasture generally have roots that improve the soil's capacity to take up water. Some ecologists argue that pastures improve stream flow and groundwater supply by allowing more rain water to soak into the ground. Farmers must tap these water supplies to provide drinking water for their cattle, (from 25 to 50 gallons per day for a single dairy cow), and their ponds and water tanks often benefit the wildlife that also live nearby.

If we begin the carbon cycle with carbon dioxide (CO_2) in the air (Fig. 4), it is transformed by photosynthesis into the organic matter that moves through the food web (Fig. 2). The organic matter is eventually burned by respiration or fire to release the carbon (mostly CO_2) back into the air. Wood and fossil fuels are the stores we usually picture as accumulators of organic matter in the carbon cycle, but soil organic matter is also important. There is often from 50,000 to 120,000 pounds per acre in soil, with the higher amounts occurring under pastures. Increasing the amount of pasture may help counteract the increase in CO_2 in the atmosphere caused by burning fossil fuels and wood. However, microbial digestion of forage in the rumen of a cow produces methane (CH_4), which has a larger effect on climate change, molecule per molecule, than CO_2. Thus, there may be little net effect of pasture on global warming through the carbon cycle. However, if fields of corn and wheat are planted into pastures, there will be more carbon stored in the soil.

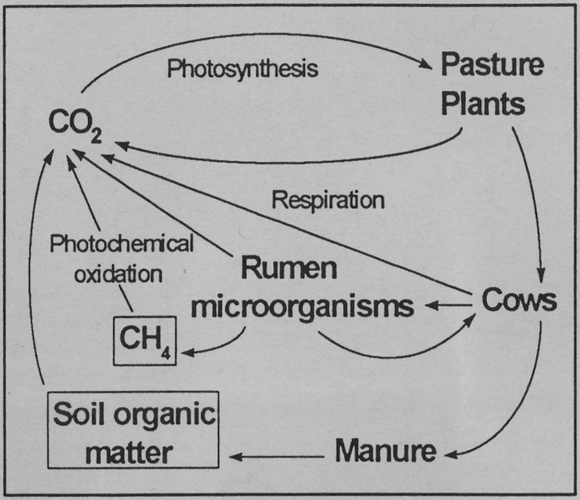

Figure 4. A partial carbon cycle emphasizing methane (CH_4) and soil organic matter, elements affected by increasing use of dairy pastures.

Nitrogen limits the productivity of most natural ecosystems. When nitrogen is in short supply, certain soil bacteria and *Rhizobium* living in the nodules of the roots of legumes are able to transform dinitrogen gas (N_2) in the atmosphere into reduced nitrogen ($-NH_2$) in living matter. This nitrogen moves through the food web, eventually to be delivered to decomposer microbes in the soil. In pasture soils, much of the decomposing nitrogen is converted to ammonia (NH_4^+) and then nitrate (NO_3^-), both of which can be taken up by plant roots. Lightning will also convert some N_2 to NO_3^-, which enters the soil with rainfall. Some nitrogen accumulates with carbon in soil organic matter to be recycled only very slowly. Nature is very conservative with the use of nitrogen, usually cycling it many times from living to dead organic matter to soil and back to living organic matter. However, ecosystems are continuously losing nitrogen, so regular inputs of new nitrogen are needed. In a pasture, some nitrogen (as well as all the other nutrients) is exported in the milk and animals that leave the farm. Soil microbes, especially *Rhizobium*, carry out the important function of resupplying the exported nitrogen.

If nitrogen levels in the soil become high, the microbial processes that capture nitrogen are inhibited. If a nitrogen-rich soil becomes wet, NO_3^- may be leached to the groundwater or converted to N_2 gas by anaerobic bacteria and escape to the atmosphere. Ammonia can volatilize into the atmosphere from urine patches and be carried down with rain into a distant ecosystem.

Pastures produce more when there is an abundance of nitrogen. The challenge for farmers is to manage the soil nitrogen supply so that there is good pasture growth without leaching of NO_3^- to groundwater. Vigorous grass growth will use a significant amount of nitrogen, but excess nitrogen cannot be destroyed. It must be taken up by plants, remain in the soil, cycle back to the atmosphere, or leach to the water table. Too much in the soil can become a pollutant in our drinking water.

Mixing of the atmosphere tends to reduce the local variations in the water, carbon, and nitrogen cycles. Most nutrient cycles do not have an atmospheric phase and thus import/export imbalances become even more critical. Wetlands tend to be natural sponges for nutrients moving in water from other ecosystems higher in elevation. The long-term sustainability of dairy farming in Europe was based on the fact that some pastures were maintained on wetlands so that nutrients captured there could be carried back in livestock manure to the higher elevation fields where they originated. Sustainability requires either "tight" cycling or replenishment of nutrients lost by removal from the soil and export out of the system.

In some places modern dairy farming has resulted in cow populations that exceed the productive capacity of the land. In such cases, farmers usually replace pastures with corn (because it provides more feed per acre) and buy much of their livestock feed from distant sources such as grain farms in the Midwest. Most of the nutrients in the imported feed end up in the livestock manure which is spread on the farmer's corn fields. Some of those imported nutrients accumulate in the soil. If the soil is eroded into surface water, accumulated phosphorus can cause eutrophication. Over long periods of time, accumulated potassium can result in such high levels of potassium in plants that the feed actually becomes toxic to cows.

THE SOIL PRINCIPLE

Nutrient management is just one aspect of taking care of the soil. In a natural ecosystem, soil health is maintained by maximizing the living soil components so essential to the food web and nutrient cycles. Should the protective plant cover be lost, it is replaced as quickly as possible. In fact, ***in an ecosystem, there is a premium on protecting the soil.*** This third principle is very important because the soil is usually the part of an ecosystem that is slowest to recover should it be damaged.

In the climates of the world where dairy farming is most important, forests are usually the natural vegetation. Forests are very effective in protecting the soil, but so are pastures on all except the steepest slopes. The fine, fibrous roots of pasture grasses bind the soil to reduce soil erosion and provide good supplies of organic matter to feed the soil life forms so important in both food webs and nutrient cycles. Most pasture plants are perennials (Table 1) and are widely recognized as soil builders. Including pastures in crop rotations is a traditional practice allowing soil to recover following production of annual grain crops and vegetables such as corn, wheat, potatoes, and tomatoes.

The soil principle is illustrated by the agricultural history of the region around the Great Lakes. Forests were originally cut down so that wheat could be grown, even on steep slopes. With annual tillage for planting, sloping soils eroded and the land became too unproductive to support economical yields. The poorer land was then abandoned for agriculture and allowed to grow back into forests. But the damage was done. In 100 to 200 years under natural succession to forests, those soils have not regained their original fertility.

When farmland is abandoned, it is possible to observe how quickly the remaining soil is covered by plants. There is a succession of different kinds of plants from year to year that progressively binds and restructures the soil to resist erosion and support a complex food web and nutrient cycle. In our climate, even pasture is eventually replaced by forest unless some kind of management is used to keep out the weedy trees. Fortunately, pastures are already good soil protectors, but weeds of all kinds cover and protect the soil, build up its organic matter content, and, especially in the case of trees, hold the soil together even on steep slopes. Some soils are too steep for pastures and should be in forest.

THE SUBSTITUTION PRINCIPLE

The fact that pasture can substitute for forest in protecting many soils is not unusual. There are often several alternatives for an ecological function, and so we have the fourth principle: ***in an ecosystem, there is usually a substitute.*** Having a substitute available depends on the biological diversity of an ecosystem. Agricultural systems that are based on crop monocultures have relatively little biological diversity compared to natural ecosystems. A pasture is much more like a natural ecosystem because of the amount of diversity present in its plant community. Diversity in the plant community leads to increased diversity in the consumer and decomposer communities that feed on those plants. The result is more natural enemies of plant pests and higher levels of natural biological control. Relatively little pesticide is needed or used in pasture production.

The easiest way to observe biological diversity in a pasture is to look at the plant community (Table 1). Each species of green plant provides an alternative for the function of photosynthesis. Grasses are usually most abundant, with several species being fairly common. One will typically find orchardgrass, quackgrass, and Kentucky bluegrass, each capable of substituting for the other in photosynthesis should some ecological stress reduce the abundance of one species. Although they are all photosynthetic, each species performs its function in a somewhat unique manner by having different life-cycle and growth characteristics (Table 1). For example, annual grasses like annual bluegrass and crabgrass can quickly fill in bare areas where the soil is exposed.

Legumes are also commonly found in pastures. The short stature of white clover helps it avoid being overgrazed, but birdsfoot trefoil and red clover can substitute in the function of fixing nitrogen symbiotically with *Rhizobium* bacteria in root nodules. White clover and Kentucky bluegrass make a common legume/grass association of complementary species. Both tolerate close, continuous grazing and the legume provides nitrogen for the grass.

Table 1. Examples of plants that contribute to the biodiversity typical of pastures in the Great Lakes region.

Group	Family	Species	Characteristics
Grasses	*Poaceae*	Orchardgrass	Perennial, tall, bunch, very early
		Quackgrass	Perennial, tall, spreading, early
		Kentucky bluegrass	Perennial, short, spreading, early
		Timothy	Perennial, tall, bunch, early
		Annual bluegrass	Annual, weedy, short, early
		Large crabgrass	Annual, weedy, short, latest
Legumes	*Fabaceae*	White clover	Perennial, short, spreading, later
		Birdsfoot trefoil	Perennial, taller, bunch, later
		Red clover	Perennial, tallest, bunch, later
Forbs	*Asteraceae*	Dandelion	Perennial, short, bunch, very early
		Thistles	Perennial or biennial, weedy, latest
	Plantaginaceae	Broadleaf plantain	Perennial, weedy, bunch, late
	Amaranthaceae	Redroot pigweed	Annual, weedy, tall, latest

Most pasture communities also have other herbaceous broadleaved plants (the forbs) well represented. The most common forbs are usually in the aster family. Dandelions may be fairly nutritious, but thistles are usually regarded as pasture weeds because they are not readily grazed. Pasture clipping can help control thistles without using herbicides. Other forbs such as broadleaf plantain are also fairly easy to find in pastures. Annual forbs like redroot pigweed are less common, but they quickly establish in places where perennials have been killed out by the kind of trampling that occurs around water tanks. If the farmer moves the location of the water tanks frequently, deeper rooted perennials can reestablish and regenerate the disturbed areas.

As the plant community gets more complex, the associated populations of insects, birds, and soil organisms also get more complex. The increasing biological diversity offers more stability to the ecosystem through the possible substitution of organisms with similar biological functions.

The community of herbivores is also more diverse in a pasture than in monocultures of crops grown in rows. The food web (Fig. 2) already illustrates this point. An additional point is that the farmer may use several classes of livestock to help manage grazing. Dry cows (those not presently lactating) or replacements (prereproductive stock) may be grouped to follow the milking cows and thus graze less desirable, weedy plants. Although sheep or goats are rarely grazed with dairy cattle in the USA, it is known that such mixed grazing increases the utilization of the plant community and helps control pasture weeds.

THE ANIMAL PRINCIPLE

The food web (Fig. 2) also reveals our last principle: ***there are always animals in a natural ecosystem***. This is also true of agroecosystems. For example, there are insects in monoculture crops that have no livestock. However, farming with livestock increases biological diversity. In addition, livestock perform such important ecological functions that we should look more closely at what they are doing in the pasture.

All the animals fill roles as consumer or decomposer organisms. The dairy cow in a pasture is the dominant primary consumer of green plants, converting some of the energy in those plants to a form that can be used as food by humans. One of the dairy cow's most important ecological functions is to increase the usefulness of the kind of plants we need anyway for agricultural sustainability. The best crop rotations for sustaining the soil and controlling pests without pesticides include perennial grasses and legumes. Most of those plant species cannot be used directly by humans for food, but they make excellent feed for cows. Even without livestock, we can use perennial grasses and legumes as green manures, plowing them directly into the soil before the crop rotation goes back to grains or vegetables. However, feeding those grasses and legumes to the cow helps us produce more food while we are building up the soil. Recent studies show that the humanly digestible food supply can be increased by as much as 1.28 times for energy and 2.76 times for protein when we efficiently use livestock to convert nonedible plants into food. More efficient and sustainable use of land already in agriculture also means we can leave more wild land in its natural state.

The food that comes from livestock also has some important virtues. In recent years there has been much publicity about the excessive fat and cholesterol in animal-based foods. Many Americans probably do eat too much fat in their diet, including the fats of meat, eggs, and dairy products. However, animal-based foods are also some of the best sources of high quality protein and essential vitamins and minerals. There is no known source of vitamin B_{12} from plants. Dairy products from cows grazing pasture not only provide vitamin B_{12}, but they are also high in vitamin E and CLA (conjugated linoleic acid), important antioxidants and cancer-fighting nutrients. Nutritionally, humans appear to need modest amounts of animal-based foods, and livestock in a mixed cropping system can contribute to a well-balanced human diet.

Dairy cows and pastures also help us manage the nutrient cycles on farms. A New York dairy cow produces 100 to 120 pounds of fresh manure daily. That is 12 to 16 pounds of dry organic matter. About 75% of the nitrogen and phosphorus and 80 to 90% of the potassium in the diet passes to the manure, so nutrients are being concentrated through the processes of digestion and excretion. Manure distribution can be managed either by moving animals at appropriate times (they release more manure while resting) or by collecting manure when animals are housed. Livestock manure is thus an important organic fertilizer that helps resupply soil organic matter, tighten nutrient cycles, and replenish nutrients exported from various fields.

SUMMARY

We have identified five ecological principles that are fundamental to agricultural sustainability:

In an ecosystem

- everything that is organic is food (energy flows)
- nothing is wasted (matter circulates)
- there is a premium on protecting the soil
- there is usually a substitute (biodiversity)
- there are always animals under natural conditions.

In addition to contributing to agricultural sustainability, well managed dairy pastures are also good places to learn about ecology.

ACKNOWLEDGMENTS

This study has been supported by funds from the Northeast Region Sustainable Agriculture Research and Education Program (SARE). We especially thank Heather Karsten, Darrell Emmick, and Tom Miller for their assistance with the associated field work.

REPRINTS

Additional copies may be obtained upon request from Gary W. Fick.

REFERENCES

Cheeke, P.R. 1993. Impacts of livestock production on society, diet/health and the environment. Interstate Publ. Danville, IL.

Chin, S.F., J.M. Storkson, and M.W. Pariza. 1993. Conjugated dienoic derivatives of linoleic acid - a new class of food-derived anticarcinogens. Am. Chem. Soc. Symp. Series 528: 262-271.

Fick, G.W., and W.J. Cox. 1995. The agronomy of dairy farming in New York State. SCAS Teaching Series No. T95-1. Dep. of Soil, Crop and Atmospheric Sciences, Cornell Univ., Ithaca, NY.

Gershuny, G., and J. Smillie. 1995. The soul of soil -- a guide to ecological soil management. 3rd ed. agAcess, Davis, CA.

Jorgensen, S.E., S.N. Nielsen, and L.A. Jorgensen. 1991. Handbook of ecological parameters and ecotoxicology. Elsevier, New York.

Odum, E.P. 1983. Basic ecology. Saunders College Publ., Philadelphia, PA.

Oltjen, J.W., and J.L. Beckett. 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74: 1406-1409.

Pimentel, D., T.W. Culliney, I.W. Buttler, D.J. Reinemann, and K.B. Beckman. 1989. Low-input sustainable agriculture using ecological management practices. Agric. Ecosyst. Environ. 27:3-24.

Van Soest, P.J. 1994. Nutritional ecology of the ruminant. 2nd ed. Cornell Univ. Press, Ithaca, NY.

CORNELL
UNIVERSITY