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Use of Organic Amendments for Increasing the Productivity of Arid Lands

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Abstract *Almost 40% of the world's land area is comprised of arid and semiarid regions that are inhabited by some 700 million people; approximately 60% of these drylands are in developing countries. Although these regions will continue to produce most of the world's food grains for expanding populations in the years ahead, the yields are extremely low. In some countries of the sub-Saharan region of Africa, there has been a sharp decline in food grain production per capita during the 1980s. Much of this can be attributed to the deterioration of the natural resource base, i.e., agricultural land.*

The principal constraints to increase agricultural production in these dryland areas are erratic and insufficient rainfall, and coarse-textured, sandy soils that are low in fertility, organic matter, and water-holding capacity. They are often poorly managed and subject to extensive degradation from desertification and wind and water erosion, and, consequently, the loss of soil productivity.

The key to improving the productivity, stability, and sustainability of these dryland farming systems is to halt any further deterioration of the soil resource. This can be achieved by the implementation of sound soil and water management practices and by proper and regular additions of organic amendments. This article discusses a number of strategies for developing sustainable conservation and production systems in these arid and semiarid regions.

Keywords organic wastes, low-input/sustainable agriculture, soil conditioners, best-management practices, soil degradative processes, soil conservation practices.

Introduction

Almost 40% of the world's land area is in the arid and semiarid regions inhabited by some 700 million people, most of whom are farmers and live in what we call developing or Third World countries. Crop and livestock production is often limited here because of insufficient rainfall and infertile and erodible soils. Agricultural enterprises can be relatively productive and sustainable provided that ecologically balanced farming systems and best-management practices are employed to stabilize the croplands and rangelands against desertification and other degradative processes. Unfortunately, population growth in many of these regions has increased rapidly during the last two or three decades, which has led to (1) overgrazing by animals, (2) increased cultivation for production of cash or export crops, and (3) increased cutting of shrubs and trees for firewood. The result has been an alarming increase in either the total loss of these fragile croplands to desertification or a severe decrease in their productivity. Consequently in some areas, e.g., the sub-Saharan region of Africa, food grain production per capita has decreased during the last decade.

Eckholm and Brown (1977) conclude that

> in many dryland farming areas, population growth prohibits a return to the ecologically sustainable fallow or rotation system once used with success. The only alternative is to adopt new cropping systems that minimize erosion and employ crop rotations, water conserving techniques, animal manures, green manures, and, where moisture permits, perhaps chemical fertilizers.

Only through the development of sustainable and environmentally sound agricultural systems for arid and semiarid environments will desertification be controlled, and the ultimate disaster of malnutrition, famine, poverty, and human misery be avoided.

This article presents some perspectives and strategies for utilizing organic wastes and residues more effectively for stabilizing arid and semiarid lands against desertification and other degradative processes, and increasing their agricultural productivity, with particular emphasis on developing countries.

We use the following definition for productivity (USDA 1957): "The capability of a soil for producing a specified plant or sequence of plants under a defined set of management practices. It is measured in terms of the outputs or harvests in relation to the inputs of production factors for a specific kind of soil under a physically defined system of management."

Nature and Availability of Organic Wastes for Land Application

Soils in arid and semiarid environments are generally low in their organic matter content because of the very rapid rate of waste or residue decomposition by the microflora following irrigation or precipitation. Another reason is that temperatures in arid climates are usually considerably higher than those of humid-temperate climates (Focht and Martin 1979). Nevertheless, the proper management of organic wastes, such as crop residues, animal manures, and sewage sludges on land, is one of the best means we have for protecting agricultural soils from wind and water erosion, and for stabilizing arid and semiarid soils against degradation processes. These organic materials can markedly increase soil productivity by providing essential plant nutrients and by improving soil phys-

ical properties. Unfortunately, the arid and semiarid regions are often characterized by a lack of good quality organic wastes and residues that can be applied advantageously to land as biofertilizers and soil conditioners (Parr *et al.* 1986).

The beneficial effects of organic materials on soil physical properties are well known, as evidenced by increased water infiltration, water-holding capacity, water content, aeration, permeability, soil aggregation, and increased rooting depth, and by decreased soil crusting, water and nutrient runoff, and bulk density (USDA 1957, Allison 1973).

Surveys of Organic Wastes and Residues

In 1978 the U.S. Congress requested that the Department of Agriculture prepare a report on: "The practicability, desirability, and feasibility of collecting, transporting, and placing organic wastes on land to improve soil tilth and fertility." This information was urgently needed because of the increasing costs of energy and fertilizers facing U.S. farmers, and the concern that excessive soil erosion associated with intensive farming systems, particularly cash grains, was causing a loss of agricultural productivity. The report (USDA 1978) contains detailed information on the availability of seven major organic waste materials for improving soil tilth and fertility: (1) animal manure, (2) crop residues, (3) sewage sludge, (4) food processing wastes, (5) industrial organic wastes, (6) logging and wood manufacturing wastes, and (7) municipal refuse. Information is reported on the quantity currently generated, current usage, potential value as fertilizers, competitive uses, and problems and constraints affecting their use. This kind of information is essential for sound agricultural planning and successful implementation of programs for recycling organic wastes on agricultural land.

Table 1 shows the amounts of different organic wastes that were produced annually in the United States, with a total production in 1978 of some 730 million dry metric tons. Clearly, this represents a national resource of considerable economic value, and the proper and efficient use of these materials for improving soil productivity should be encouraged. Crop residues comprise about 50% of the total, and animal manures about 22%. Thus the traditional on-farm agricultural wastes make up nearly 75% of the total annual U.S. production of organic wastes listed in Table 1. Currently, about three-quarters of these two wastes are being applied to cropland.

Most of the developing countries lack reliable information on the types, amounts, and availability of different organic wastes that might be used to increase the tilth, fertility, and productivity of their agricultural soils. The compilation of surveys such as the USDA report is a necessary prerequisite for developing countries that wish to establish national organic waste management and recycling programs for agricultural benefit (Parr and Papendick 1983). Both the United Nations Environment Programme (UNEP) and the Food and Agricultural Organization (FAO) have emphasized the need for basic information on waste generation and utilization in developing countries (UNEP/FAO 1977).

Constraints and Competitive Uses

If available, traditional agricultural wastes such as animal manures and crop residues are usually applied to cropland throughout the world. However, some organic wastes in both developed and developing countries are not used extensively on land because of certain constraints related to undesirable chemical and physical properties. For example, (1) some sewage sludge may contain excessive amounts of heavy metals and organic chem-

Table 1

Annual production of organic wastes in the United States, current use on land, and probability of increased use.

Organic wastes	Total production: Million metric tons	Total production: Percentage of total	Current use on land[a] (%)	Probability of increased use on land[b]
Animal manures	159	21.8	90	Low
Crop residues	391	53.7	68	Low
Sewage sludge and septage	4	0.5	23	Medium
Food processing	3	0.4	(13)	Low
Industrial organic	7	1.0	3	Low
Logging and wood manufacturing	32	4.5	(5)	Very low
Municipal refuse	132	18.1	(1)	Low
Total	728	100.0	—	—

[a] Values in parentheses are rough estimates because of insufficient data.

[b] Medium indicates a likely increase of 20 to 50%, low indicates a 5 to 20% increase, and very low indicates less than 5% increase.

icals that could be toxic to plants, impair the productivity of agricultural soils, or endanger the food chain and human health, (2) some food processing wastes may have high acidity or alkalinity that could adversely affect soil pH and soil structure, and (3) municipal refuse (i.e., garbage or solid waste) may contain considerable amounts of glass, plastic, and metal fragments that might detract aesthetically when applied to land as a soil amendment. There are certain competitive uses of some materials that would prohibit their application to land. For example, cotton gin trash and sugarcane bagasse are increasingly used as fuel or energy sources, and for the manufacture of paper and cardboard products, whereas in developing countries cereal straws have multipurpose use for fodder, fuel, mats, bags, thatch, rope, etc.

A publication by the National Academy of Sciences (NAS 1981) cites a number of examples of how new and improved technologies are converting various organic wastes into fish and animal feeds, food for human beings, and fuels such as biogas and alcohol. This, of course, will further contribute to the growing shortage of good quality organic wastes for improving the productivity of agricultural soils in both developed and developing countries.

Table 1 indicates that the potential for increased use of certain wastes in the United States as biofertilizers and soil conditioners is low. Animal manures and crop residues are already being utilized extensively, whereas competitive uses for wastes from the food processing and wood products industries will restrict their availability as organic amendments. The use of organic industrial wastes will be limited by the degree of toxicity that they might impart to soils and plants. Although the projected probability for increased use of municipal refuse was considered low at the time the report was compiled, the development of cocomposting technology could enhance its utilization considerably. The application of municipal sewage sludges on land in the Unites States has already increased from about 25% in the mid 1970s to an estimated 40 to 45% at the present time.

The USDA report concluded that there is a growing shortage of good quality organic wastes for use in maintaining and improving the productivity of our agricultural soils, and that this situation will intensify in the future. The report cited a number of ways in which our limited amounts of organic wastes might be used more effectively as soil amendments. These include:

(1) Improving methods of collection, storage, and processing (e.g., composting) of animal manures to minimize the loss of nitrogen that often occurs in these operations.
(2) Applying manures to land that are presently being wasted.
(3) Applying crop residues to land that are not now being fully utilized.
(4) Increasing the use of sewage sludge on land.
(5) Increasing the use of the organic/compostable fraction of municipal refuse.

Process Technology to Enhance the Usefulness and Acceptability of Organic Wastes as Fertilizers and Soil Conditioners

Some of the problems associated with various organic wastes, such as offensive odors, human pathogens, and storage and handling constraints, can be resolved through composting. This ancient practice has been used by farmers for centuries to convert human and agricultural wastes into humuslike materials that can markedly improve the tilth, fertility, and productivity of agricultural soils. Through composting, organic wastes are

decomposed and stabilized, pathogens are destroyed, plant nutrients are made more available, and malodors are abated.

During the past decade, there has been much interest in composting as a means of stabilizing municipal sewage sludges, particularly in developed countries, for land application as biofertilizers and soil conditioners. The U.S. Department of Agriculture at Beltsville, Maryland, conducted extensive research on composting technology during the 1970s and early 1980s. This effort led to the development of the highly successful Beltsville Aerated Rapid Composting (BARC) Method for composting sewage sludges (Willson *et al.* 1980). The method has now been adopted by more than 90 cities and municipalities throughout the U.S. and Canada (Willson and Dalmat 1983), and is considered to be an economically viable alternative to such ultimate disposal methods as landfilling, incinerating, and ocean dumping (Colacicco 1982). Some developing countries have also adopted this method for cocomposting municipal refuse and pit latrine wastes (Shuval *et al.* 1981, Dalmat *et al.* 1982). The method is simple and relatively inexpensive, yet effective, and allows considerable trade-off between capital and labor.

The possible uses of sewage sludge compost for soil improvement and plant growth have been discussed by Hornick *et al.* (1979, 1984). These include: (1) establishment, maintenance, and production of turfgrass and sod, (2) use in vegetable gardens, (3) production of field crops and forage grasses, (4) use on nursery crops and ornamentals, (5) use in potting mixes, and (6) reclamation and revegetation of disturbed lands. Recommendations are provided on the time, methods, and rates of compost application for different soils and management practices.

Some organic wastes may have chemical, physical, or microbiological properties that would greatly limit the extent to which they could be composted alone. For example, they may be extremely acidic or alkaline, or may have an unusually high or low C:N ratio, or may vary widely in their solids content. Selective cocomposting of these wastes may alleviate these deficiencies and provide a readily compostable mixture and higher quality product. Materials for cocomposting might include: sewage sludges, pit latrine waste ("night-soil"), municipal solid wastes, and certain industrial wastes.

Factors Affecting the Decomposition of Organic Wastes and Residues by Microorganisms in Arid Environments

Some agricultural regions with humid-temperate climates produce excessive amounts of crop residues, far more than is needed for control of erosion and for maintaining soil productivity. Arid and semiarid regions, however, often produce insufficient amounts of residues to stabilize soils from desertification and other degradative processes and to maintain their productivity (Parr and Papendick 1978, Hornick and Parr 1987).

Because of mounting energy costs and increased soil erosion from intensive cropping and tillage systems, many farmers in the United States and elsewhere have shifted to conservation tillage methods that leave much of the crop residue at or near the soil surface. Most of our knowledge of the rate and extent of residue decomposition is based on mixing or incorporating them into soils under constant moisture and temperature regimes. As pointed out by Focht and Martin (1979), because of intermittent wetting and drying cycles and extreme temperature fluctuation in aridisols, microbiological processes in these soils would be described more accurately by rapid transient-state kinetics than by steady-state conditions.

The development of effective management systems to maximize the beneficial use of

organic wastes and residues in arid and semiarid regions will require a thorough understanding of the factors affecting their decomposition. This will likely involve the positioning of organic wastes or residues at the surface for modification of the soil environment, and seeking ways of controlling the decomposition of limited amounts of materials, thereby extending the time during which soils are effectively stabilized. Unfortunately, our knowledge of residue decomposition under such conditions is rather limited.

Interaction of Factors Limiting Microbial Growth and Activity in Soil

The rate of decomposition of an organic waste or crop residue depends primarily on its chemical composition and on those factors that affect the soil environment. A summary of the possible chemical and physical characteristics of organic wastes and residues is presented in Table 2 along with the different soil and management factors that can affect their decomposition. These have been compiled from a number of references, including Parr and Papendick (1978), Dommergues *et al.* (1979), and Focht and Martin (1979). A more thorough and comprehensive discussion of these factors is presented by Stott and Martin (1989).

Factors having the greatest effect on microbial growth and activity will have the greatest potential for altering the rate of residue decomposition in soil. On a microscale, the soil environment is heterogeneous and highly dynamic, with many components being subject to rapid changes and frequent fluctuations, especially under arid and semiarid conditions. Microbial growth and activity within this complex system are controlled by soil factors, by crop residue and organic waste characteristics, and by certain management practices.

Soil factors having the greatest impact on waste/residue decomposition include water, temperature, pH, aeration or oxygen supply, and available nutrients. Soil salinity and the type and content of clay can also be important. It is noteworthy that the growth and activity of a particular organism may be limited by either insufficient or excessive levels of a given factor. Thus each group of microorganisms has "an ecological minimum and

Table 2
Characteristics of crop residues and organic wastes, and soil and management factors that affect their decomposition in soil.

Crop residue factors	Organic waste factors		Soil factors	Management factors
General	*Chemical*	*Physical*	*General*	*Application*
C:N Ratio	pH	Solid	Moisture	Loading rate
Particle size	Salinity	Liquid	Temperature	Mode/method
Available nutrients	Acidity	Slurry	pH	Time/frequency
Indigenous microflora	Alkalinity	Sludge	EH	*Agronomic*
Age of material	BOD	Particle size	Aeration	Tillage
	COD	*Microbiological*	Available nutrients	Cropping
	C:N ratio	Indigenous microflora	Clay content	Climate
	Heavy metals		Organic matter	Irrigation
	Toxic organics		Salinity	
	Plant nutrients		Indigenous microflora	

maximum with a range in between which represents the limits of tolerance'' (Odum 1971).

Properties of some organic wastes that can limit their rate of decomposition and even impair the properties and productivity of agricultural soils include extreme acidity, salinity and alkalinity, heavy metals, toxic organic constituents, certain physical characteristics, and the indigenous microflora. Some wastes from industrial chemical processes are probably too hazardous for direct application to soil and should be avoided (Parr *et al.* 1983).

Crop residue characteristics that affect their rate and extent of decomposition in soils include C:N ratio, particle size or degree of dissection, age of material, and the lignin content. Management factors must also be considered since the mode and method, rate, time, and frequency of waste of residue application can greatly influence the rate and extent of decomposition (SCSA 1976, Parr and Papendick 1978). The method of application determines whether residue is mixed with the soil or positioned so as to be layered or banded in the soil, or concentrated mainly at the surface. Additional management factors include tillage practices, cropping sequences or rotations, climate, and irrigation.

Many of the factors listed in Table 2 are not independent; a change in one may affect a change in others. For example, high soil moisture may result in lower soil temperatures, and surface residues may affect soil moisture and temperature simultaneously. Because of these strong interactions, it is often difficult to isolate effects of specific environmental factors on residue decomposition.

The Indigenous Microflora of Organic Wastes and Residues

Most organic wastes and crop residues contain populations of indigenous microorganisms, including bacteria, actinomycetes, and fungi. There is evidence that even after application to soil, the indigenous microflora can contribute significantly to the decomposition process. For example, Hallam and Bartholomew (1953) reported that under controlled laboratory conditions the total decomposition of corn stover incubated alone was considerably greater than when the same amount of residue was mixed with soil. In another laboratory study, Parr and Papendick (1978) reported that sewage sludge applied to soil in a localized band decomposed more rapidly than when the same amount of sludge and soil were mixed prior to incubation (Fig. 1). Plate counts revealed a significantly higher initial indigenous microbial population in the sludge compared with the soil, and suggested that the indigenous microflora played a major role in decomposing the sludge.

Future research is needed to investigate the nature of the interaction between the indigenous microfloras of organic wastes and crop residues, depending on the mode and method of application to soil, i.e., whether they are mixed, layered, or banded in the soil, or positioned at the surface. This could provide vital information for managing wastes and residues in soils under arid and semiarid conditions that would slow their rate of decomposition, thereby extending their residual and beneficial effectiveness.

Nutrient Availability and Organic Stability Characteristics of Wastes and Residues

Based on their decomposability in soils, organic wastes and residues generally fall into two categories: (1) materials such as fresh animal manures, which are metabolized rapidly by the soil microflora, thereby releasing available nutrients for plant uptake, and (2)

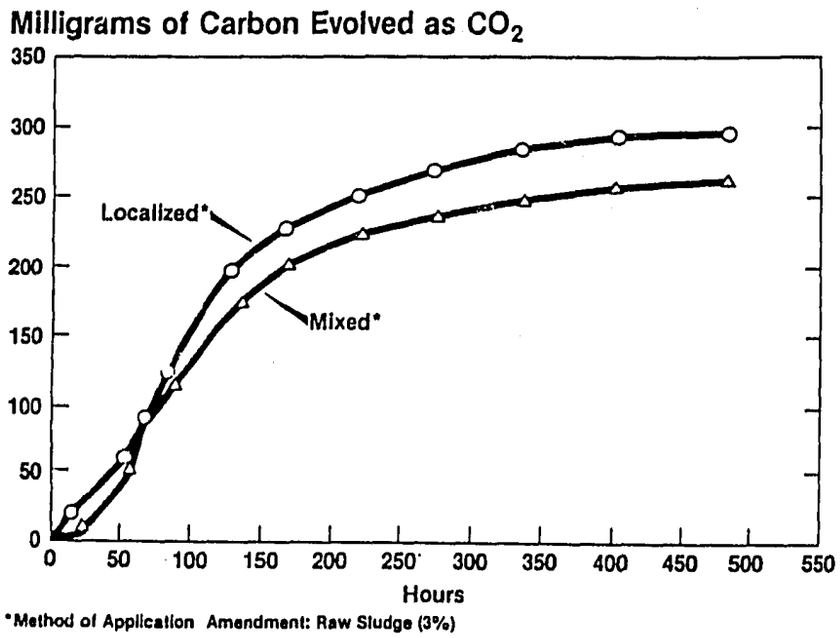

Figure 1. Decomposition of raw sewage sludge applied to soil, at a rate of 67 metric tons ha^{-1}, in a localized band or mixed uniformly with the soil.

materials such as composted refuse that have a higher degree of organic stability and resistance to microbial attack and would release their contained nutrients at a relatively slower rate. Farmers in arid and semiarid environments may have occasion to use both types of organic amendments in their management practices. For example, where there is an immediate need to stabilize soils against desertification and erosion, amendments having a high level of organic stability would provide for initial improvement of soil physical properties and moisture retention. Once stabilized, however, materials could be applied that would provide a higher level of nutrient availability.

Table 3 lists some organic materials that would differ considerably in these two properties. Whereas these are hypothetical values and would have to be verified experimentally, the concept is the important consideration (Parr and Papendick 1983, Parr *et al.* 1986). A high nutrient availability index (NAI) indicates materials that would release nutrients relatively rapidly, whereas a high organic stability index (OSI) would be associated with more stable forms of organic matter. Materials with a high NAI value usually would be expected to have a low OSI value, and conversely. Research is needed to develop reliable numerical indexes that would allow a realistic basis for predicting the nutrient availability and organic stability of different wastes. This would help to ensure that limited amounts of organic materials are used to the greatest advantage in stabilizing arid and semiarid lands and improving their productivity.

The Concept of Soil Water Energy

Water availability is the factor that most often limits agricultural production in dryland farming systems and becomes extremely critical in the very dry environments that characterize the arid and semiarid zones. Not only is the long-term average precipitation low in

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Table 3
Hypothetical nutrient availability indexes (NAI) and organic stability indexes (OSI) for composted and uncomposted organic materials.

Product	Nutrient availability index[a]	Organic stability index[a]
Beef manure	70	30
Rice straw	15	85
Sewage sludge	80	20
Sewage sludge—woodchip compost	35	65
Refuse compost	25	75
Refuse-pit latrine compost	40	60
Poultry manure—rice straw compost	65	35

[a] Values are hypothetical, but are based mainly on what is known of the C:N ratios of organic materials cited, and the decomposability of the various components (i.e. cellulose, hemicellulose, lignin, sugars, proteins, etc.) that comprise them (Parr & Papendick 1978).

arid climates, but the distribution is often highly irregular. There may be a complete lack of moisture for seed germination and plant growth for most of the year. Whereas it is true that under arid conditions the soil may become wetted to some depth and levels that are optimum for the growth of microorganisms and plants, this is infrequent and of short duration compared with the time that water contents are marginal, or below that needed for economic biomass production. On the other hand, the water content at the soil surface or on surface residues is subject to daily fluctuations from moistening by atmospheric condensation (dew, frost, fog mist) and may provide sufficient moisture for short times to influence microbial processes such as organic matter decomposition, nitrogen fixation, and nitrogen mineralization.

Water Potential and Water Availability

The availability of water in soil or other porous materials (e.g., crop residues or other organic amendments) to living organisms is best described by the concept of water potential. Water potential is the free energy of water in a system or, alternatively, the additional work required for plants and microorganisms to obtain water from soils or organic materials relative to pure, free water. The presence of solutes in water, soil matric forces, and certain other forces act on water in most porous systems, which reduces its potential energy. Since pure, free water is assigned zero water potential, the potential energy of water in these systems is almost always negative; that is, the lower or more negative the value of the water potential, the less available is the water to living systems.

Water potential is usually expressed in terms of pressure units per unit mass or volume of water, e.g., atmospheres, bars, Joules kg^{-1}, or Pascals. Water potential is also related to the relative humidity in equilibrium with the water by the equation:

$$\Psi = (RT/V) \ln h$$

where Ψ is the water potential, R is the ideal gas constant, T is the absolute temperature, V is the volume of a mole of water, and h is the relative humidity. For water potentials in

the plant growth range, an approximate relationship between water potential in bars and relative humidity at 20°C is $\Psi = 1350$ (h-1). A common misconception is that soil water in the liquid phase is more available to microorganisms than in the vapor phase. The fact is, however, that whenever the soil liquid and vapor phases are in equilibrium, which is often the case, they are at the same potential and equally available.

The water content of soil, crop residues, or other organic materials can be related to water potential through what is commonly termed as moisture characteristic curves (Papendick and Campbell 1981). These curves are unique for different soils and organic materials and depend on the texture and organic matter content of soils and the physical composition and structure of the organic materials. For example, soils with high amounts of clay and/or organic matter hold considerably more water at a given water potential than soils with a high content of sand on a per-unit-mass basis. On the other hand, organic materials such as straw hold considerably greater amounts of water per unit weight than soil, and over a wide range of water potentials. Moisture characteristic curves for soil and straw were reported by Parr and Papendick (1978).

Optimum water potentials for growth of most plants and microorganisms are in the range of -0.3 to -0.1 bars (1 bar = 0.99 atm. = 100 Joules/kg = 10^5 Pascals = 0.1 mPa), which for most soils corresponds to the water content of the rooting zone at "field capacity," a moisture constant widely used to represent the upper limit of available water for plants in particular.

Stress develops and growth is slowed for many plants when the soil water potential of the root zone falls below several bars, with the effect becoming more severe with increased evaporative demand. Few crop plants can survive when the soil water potential falls below -15 bars (-1.5 mPa, referred to as the permanent wilting point). The volume of water held in the root zone between field capacity and the soil water content at -15 bars is commonly referred to as the plant available water. The amount of plant available water that a soil will hold per unit depth depends largely on textural properties and the organic matter content. Maximum water-holding capacities are usually associated with silt loam soils having large contents of clay and organic matter.

Microorganisms in soil are not subjected to aerial evaporative water losses like plants, and their internal water status is controlled primarily by the humidity of the soil, organic waste, or crop residue, and virtually not at all by the water flow properties of the soil. Moreover, most soil microorganisms can survive at water potentials much lower than -1.5 mPa, whereas many can actually grow and reproduce at such extremes.

Control of the Soil Water Regime

The effective use of organic wastes and crop residues for stabilizing soils under arid and semiarid conditions will require management practices to maximize water conservation and to control the water potential of soils and organic residues. Such measures will help to regulate the decomposition rate of organic materials and to enhance the accumulation of organic matter. The water status, aggregation, and productivity of soil are all interrelated and strongly influenced by the soil organic matter content. Increasing the soil organic matter content not only increases the water retention capacity of soil, but the infiltration capacity as well. Organic matter and decomposition products and compounds of microbial metabolism facilitate the binding of primary particles into aggregates that provide maximum protection against wind and water erosion. Increasing the organic matter content of arid and semiarid soils is perhaps the single most important way of increasing their agricultural productivity.

Management for water conservation includes two basic objectives: (1) to maximize intake and retention of precipitation, and (2) to minimize evapotranspiration losses. Increasing water storage and the total water available for crop production can be achieved in several ways, but diversity in climate and soils found in dryland regions precludes any precise formula for a universal management system. Techniques to conserve water are based primarily on crop residue management, weed control, snow catchment (in cold arid regions), water impoundment, and evaporation suppression.

Fallow. Fallow in one out of 2 to 4 years is used extensively to achieve economic crop production in widespread areas of low rainfall. Enough water is saved over a fallow period to greatly stabilize production and minimize the hazards of drought. Traditionally, the practice has been criticized because of low water storage efficiency (often less than 25% of the total precipitation). However, fallow efficiencies can be substantially improved through better methods of weed control, residue management, and conservation tillage practices.

Weed Control. Weeds are prime users of soil moisture that is often critically needed for crop production. For example, research in the central Great Plains of the United States shows that the production of 1120 kg ha^{-1} of dry matter by weeds consumed 76 mm of water that otherwise could have produced an additional 700 to 1,300 kg ha^{-1} of wheat grain (Greb *et al.* 1979). Traditionally, weed control in dryfarming systems has been achieved through tillage. However, excessive tillage, which is often required to control persistent weed infestations, increases the potential for rapid decomposition of soil organic matter and crop residues, and increases soil erosion and moisture loss. During the past several decades, development of effective herbicides and application methods has allowed some dryland farmers to greatly reduce their tillage operations while achieving satisfactory weed control. This has resulted in conservation of crop residues, water, and soil.

Snow Management. Snow is an important source of water in cold arid regions, and the moisture from it is much more efficiently stored in soil than from rain. Nevertheless, the snow resource is not always used to the best advantage because of blowing from fields and snowmelt runoff. With improved catchment, it is possible in some regions that the benefits of one season of snow water could match the soil water accumulation of a year's fallow. Various methods have been devised for retaining snow on the field:

(1) Stubble management—retaining tall standing stubble after harvest or alternating strips of tall and short stubble.
(2) Vegetative barriers—growing plants (wheatgrass, sunflowers, mustard) in single or double rows to deposit drifting snow onto a crop area.
(3) Snowridging—collecting and compacting snow on fields into high ridges or windrows, which then serve to trap drifting snow.

Runoff Control. Control measures are aimed at reducing runoff from rains where soils have little surface protection and from rain and snowmelt on frozen soils. The following approaches are based on methods either to improve infiltration or to impound runoff water.

Conservation tillage methods that retain maximum amounts of surface residues but break up subsoil layers that restrict water flow may slow runoff. This would enhance

water movement to the deeper soil depths during periods of rain or snow melt. Examples of some methods include chisel plowing, subsoiling with subsurface sweeps, and paraplowing (noninversion plowing). No-till culture is gaining prominence as a water-conserving measure and for erosion control. It provides an effective means for conserving soil organic matter and maintaining most of the crop residue near the soil surface where it can provide maximum soil protection.

Slot mulching involves crop residues or other organic materials that are compacted into narrow slots 10 to 25 cm deep on certain contour intervals and left exposed at the soil surface (Saxton *et al.* 1981). These slots maintain macroporosity and intercept water during periods of runoff. Infiltration and water storage are increased, particularly for slowly permeable soils or when the soil near the surface is frozen.

Water impoundment includes various systems that have been successfully developed to trap runoff, to redistribute it on croplands, and to increase time for infiltration. These include formation of shallow depressions such as "level pans" to collect runoff from adjacent steeper areas, and conservation bench terraces to impound runoff and spread the water over a wide area.

Evaporation Suppression. Evaporation is the major source of water loss in dry regions. Some opportunities for reducing evaporative loss depend upon crop residue management and tillage practices.

In *crop residue management,* surface residues are effective for reducing evaporative loss mainly during periods when the soil surface is frequently wet from intermittent precipitation. The benefits of mulched surfaces for water conservation are considerably less during extended dry periods. In fact, surface residues may increase the loss of stored water during long periods without rain, compared with bare surfaces, by keeping the soil surface wetter for a longer time, thereby allowing a greater evaporative loss.

Some type of *tillage* to break the surface crust of a moist soil can be beneficial. This hastens surface drying, which slows evaporation by forming a barrier that prevents the flow of liquid water to the surface.

Water Potential as a Selective Influence upon the Soil and Residue Microflora

Water requirements for growth and survival of different microorganisms vary considerably and, hence, water availability may exert a strong selective effect on the microflora under field conditions. Griffin (1981) reported that in pure culture the growth of some fungi is negligible at −20 bars (−2 mPa) water potential, whereas others were able to grow at −400 bars (−40 mPa). However, water potential may not be the sole factor determining the activity of microorganisms. Microbial antagonism may also have some influence here. Some fungi grow almost equally well in pure or mixed cultures at low water potentials, but better in pure cultures at high water potentials. This indicates that there is reduced antagonism from the general microflora in the former situation. Cook and Papendick (1972) pointed out that water potentials in dryland systems may be −100 bars (−10 mPa) or less very near the soil surface, but well within the plant growth range at deeper depths in the rooting zone. These surface water potentials are too low for the fungus that causes take-all foot rot of wheat (*Gaeumannomyces graminis*), but are within the growth range for *Fusarium culmorum* that causes dryland foot rot of this crop. Take-all, however, can be a serious disease in irrigated wheat.

Questions have been raised as to whether long, dry periods common in arid climates

will cause changes in microflora that are indigenous to undecomposed crop residues or organic wastes that come to reside at or near the soil surface We really do not know whether these changes would have any significant effect on the subsequent rate and extent of decomposition, or the nature of microbial by-products, when water potentials again become favorable for rapid microbial growth and activity. Such information may help to provide a better understanding of decomposition processes in the field under extremely dry conditions.

Some control of the soil water potential may be desirable and necessary as a means of managing organic wastes and residues for stabilizing the soil, and improving its productivity. For example, high water potentials would normally accelerate the decomposition process, whereas low potentials would slow decomposition and allow for longer retention of residues for controlling wind and water erosion (Parr and Papendick 1978). The water potential may also influence the production of decomposition by-products that are important for soil aggregation. Since organic wastes and crop residues are applied in ways that confine them at or near the soil surface, it is this zone that is most important in any attempt to regulate the water content, and hence, the water potential. Some possible soil and residue management practices that may be used to control the soil water potential in the surface layers include the following.

Placement of Organic Wastes and Crop Residues. Positioning organic materials, particularly crop residues, on the soil surface reduces the rate of evaporation from the soil and will generally maintain higher water potentials in the shallow layers for considerably longer periods compared with bare surfaces. Surface residue management can be achieved with the use of subsurface implements for seedbed preparation or the use of no-till methods.

Soil Texture Modification. Many soils in the more arid regions have high contents of sand in the surface layers, but may have finer textured subsoils. It may be possible with deep plowing to blend the upper soil horizons with subsoil material to form a more desirable texture, which would increase the available water-holding capacity of the 0 to 15 cm layer.

Control of Soil-wetting Characteristics through Chemical Modification of Hydrophobic/Hydrophilic Properties. Certain chemicals may be developed to increase the soil-wetting characteristics, which, in turn, would increase the retention of water in the shallow layers, or conversely, to decrease the wetting characteristics of the soil surface, thereby minimizing capillary flow to the surface and reducing evaporation.

Use of Plant Species with Low Transpiration Capacity. Development of these types of crop plants may enable more even distribution and use of stored soil water during a cropping season. This would allow for more of the reserve moisture to be used in the later stages of growth when drought stress is common.

Crop Characteristics and Planting Geometry. Use of crops with different rooting characteristics (deep vs. shallow rooting) and varying the row spacings and plant populations may provide for more efficient extraction of the available water from the entire profile, and possibly from specific depths in the profile at certain times during the growing season. These approaches should provide for increased control of the soil water regime.

Changing the Surface Albedo. Use of materials or methods to lighten the color of crop residues on the soil surface would increase the albedo, and thereby lower the solar energy input to soil. This, in turn, could greatly reduce the evaporative loss of water from soil. One practical approach would be to develop crops with lighter colored residues, or with residues that resist darkening with age. Other methods might include dusting certain materials on the soil residue surface such as lime, chalk, or ash.

The Value of Organic Wastes and Residues as Fertilizers and Soil Conditioners

The value of organic materials as fertilizers and soil conditioners is determined by their ability to increase the yield or quality of crops. Organic materials contain significant amounts of macronutrients, i.e., nitrogen, phosphorus, and potassium, and the simplest and most common method of placing an economic value on organic materials is to assess the market value of these macronutrients. However, many organic materials contain other components that can contribute significantly to increased crop yields, including organic matter, secondary and micronutrients, and sometimes lime. In some cases, the organic matter fraction of a particular material may have a higher value than its nutrient content because of its beneficial effect on soil physical properties. A brief discussion of the agronomic and economic values of organic wastes is relevant to the development of strategies for limiting the degradation of arid and semiarid lands and increasing their agricultural productivity (Parr and Colacicco 1987).

The Agronomic Value

The agronomic value of an organic amendment (waste or residue) to soil is the increased crop yield or quality derived from its application. There are considerable data in the literature that demonstrate the effect of organic materials on crop yield, but less of how they affect crop quality. Crop yield response to additions of organic materials is highly variable and is dependent upon the crop, soil type, climatic conditions, management practices, and the organic material used. In most cases, crop yield response to the addition of organic materials is nonlinear. The greatest yield response is obtained with the first few increments of organic material, followed by progressively smaller yield increases with additional increments. Thus, as with chemical fertilizers and other production inputs, crop yield response to an organic amendment follows the law of diminishing returns, and this is responsible for the decreased value per unit of material as the application rate increases. Obviously, both the agronomic and economic value per unit of organic material to the farmer are correspondingly higher at low, rather than high, application rates.

Organic materials decompose or mineralize in soil at variable rates. They do, however, have a greater residual effect on soil fertility than most chemical fertilizers because of the slow-release character of the nitrogen and phosphorus components. Thus a significant portion of the value of organic materials as biofertilizers is attributable to their capacity to elicit yield responses from succeeding crops. This delayed response must be accounted for to assess the true value of the material.

Higher crop yields are often obtained when organic wastes are applied to soil in combination with chemical fertilizers than when each is applied alone (Sikora *et al.*

1980, Tester *et al.* 1982). This would suggest that certain organic amendments have considerable potential to increase the use efficiency of chemical fertilizers by crops. The addition of organic wastes and residues can often elicit different crop responses depending on the soil type. For example, Sikora *et al.* (1980) reported that higher crop yields were obtained from a marginal loamy sand soil than from a fertile silt loam when both were amended with sewage sludge compost at the same time, reversing the relative yield ranking of the unamended soils.

The Economic Value

The economic value of an organic waste or residue to a farmer is the value of the increase in crop yield and/or crop quality that is derived from its use. The economic value per unit of material can be defined in two ways. First, the marginal value of the material is defined as the increased revenue derived from the last unit or increment of material applied. The marginal value is the maximum amount that a farmer would be willing to pay for the material and is analogous to its free market price. The marginal value must be known so as to properly allocate the material among other competing uses and products. Second, the average value of the material is the average increase in revenue derived from application of the material. The average value of the material must be known, for example, so as to properly evaluate the feasibility of developing a resource recycling or composting project. Selecting the incorrect measure of "value" can lead to erroneous assumptions and costly decisions because the marginal value of an organic material is always lower than its average value.

The marginal and average values of a refuse-sewage sludge compost as affected by the rate of application to corn are shown in Figure 2. Data from Mays *et al.* (1973) and

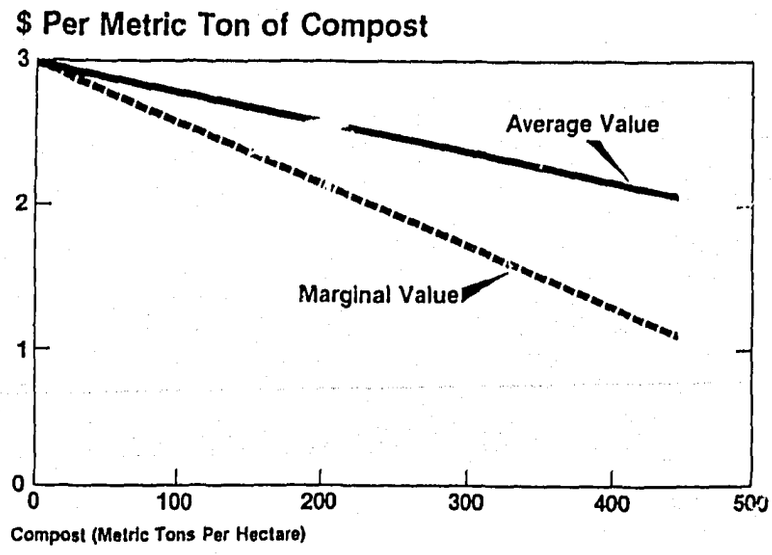

Figure 2. The average and marginal values (in U.S. dollars) of municipal refuse compost as affected by changes in the application rate of compost to corn (yield data from Mays *et al.* 1973, Duggan and Wiles 1976).

Duggan *et al.* (1976) were used to estimate the decomposition rate of compost and the corn yield response function. Both the marginal and average value of the compost started at $3.30 (U.S.) per ton at the low application rate and gradually declined as the rate was increased. In this example, the rate at which the average value of compost decreased is one-half that of the marginal value. An accurate estimate of the decomposition rate of compost is important in determining its economic value. Future yield increases due to residual effects must be included in estimating the current economic value of an organic waste or residue.

Most farmers feel that a bushel of grain would probably be worth more today than at some time in the future. This is even more true in a developing country where a farmer's immediate survival may be in doubt because of impending natural disasters or other factors, and would place an even higher relative value on the current crop. This "time preference" for income must also be included in the value of organic amendments by discounting the value of future yield increases. The future increase in income was discounted by 15% to develop the value relationships in Figure 2. The discounted future increase and the first-year increase in income constitute two-thirds and one-third, respectively, of the value relationship.

Management Practices to Maximize the Effective Use of Organic Wastes and Residues on Arid Lands

Reintroduction of Best Management Practices

Many farmers in developing countries have shifted toward intensive row cropping for short-term economic gain, and have neglected soil and water conservation practices. This has often resulted in increased soil erosion, sedimentation, and nutrient runoff and enrichment of surface waters. In arid and semiarid environments, it has led to accelerated desertification, deterioration of soil physical properties, and loss of agricultural productivity. Thus there is an urgent need to reintroduce those soil and crop management practices that are considered to be "best-management practices" for controlling soil erosion and maintaining soil productivity (USDA/USEPA 1975, 1976). These include the use of sod-based rotations, contour cropping, conservation tillage, cover crops, mulching, grass strips, strip cropping, and others. The effectiveness of these practices might be significantly enhanced by the selective use of composted organic wastes.

In many developing countries composts are often applied on a broadcast/plowdown basis and at rates that are too low to effectively modify soil physical properties, or to provide adequate levels of plant nutrients to sustain crop growth and yield. Since composting is a costly process in most developing countries, there are ways that the farmer can increase the benefit-cost ratio in using these materials to enhance soil productivity and crop yields. This can be done through localized placement techniques such as side-dressing, banding, broad bed and furrow systems, and micro-terraces. Often the crop can be planted, or seedlings transplanted directly into the compost-treated zones, which would provide more favorable moisture conditions and available nutrients for plant growth. Such methods used in conjunction with certain multiple cropping systems (ASA 1976, Francis 1986) may have considerable potential for increasing the agricultural productivity of arid and semiarid lands. Also, where croplands are threatened by various degradative processes, permanent grass strips or tree plantings could be rapidly established after localized placement of compost in soil.

Special Management Practices

There are problems involved in handling and applying organic wastes to land because their physical characteristics are so variable. Such wastes are almost always bulky and can range from liquid on one extreme to dry solid material on the other. Special management practices may be necessary to obtain the full value of organic wastes and crop residues as soil amendments and biofertilizers for arid lands. Methods of application must be simple, inexpensive, energy efficient, and effective for nutrient recycling and erosion control.

An example of a particularly effective soil erosion control measure for sloping lands is vertical mulching, a subsoiling operation that incorporates organic materials such as crop residues into a vertical channel 30 to 40 cm deep and some 10 to 12 cm wide at the soil surface (Parr 1959). The operation is usually conducted on the contour, with spacing ranging from 5 to 10 m. Several rather simple tractor-driven machines have been designed for the vertical mulching procedure.

A modification of the vertical mulching procedure referred to as "slot mulch" has been demonstrated as an effective means of controlling erosion on steeply sloping lands in the semiarid winter wheat area of eastern Washington State (Saxton *et al.* 1981). This technique is performed with a specially designed machine that gathers and compresses crop residues, such as wheat straw, into a vertical channel or slot approximately 10 to 25 cm deep and 3 to 4 cm wide at the soil surface. The slots are formed on the contour and are highly effective in intercepting runoff during winter storms. Both techniques enhance root penetration and development and provide for effective water conservation and storage for crop use.

This concept of residue management may have application in developing countries for restoring the productivity of croplands that have been impaired by certain degradative processes. A variety of organic wastes and crop residues, including composted materials, could be used in either vertical or slot mulching. Slot mulching would require less energy than vertical mulching and could be accomplished more readily with hand labor.

Organic Farming and Low-input/Sustainable Agriculture

The USDA (1980) "Report and Recommendations on Organic Farming" identified a large number of farmers in the United States who are successfully and profitably operating both large and small commercial farms with minimal or no inputs of chemical fertilizers and pesticides. This was also pointed out in a more recent study by Parr *et al.* (1989) on sustainable agriculture in the United States. These studies showed that some farmers rely almost entirely on recycling of organic materials to supply plant nutrients and to maintain soil organic matter, tilth, and productivity. These farmers have a strong commitment to protecting the soil from wind and water erosion, which they do by using sod-based rotations, legumes, green manures, and animal manures. They also subscribe to many of the "best-management practices" cited above.

Such practices could significantly reduce the pollution of surface waters and groundwater by fertilizers and pesticides, lower energy costs, reduce the dependence of farmers on external inputs (e.g. agricultural chemicals), protect and conserve the soil resource base, and maintain an acceptable level of soil productivity over the long term.

The development of stable, productive, profitable, and sustainable farming systems is urgently needed throughout the arid and semiarid regions, both in the United States and in the Third World. The "key" to sustainability is protection and conservation of the soil

resource base. This can best be done by proper use and regular additions of organic amendments. National governments, particularly in the Third World, should give high priority to the establishment of organic waste recycling programs that would facilitate the collection, processing (e.g., composting or cocomposting), and utilization of organic wastes for improving the tilth, fertility, and productivity of agricultural lands. Such a program was initiated in Tanzania by the Rodale Research Center (1983) with some support from the U.S. Agency for International Development. The basic premise here is that the rehabilitation and reclamation of agricultural lands and maintenance of soil productivity are vital to the strength, health, and economic stability of any country.

Soil Productivity: The Resultant of Soil Conservation and Soil Degradation

In developing more sustainable conservation and production systems for the arid and semiarid regions, we need to be reminded that the potential productivity of a particular soil is the resultant of soil conservation practices and soil degradation processes as shown in Figure 3 by Hornick and Parr (1987). For most agricultural soils degradative processes such as erosion, nutrient runoff, and organic matter loss are occurring simultaneously with conservation practices such as crop rotations, reduced tillage, and residue management.

The productivity level of a soil, then, will depend upon the severity of any of the degradation processes and the degree to which they are offset by the conservation practices. On our best agricultural soils (e.g. gently sloping, medium textured, well structured, having a deep profile, and well drained) a high level of productivity can be maintained with relatively few but essential conservation practices. However, many of the soils in the arid and semiarid regions are fragile and marginal (e.g., steeply sloping, sandy or coarse-textured, poorly structured, of shallow depth, low in organic matter, and low in fertility) and the conservation inputs must be maximized to limit soil degradation and to prevent the loss of soil productivity. The single most important component in this dynamic equilibrium is the proper and regular addition of organic amendments.

Future Research Needs

As both developed and developing countries begin to utilize municipal wastes (e.g., sewage sludges and effluents, and garbage) and industrial wastes (e.g., food processing

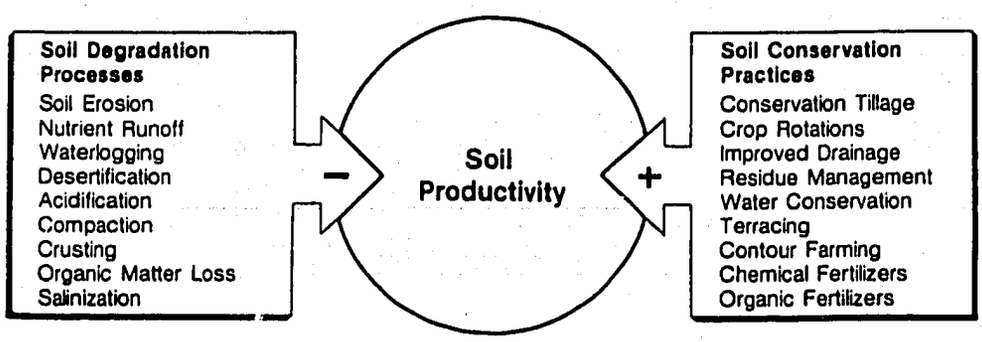

Figure 3. Soil productivity is the resultant of the interaction of degradation processes that tend to lower its potential and conservation practices that tend to raise it.

and acceptable industrial organic wastes) for land application, in addition to traditional organic sources such as animal manures and crop residues, research will be needed to determine how these wastes differ in their ability to improve soil tilth and fertility.

For those countries in arid and semiarid regions, and where desertification and loss of soil productivity have become serious problems, special research efforts will be required to investigate the interaction of soil, residue, waste, and management factors and how they affect the decomposition of organic materials by microorganisms. Such information is urgently needed if we are to develop successful management systems for these very fragile croplands and rangelands, and to maximize the beneficial effects of organic materials to offset degradative processes and increase soil productivity. Future research should focus on the following areas:

(1) Conduct surveys of kinds, amounts, and quality of available organic materials.
(2) Explore chemical, physical, and biological modifications to enhance the value and quality of organic materials.
(3) Develop management strategies for the collection, storage, transport, and handling/processing of organic materials.
(4) Investigate the interaction of mode/method, rate, time, and frequency of application of organic materials to soil for maximum effectiveness and efficiency.
(5) Investigate the role of organic materials as amendments for control of soilborne plant diseases.
(6) Determine the economic value of the organic component of different organic wastes.
(7) Develop methods and management practices for controlling the soil-residue-water regime under field conditions.
(8) Investigate the role of the indigenous waste/residue microflora in the decomposition process.
(9) Investigate chemical treatment of organic wastes and residues to inhibit/retard the rate of decomposition to increase their residual effectiveness.
(10) Determine actual amounts of organic materials needed to limit degradative processes and to increase the agricultural productivity of arid and semiarid lands.
(11) Determine how various nontraditional organic wastes differ in their ability to improve the tilth, fertility, and productivity of soils.
(12) Develop criteria by which the relative effectiveness of different organic amendments as fertilizers and soil conditioners can be compared.
(13) Develop criteria for predicting the nutrient availability and organic stability of different organic wastes under different soil, climatic and cropping conditions.
(14) Develop procedures and analytical techniques that would meaningfully and accurately determine the economic value of organic materials for stabilizing arid and semiarid lands and for increasing their agricultural productivity.
(15) Using a systems approach, determine the most effective strategies for utilizing organic amendments to ensure the long-term sustainability of arid and semiarid lands.

References

Allison, F.E. 1973. *Soil Organic Matter and Its Role in Crop Production*. Elsevier Scientific, New York.

ASA (American Society of Agronomy). 1976. *Multiple Cropping*. ASA Special Publication No. 27. Madison, Wisconsin.

Barbarika, A., D. Colacicco, and W.J. Bellows. 1980. The value and use of organic wastes. *Maryland Agri-Economics, May 1980*. Cooperative Extension Service, University of Maryland, College Park, 5 pp.

Colacicco, D. 1982. Economic aspects of composting. *BioCycle*. 23(5):26–30.

Cook, R.J. and R.I. Papendick. 1972. Influence of water potential of soils and plants on root disease. *Annual Review of Phytopathology* 10:349–374.

Dalmat, D.J., J.J. Parr, A. Von Lignau, and P.A. LaGuerre. 1982. Co-composting's potential for developing nations. *BioCycle* 23(6):43–47.

Dommergues, Y.R., L.W. Belser, and E.L. Schmidt. 1978. Limiting factors for microbial growth and activity in soil, pp. 49–104, in: M. Alexander, ed., *Advances in Microbial Ecology*, Vol 2. Plenum Press, New York.

Duggan, J.C. and C.C. Wiles. 1976. Effects of municipal compost and nitrogen fertilizer on selected soils and plants. *Compost Science* 17(5):24–31.

Eckholm, E. and L.R. Brown. 1977. *Spreading Deserts—the Hand of Man*. Worldwatch Paper No. 13. Worldwatch Institute, Washington, D.C.

Focht D.D. and J.P. Martin. 1979. Microbiological and biochemical aspects of semiarid agricultural soils, pp. 119–147, in: A.E. Hall, G.H. Cannell, and H.W. Lawton, eds., *Agriculture in Semiarid Environments*. Springer-Verlag, New York.

Francis, C.A. 1986. *Multiple Cropping Systems*. MacMillan, New York.

Greb, B.W., D.E. Smika, and J.R. Welsh. 1979. Technology and wheat yields in the central Great Plains: Experiment station advances. *Journal of Soil and Water Conservation* 34:264–268.

Griffin, D.M. 1981. Water potential as a selective factor in the microbial ecology of soils, pp. 141–151, in: J.F. Parr, W.R. Gardner, and L.F. Elliott, eds., *Water Potential Relations in Soil Microbiology*. Special Publ. No. 9. Soil Science Society of America, Madison, Wisconsin.

Hallam, M.F.J. and W.V. Bartholomew. 1953. Influence of plant residue addition in accelerating the decomposition of soil organic matter. *Soil Science Society of America Proceedings* 17:365–368.

Hornick, S.B. and J.F. Parr. 1987. Restoring the productivity of marginal soils with organic amendments. *American Journal of Alternative Agriculture* 2:64–68.

Hornick, S.B., J.J. Murray, R.L. Chaney, L.J. Sikora, J.F. Parr, W.D. Burge, G.B. Willson, and C.F. Tester. 1979. *Use of Sewage Sludge Compost for Soil Improvement and Plant Growth*. Science and Education Administration, Agricultural Reviews and Manuals, Northeastern Region Series 6. U.S. Department of Agriculture. Beltsville, Maryland.

Hornick, S.B., L.J. Sikora, S.B. Sterrett, J.J. Murray, P.D. Millner, W.D. Burge, D. Colacicco, J.F. Parr, R.L. Chaney, and G.B. Willson. 1984. *Utilization of Sewage Sludge Compost as a Soil Conditioner and Fertilizer for Plant Growth*. Agricultural Information Bulletin No. 464. U.S. Department of Agriculture. Beltsville, Maryland. 32 pp.

Mays, D.A., G.L. Terman, J.C. Duggan. 1973. Municipal Compost: Effects on crop yields and soil properties. *Journal of Environmental Quality* 2:89–92.

NAS (National Academy of Sciences). 1981. *Food, Fuel, and Fertilizer from Organic Wastes*. National Academy Press, Washington, D.C.

Odum, E.P. 1971. *Fundamentals of Ecology*. W.B. Saunders, Philadelphia.

Papendick, R.I. and G.S. Campbell. 1981. Theory and measurement of water potential, pp. 1–22, in: J.F. Parr, W.R. Gardner, and L.F. Elliott, eds., *Water Potential Relations in Soil Microbiology*. Special Publ. No. 9. Soil Science Society of America. Madison, Wisconsin.

Parr, J.F. 1959. Effects of vertical mulching and subsoiling on soil physical properties. *Agronomy Journal* 51:412–414.

Parr, J.F. and D. Colacicco. 1987. Organic materials as alternative nutrient sources, pp. 81–99, in: Z.R. Helsel, ed., *Energy in Plant Nutrition and Pest Control*. Elsevier Science, New York.

Parr, J.F., and R.I. Papendick. 1978. Factors affecting the decomposition of crop residues by microorganisms, pp. 101–129, in: W.R. Oschwald, ed., *Crop Residue Management Systems*. Special Publ. No. 31. American Society of Agronomy, Madison, Wisconsin.

Parr, J.F., and R.I. Papendick. 1983. Strategies for improving soil productivity in developing countries with organic wastes, pp. 131–143, in: W. Lockeretz, ed., *Environmentally Sound Agriculture*. Praeger Scientific, New York.

Parr, J.F., W.R. Gardner, and L.F. Elliott, eds. 1981. *Water Potential Relations in Soil Microbiology*. Special Publ. No. 9. Soil Science Society of America, Madison, Wisconsin.

Parr, J.F., P.B. Marsh, and J.M. Kla, eds. 1983. *Land Treatment of Hazardous Wastes*. Noyes Data Corporation, Park Ridge, New Jersey.

Parr, J.F., R.I. Papendick, and D. Colacicco. 1986. Recycling of organic wastes for a sustainable agriculture. *Biological Agriculture and Horticulture* 3:115–130.

Parr, J.F., R.I. Papendick, I.G. Youngberg, and R.E. Meyer. 1989. Sustainable agriculture in the United States. In: *Proceedings of the International Conference on Sustainable Agricultural Systems*. Soil and Water Conservation Society. Ankeny, Iowa (in press).

Rodale Research Center. 1983. *Resource-efficient Farming Methods for Tanzania*. Rodale Press, Emmaus, Pennsylvania.

Saxton, K.E., D.K. McCool, and R.I. Papendick. 1981. Slot mulch for runoff and erosion control. *Journal of Soil and Water Conservation* 36:44–47.

SCSA (Soil Conservation Society of America). 1976. *Land Application of Waste Materials*. SCSA, Ankeny, Iowa.

Shuval, H.I., C.G. Gunnerson, and D.S. Julius. 1981. *Appropriate Technology for Water Supply and Sanitation: Night-soil Composting*. Vol. 10. The World Bank, Washington, D.C.

Stott, D.E., and J.P. Martin. 1989. Organic matter decomposition and retention in arid soils. *Arid Soil Research and Rehabilitation, Special Issue*, 3:115–148.

Tester, C.J., L.J. Sikora, J.M. Taylor, and J.F. Parr. 1982. Nitrogen utilization by tall fescue from sewage sludge compost amended soils. *Agronomy Journal* 74:1013–1018.

UNEP/FAO (United Nations Environment Programme/Food and Agriculture Organization). 1977. *Residue Utilization—Management of Agricultural and Agro-industrial Wastes*. Report of UNEP/FAO Seminar held in Rome, January 13–21, 1977. UNEP/FAO, Rome.

USDA (U.S. Department of Agriculture). 1957. *Soil. The Yearbook of Agriculture*. U.S. Government Printing Office, Washington, D.C.

USDA (U.S. Department of Agriculture). 1978. *Improving Soils with Organic Wastes*. U.S. Government Printing Office, Washington, D.C.

USDA (U.S. Department of Agriculture). 1980. *Report and Recommendations on Organic Farming*. U.S. Government Printing Office, Washington, D.C.

USDA/USEPA (U.S. Department of Agriculture/U.S. Environmental Protection Agency). 1975. *Control of Water Pollution From Cropland. Vol. 1: A Manual for Guideline Development*. U.S. Government Printing Office, Washington, D.C.

USDA/USEPA (U.S. Department of Agriculture/U.S. Environmental Protection Agency). 1976. *Control of Water Pollution from Cropland. Volume II: An Overview*. U.S. Government Printing Office, Washington, D.C.

Willson, G.B. and D. Dalmat. 1983. Sewage sludge composting plants in the United States. *BioCycle* 24:20–33.

Willson, G.B., J.F. Parr, E. Epstein, P.B. Marsh, R.L. Chaney, D. Colacicco, W.D. Burge, L.J. Sikora, C.F. Tester, and S.B. Hornick. 1980. *Manual for Composting Sewage Sludge by the Beltsville Aerated Pile Method*. U.S. Department of Agriculture/U.S. Environmental Protection Agency. EPA-600/8-80-022. U.S. Government Printing Office, Washington, D.C.