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An Overview of Soil and Water Management: The Challenge of Enhancing Productivity and Sustainability

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During the greater part of its existence on earth, the human species subsisted as roving bands or clans engaged in hunting, gathering, and scavenging. From its origin in Africa, the species known as *Homo sapiens* gradually spread to all other habitable continents, adapting to the various ecological conditions and to the vicissitudes of changing climates. The momentous transition from the traditional nomadic mode of life to sedentary farming first took place in the Fertile Crescent, part of the region known today as the Near East, during the so-called Neolithic Age, which began some ten millennia ago.

Subsequently, agriculture in various forms has developed and spread throughout most of the habitable continents. The attainment of relative food security by means of farming and grazing (along with sanitation and medical advances) has enabled the gradual growth of population, from perhaps a few million in Neolithic times to well over six billion today. Current and foreseeable trends are projected to increase the globe's population to some nine or even ten billion by the middle of this century. So far, food production has managed to keep pace, by and large, with population growth (although not in all regions—notably not in parts of Sub-Saharan Africa).

However, the increase of food production has been achieved at a great ecological cost: the progressive encroachment on extensive land and water resources and the eradication of their native biota. Agriculture has indeed appropriated a goodly fraction of the terrestrial domain's net primary productivity, leaving less and less of it to sustain natural ecosystems. Among the most egregious processes of degradation resulting from the spread of agriculture are land denudation and soil erosion, nutrient depletion, salination, and waterlogging, as well as diversion and pollution of surface and subsurface water resources. All these processes amount to an unsustainable exploitation of the Earth's natural resources and its biotic communities. Now looms the prospect of anthropogenic climate change, which threatens to further disrupt established patterns of food production.

The future of agriculture hangs in the balance. What can be done to rectify the destructive practices of the past and present and to ensure the sustainability of agriculture in the face of rising demands, a changing climate, and the growing scarcity and cost of conventional energy sources?

The first requirement is to intensify production on lands that can be improved and managed efficiently, while relieving the pressure on vulnerable or fragile lands that are not, or cannot be, so managed. As currently practiced, much of the world's agriculture is unsustainable, as well as exceedingly inefficient in terms of its energy balance, conservation of resources, and

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doi:10.2136/2011.soilmanagement.c1

Soil Management: Building a Stable Base for Agriculture. Jerry L. Hatfield and Thomas J. Sauer (ed.)

productivity. Hence there is great latitude for improving both the economic efficiency and ecological sustainability of production and resource utilization.

Modes of Cultivation

Agricultural soil management generally consists of a series of practices that include cultivation, planting, fertilization, pest control, irrigation, drainage, and erosion control. The more efficiently these practices are performed and optimized, the more productive and sustainable can agriculture become.

Cultivation or *tillage* is defined as the mechanical manipulation of the soil to improve conditions affecting the various stages of crop production. Three principal aims are generally attributed to tillage: control of weeds, incorporation of organic matter into the soil, and preparation of a favorable seedbed to facilitate germination and seedling establishment. An additional rationale is sometimes claimed for tillage, namely the conservation of soil moisture by enhancing infiltration and inhibiting evaporation. Not all of these traditional claims can be substantiated in many cases.

A distinction must be made between primary tillage and secondary tillage. *Primary tillage* is typically performed by means of moldboard or disk plows, which slice and pulverize a layer of topsoil along parallel furrows and invert it so as to cover the surface residues of plant matter remaining from preceding seasons. An alternative mode of primary tillage is the use of subsoilers and chisels, which break and loosen the topsoil without inverting it. All such methods of primary tillage are generally designed to penetrate to a depth of at least 20 cm, and sometimes to a depth as great as 50 cm.

Secondary tillage is often performed subsequent to primary tillage to repeatedly loosen the topsoil (generally to a depth of no more than 20 cm) and thereby cut the roots of weeds that grow between the rows during the crop growing season. In other cases, secondary "light" tillage is performed in lieu of primary tillage in soils that are naturally loose and require no deeper tillage at all. The implements used for secondary tillage are disk harrows, spike harrows, sweeps, rotary hoes, and various other tools that work the soil to shallow depth and also help to disrupt crusts where they occur. Often, however, such implements, while effective in the short run, ultimately contribute to the degradation of soil structure by excessively pulverizing and grinding down the soil's natural aggregates.

In recent decades, the advent of chemical herbicides has reduced the importance of tillage as the primary methods for the eradication of weeds, although the high cost of such chemical treatments and their residual environmental effects limit their application, especially in developing countries. At the same time, the formerly prevalent practice of inverting the topsoil to bury manures and plant residues has become a less important function of tillage in modern field management. Plant residues can, and in many cases should, be left over the surface as a *stubble mulch* to protect against evaporation and erosion.

An essential task of agriculture is soil structure management because it affects water infiltration and runoff, wind erosion and evaporation, gas exchange and soil aeration, as well as the planting and germination of crops. However, tillage practices suitable in one location may become harmful in another. Arid-zone soils with low organic matter contents and unstable aggregates are particularly vulnerable to compaction, crusting, and erosion by wind (during dry spells) and by water (during rainstorms). The precise effects of various modes of tillage must be defined for each set of conditions to ensure the sustainability of soil management.

Tillage operations are especially consumptive of energy. The amount of earth-work involved in repeatedly loosening, inverting, and then recompacting the topsoil is indeed very considerable. In a typical field of 1 ha, the topsoil to a depth of only 30 cm weighs no less than 4000 tons. In an extensive farm of 1000 ha, the mass of soil thus manipulated in each cycle of operation may exceed 4 million tons. The consumption of energy, as well as the wear and tear of tractors and implements, increases steeply as the depth of tillage increases. With the rising cost of fuel, the costs of tillage also increase progressively. Much damage is done to soil structure by the repeated passage over the soil of heavy tractors and other machinery, and such damage, which induces erosion while inhibiting infiltration, aeration, germination, and root development, is difficult to rectify.

Current trends in soil management are aimed at minimizing tillage operations and overland traffic, both to reduce costs and to avoid soil compaction, while tailoring each operation to its specific zone and objective. This approach, in principle, underlies the methods variously termed *minimum tillage*, *precision tillage*, and even *zero tillage* or *no-till*. The tendency is to adopt a system of "precision farming," which consists of a balanced combination of practices designed to optimize nutrient supply, tillage, water use, and pest control. Instead of treating a large block of land uniformly, the effort is to define the soil's inherent heterogeneity so as to adapt all operations to the space-variable and time-variable requirements for applying pesticides, fertilizers, seeds, and water.

The entire set of practices thus described replaces the old tradition of "clean cultivation" of the entire top layer of the soil, which in the past entailed burning or plowing-in the stubble of previous crops and disrupting the natural structure of the soil, thus making it more vulnerable to erosion. Instead, special equipment is used that is designed to sow seeds into narrow slits while retaining the residues on the surface between the rows. The organic matter remains at the surface, called *mulch*, helping to conserve moisture and protect the soil against erosion. The problematic aspect of zero tillage is that it relies on the use of herbicides instead of mechanical cultivation to eradicate weeds that might otherwise compete with crop plants for moisture, nutrients, space, and sunlight.

The Practice of Irrigation

Irrigation is the supply of water to agricultural crops so as to permit farming in arid regions and to offset periodic droughts in semiarid regions. Wherever rain-fed farming is a high-risk enterprise due to erratic rainfall, irrigation can help to ensure stable and reliable production.

Irrigation has long played a key role in feeding populations and is expected to play a still greater role in the future. Although irrigated land amounts to only some 17% of the world's cropland, it contributes about 40% of the value of agricultural production. That vital contribution is most important in arid regions, where the natural supply of water by rainfall is least even as the demand for water, imposed by the bright sun and dry wind, is greatest.

Ideally, irrigation not only raises the yield of specific crops but also prolongs the effective crop-growing period in areas with extended dry seasons, thus permitting multiple cropping each year where only a single crop could be grown otherwise. With the security provided by irrigation, additional inputs needed to intensify production (e.g., pesticides, fertilizers, improved varieties, physiological treatments, environmental controls, and soil amendments) can become economically feasible. Irrigation reduces the risk of such expensive inputs being wasted by crop failure due to lack of water.

The practice of irrigation consists of applying water to the part of the soil that serves as the root zone, for the immediate and subsequent use of the crop. However, the initiation and continuation of irrigation in a given area tends to induce a series of processes that can profoundly affect both the on-site and the related off-site environments. Over time, some of its potentially self-destructive effects may make the very practice of irrigation unsustainable.

Off-Site Aspects of Irrigation

The first requirement of an irrigation project is a dependable supply of fresh water and the means to deliver it to the site to be irrigated. The second requirement is the availability of suitable land and soil in which to grow the crops under irrigation. The third requirement is an outlet for the safe disposal of wastewater from the irrigated land. Every irrigation project therefore consists of withdrawing water from some source (e.g., a lake, an aquifer, or a river) and diverting it to the site of irrigation. In the process, inevitably, that water is denied to some other site that had been its natural recipient. In the typical case of a river valley project, changes take place both in the upstream and in the downstream sections of the riverine domain.

River flow is generally time-variable. More often than not, the season of peak irrigation demand coincides with the period of low river flow. Hence, an irrigation project typically requires the construction of engineering structures—dams and canals—designed to regulate the flow so as to ensure adequate storage and supply throughout the growing season.

Dam construction is a problem in itself. Appropriate locations for dams are relatively rare. The ideal topographic, geologic, and climatic conditions are seldom found in the proximity of target irrigation projects, and less-than-ideal conditions may make the construction and maintenance of dams economically prohibitive and environmentally unsustainable. Unfavorable topography may require very massive construction and may result in the submergence of very large areas, with consequent damage to natural ecosystems, displacement of long-established human populations and infrastructure, and loss of historical cultural heritage and scenic sites. Some areas are inherently vulnerable to potential natural disasters such as earthquakes. Porous or fractured substrata may cause great losses of water by practically uncontrollable seepage, and a dry climate may impose additional losses of water by evaporation. A case in point is the Aswan Dam and its associated lake in Egypt, located in the midst of the Earth's driest desert, where evaporative losses of water may be in the range of 12 to 16 billion cubic meters per year—some 20% of the inflow.

Additional losses of water by evaporation and uncontrolled seepage occur in the system of conveyance from a dam to the fields. Generally, this conveyance takes place via canals and ditches, which, in the interest of minimizing costs, are often dug into the ground and left unlined (i.e., not underlain with concrete or some other impervious and scour-resistant material). Even where closed conduits (i.e., metallic, ceramic, or concrete pipes) are installed, in time they tend to develop leaks and to incur considerable losses of water and hydraulic pressure.

Water storage behind dams is also subject to silting, which, gradually over a period of some decades, reduces a dam's capacity and may eventually clog up its storage basin entirely. Silt accumulation in reservoirs and canals is especially rapid in regions where the upper watersheds of the river have been denuded of their natural vegetative cover by overgrazing and further destabilized by excessive cultivation, thus subjecting the catchments to accelerated soil erosion.

Thus far, we have listed processes that may take place upstream of an irrigated area. In addition, irrigation also entails a series of processes that occur downstream. The first of these is the diminution of the river flow resulting from the extraction of the water used for irrigation. Consequently, all the associated riparian ecosystems along the riverbanks, floodplain, and estuary are deprived of vital water supplies and thereby impoverished. Natural wetlands that were originally biologically diverse and highly productive may be subject to periodic or permanent desiccation, and even to the eradication of vital species or biotic habitats, especially spawning fisheries. Where a river discharges naturally into a freshwater lake, the deprivation of the lake's inflow resulting from the river's diversion for irrigation may cause the lake to shrink markedly, and in places drastically. The shrinkage of the Aral Sea in central Asia is a prime example of the sort of environmental disaster that can be caused by large-scale irrigation development.

These environmentally damaging processes are often exacerbated by the downstream disposal of irrigation-generated wastes. Drainage from irrigated lands may be laden with salts, as well as with residues of the fertilizers and pesticides that are often applied in excess to the irrigated crops. If the drainage from the bottom of the root zone percolates toward an aquifer, it may gradually contaminate its groundwater and make the aquifer unusable for humans. In extreme cases it may even become unsuitable for irrigation. Nitrates, as well as chlorides, may accumulate in groundwater underlying irrigated lands, to the extent of posing a health hazard to communities relying on wells. Other agents contained in the drainage from irrigated agriculture, as well as from households and industries, are various toxic and carcinogenic elements and compounds from pesticides.

Where the drainage from irrigated lands is channeled through ditches or pipes and discharged into the river downstream, it may pollute the water there and make it unusable for people as well as harmful to natural fauna and flora. The alternative to discharging the drainage into the river is to convey it to the sea, to lagoons or wetlands (whose biota, however, may also be vulnerable to the pollutants), to environmentally isolated evaporation basins in the desert, or to very deep aquifers where the pollutants are diluted. All of these alternatives may be quite expensive to carry out, and perhaps unsustainable in the long run. The Kesterson Reservoir in the Central Valley of California is an example where the discharge of drainage from irrigated areas into wetlands has resulted in damage to wildlife because of the accumulation of waterborne toxic elements.

On-Site Aspects of Irrigation: The Hazard of Soil Degradation

The twin processes of degradation that typically affect irrigated lands in river valleys and low-lying coastal plains, specifically those in arid regions, are waterlogging and salination. Waterlogging results from the tendency of irrigators to apply a volume of water to the soil in excess of the amount of soil water taken up by the crop. In part, this is a matter of necessity, to prevent the root zone from accumulating salts.

Irrigation water is never entirely pure; hence, the application of irrigation necessarily adds water-borne salts to the soil. Moreover, many arid-zone soils and subsoils contain natural reserves of salts, which are also mobilized by irrigation. Since crop roots typically exclude most salts, the salts left in the root zone tend to accumulate to the detriment of the crop, unless leached from the soil and driven downward by drainage.

Maintaining an optimal balance of water and salts in the root zone is a delicate dynamic process. Water flowing downward below the root zone eventually reaches the water table and augments the groundwater saturating the substrata. If the water table remains deep and the groundwater beneath it has its natural outflow, the balance of water and salts in the root zone can remain favorable to crop growth. If, however, the water table is shallow and the rate of natural groundwater drainage is slow, the addition of irrigation water from above will cause the water table to rise. Sooner or later (perhaps within a few decades) the water table approaches the soil surface. The root zone then becomes saturated with water and deprived of oxygen. Since most crop plants require oxygen in the soil for their roots to respire, the saturation of the root zone itself restricts crop growth and, in the case of sensitive plants, may cause total crop failure.

The deleterious effect on soil productivity resulting from waterlogging is further exacerbated by soil salination, which typically occurs in arid regions wherever the groundwater is brackish and the water table rises toward the surface. Instead of percolating downward and leaching away the salts, the groundwater seeps upward to the soil surface in response to evaporation-induced suction gradients. As the groundwater evaporates, it leaves salts behind. So much salt can accumulate at and near the surface as to render the soil sterile to most crops. In this manner, well-intentioned irrigation projects can, quite inadvertently, cause the degradation of originally productive soils.

A further scourge of irrigation is the phenomenon of soil sodicity (also called alkalinity), a condition caused by the specific effect of sodium ions adsorbed onto the electrostatically charged clay particles. Such particles normally attract a swarm of cations in the aqueous phase (the ambient solution) that surrounds the particles. These cations are exchangeable, in the sense that they can be replaced by other cations whenever the composition of the ambient solution changes.

Divalent cations such as calcium ions tend to compress the ionic swarm surrounding the particles, thus allowing the particles to approach one another sufficiently to clump together and to form flocs (a process termed *flocculation*, which contributes to the formation of a desirable soil structure). In contrast, monovalent cations such as sodium tend to diffuse farther away from the particle surfaces and thus to thicken the hydration envelope surrounding each particle. This, in turn, causes swelling and dispersion of the soil flocs (a process termed *deflocculation*, which in effect thickens the hydration envelopes surrounding the clay particle and causes them to draw apart from one another). The latter process destroys soil aggregates and restricts the soil's permeability to water and air. When wet, a sodic soil becomes a slick and sticky mud; when dry, however, it hardens to form a tough crust. This condition reduces the entry of water and air into the soil and also forms a barrier to the emergence of germinating seedlings and to the penetration of their roots.

Sustainability of Irrigation

The sustainability of irrigation is never to be taken for granted. Waterlogging and salination of soils, along with other degradation processes, not only have caused the collapse of irrigation-based societies in the past, but are indeed threatening the viability of irrigation at present. The problem is global in scope. Decimation of natural ecosystems, deterioration of soil productivity, depletion and pollution of water resources, and conflicts among sectors and states over dwindling supplies and rising demands have become prevalent and pressing problems closely linked with the practice of irrigation in various regions.

Irrigated agriculture can be sustained in the long term only if and where certain stringent requirements are met. The requirements are effective prevention of upstream, on-site, and downstream damage to the environment.

Although there are cases where the degradation is already severe and remediation may seem impractical or prohibitive, in most cases irrigation projects can and should be made sustainable, provided the correct diagnosis and actions are undertaken.

To be and remain viable, irrigated agriculture must strive for a balance between the immediate need to maximize production and the ultimate need to ensure continued productivity in the future. It must also strive to achieve a harmonious interaction with the external environment, which includes both natural ecosystems and other human enterprises. More specifically, irrigation projects should ensure that water supplies of adequate quality are and will continue to be available, the salt balance and hence the productivity of the land can be maintained, the drainage effluent can be disposed of safely, public health can be safeguarded, and the economic returns can justify the costs of initial investment and subsequent continuing upkeep.

The key to ensuring the sustainability of irrigation is the timely installation and continuous operation of a drainage system to prevent waterlogging and to dispose safely of excess salts. All too often drainage creates off-site problems beyond the on-site costs of installation and maintenance, since the discharge of briny effluent (e.g., into a stream or a lake) can degrade the quality of water along its downstream course. Where access to the open sea is feasible, solving the problem is likely to be easier than in closed basins or in areas far from the sea. In those cases, the disposal terminus eventually becomes unfit for human use, as well as for wildlife, hence the importance of reducing the volume and salinity of effluents by such means as improving the efficiency of water use, a task that in itself can bring economic and environmental rewards. Modern irrigation technology offers the opportunity to conserve water through reduced transport and application losses, coupled with increased yields per unit volume of water.

Modern Irrigation

In recent decades, revolutionary developments have taken place in the science and art of irrigation. A more comprehensive understanding has evolved regarding the soil–crop–water regime as affected by climatic, physiologic, and soil edaphic factors. These conceptual developments have led to technical innovations in water control that have made possible the maintenance of near-optimal conditions of soil moisture, aeration, and nutrients throughout the growing season.

Foremost among the innovations are techniques of high-frequency, low-volume, partial-area applications of water and of fertilizers directly into the rooting zone at rates calibrated to satisfy crop needs. Properly applied, these irrigation methods can raise yields while minimizing waste (by runoff, evaporation, and excessive seepage), reducing drainage requirements, and promoting the integration of irrigation with essential concurrent operations such as fertilization and pest control. The use of brackish water has become more feasible, as has the use of sandy, stony, and steep lands previously considered unirrigable. Additional potential benefits include increased crop diversification and cropping intensity (i.e., the number of crops that can be grown in succession each year).

The traditional method of irrigation consisted of flooding the land to some depth with a large volume of water so as to saturate the soil completely, then waiting some days or weeks until the moisture stored in the soil was nearly depleted before flooding the land once again. In this low-frequency, high-volume, total-area pattern of irrigation, the typical cycle consisted of periods of excessive moisture alternating with periods of insufficiency. Optimal conditions occurred only briefly in transition from one extreme condition to the other.

In contrast, the newer methods of irrigation are designed to apply a small, measured volume of water at frequent intervals precisely to where the roots are concentrated. The aim is to reduce fluctuations in the moisture content of the root zone by maintaining optimal conditions continuously, without subjecting the crop either to oxygen stress from excess moisture or to water stress from lack of moisture. Moreover, applying the water to the base of the plants (at the soil surface or just below it, along the crop rows) has the effect of keeping much of the soil surface between the rows in a dry state, thus helping not only to reduce evaporation but also to suppress the proliferation of weeds.

Since the high-frequency irrigation systems can be adjusted to supply water at very nearly the exact rate required by the crop, the irrigator no longer needs to depend on the soil's ability to store water during long intervals between irrigations. Hence the water-storage properties of the soil, once considered essential, are no longer decisive in determining whether a soil is suitable for irrigation. New lands, traditionally believed to be unsuitable for irrigation, can now be brought into production. Examples are coarse sands and gravels, where moisture storage capacity is very low and where the conveyance and spreading of water by surface flooding would cause too much seepage.

Of particular interest is the method of *drip irrigation* (also called *trickle irrigation*) and its many variants, such as *microsprayer irrigation*. The idea of applying the water slowly, literally one drop at a time, at a rate that is absorbed by the root zone continuously, is not entirely new. However, what has made it practical was the development of low-cost weathering-resistant plastic tubing and variously designed emitter fittings. System assemblies are now available that are capable of maintaining sufficient pressure in thin lateral tubes to ensure uniform discharge of water throughout the field, with a minimum of clogging. A variant of the system is the subsurface placement of perforated or porous tubes that can ooze water continuously with practically no loss due to evaporation.

The application systems described have been supplemented by ancillary equipment such as filters, timing or metering valves (enabling the irrigator to predetermine the quantity, duration, and frequency of irrigation), and even equipment to inject fertilizers and pesticides into the water supply. Mechanical clogging by suspended particles in the water supply can be prevented by proper filtration, whereas chemical clogging by precipitating salts and biological clogging by algae can be reduced by slight acidification and algicidal treatment of the water. Numerous trials in varied locations have resulted in increased yields of both orchard and field crops (perennial as well as annual), particularly in adverse conditions of soil, water, and climate. Drip irrigation is also applied widely for greenhouses and gardens and lends itself readily to labor-saving automation.

A variant of high-frequency irrigation applicable to large-scale mechanized farms is the so-called *center-pivot irrigation system*. It consists of a central vertical pipe that delivers water to a horizontal rotating tube fitted with sprinklers or drippers. The horizontal tube circles continuously, and can thus irrigate a large area automatically. The speed of rotation can be adjusted so that every spot of land (and every plant) receives an increment of irrigation at high frequency (e.g., several times daily) throughout the growing season. The water-application rate can be adjusted according to the variable (weather-determined) evaporative demand and to the stage of crop growth. The circular pattern of center-pivot irrigation systems can be observed from the air by airline passengers flying over large sections of the U.S. Great Plains.

Drainage Requirements

The term *soil drainage* refers in a general sense to the outflow of water from soil. More specifically, it can serve to describe the artificial removal of excess water or the set of management practices designed to prevent the occurrence of excess water. The removal of free water wherever it tends to accumulate over the soil surface, achieved by appropriately shaping the land surface, is termed *surface drainage*. The removal of excess water from within the soil, generally by lowering the water-table or by preventing its rise, is termed *groundwater drainage*, and it is an integral aspect of sustainable soil management.

Groundwater drainage is generally achieved by means of ditches, pipes, or "mole channels," into which groundwater flows as a result of the hydraulic pressure gradients existing in the soil. The drains themselves are made to direct the excess water, by gravity or by pumping, to an outlet, which may be a stream, a lake, an evaporation pond, or the sea. In some places, drainage water may be recycled, or reused, for agricultural, industrial, or ecological purposes.

Water-Use Efficiency

Any concept of efficiency is a measure of the output obtainable from a given input. Irrigation efficiency, or water-use efficiency, can be defined in different ways, however, depending on the nature of the inputs and outputs considered. For example, one can define as an economic criterion of efficiency the financial returns in relation to the money invested in the installation and operation of a water-supply system. The difficulty is that costs and prices fluctuate from year to year and vary widely from place to place, so they are not universally comparable. Another criterion for the relative merit of an irrigation system is an agronomic one, namely the added yield resulting from irrigation per unit of land area, or per unit volume of water applied.

A widely used expression of efficiency is the *crop water-use efficiency*, which is defined as the amount of vegetative dry matter produced per unit volume of water taken up by the crop from the soil. Because most of the water taken by plants in the field is transpired, while generally only a small amount is retained, the plant water-use efficiency is in effect the reciprocal of what had long been known as the *transpiration ratio*, defined as the mass of water transpired per unit mass of the dry matter produced by the plants.

What irrigation engineers term *irrigation efficiency* is defined as the net amount of water added to the root zone divided by the amount of water taken from some source. As such, this criterion of efficiency can be applied to large regional projects, to individual farms, or to specific fields. In each case, the difference between the amount withdrawn from the source and the net amount of water added to the root zone represents the loss incurred in conveyance and distribution.

The *agronomic efficiency of water use* (WUE) can be defined as follows:

$$\mathrm{WUE} = P/W \qquad [1]$$

where P is crop production, either in terms of total dry matter or the marketable product, and W is the volume of water applied.

Since only a fraction of the applied water is actually absorbed and used by the crop, we need to consider the various components of the denominator W as follows:

$$W = R + D + E_d + E_s + T_w + T_c \qquad [2]$$

Here R is the volume of water lost by runoff from the field, D is the volume drained out of the root zone by deep percolation, E_d is the volume lost by evaporation during delivery and application of water to the field, E_s is the volume evaporated from the soil, T_w is the volume transpired by weeds, and T_c is the volume transpired by the crop. All these volumes pertain to the same unit area and time period.

Water-use efficiency can be maximized by increasing crop yield (P) and by reducing the amount of water use (W). Crop yields can be increased by using high-potential varieties that are well adapted to the local soil and climate and by optimizing agronomic practices. The latter includes proper timing and performance of planting and harvesting, tillage, fertilization, and pest control. Of the items included in the term W, the one that generally should not be reduced is the transpiration by the crop. In the open field, little can be done to limit transpiration without curtailing growth and yield. This is because the unrestricted absorption of carbon dioxide, required to maximize photosynthesis, depends on the stomates remaining open, a condition that generally allows unrestricted transpiration as well. (Differences do exist, however, between C3 and C4 plants with respect to their physiological responses to water stress.)

Plant diseases and pests, as well as competing weeds and deficient fertility of the soil, may depress yields without a proportionate decrease in water use. All management practices can thus influence water-use efficiency, and none can be considered in isolation from the others. Given the expected increase in the world's population and the necessity to alleviate human deprivation while maintaining biodiversity and environmental quality, and given the limited availability of suitable land and water resources, there is an imperative need to improve the efficiency and ensure the sustainability of soil and water management in all regions of agricultural production.

Contemporary Issues

Several problems beset the present and threaten the future of agriculture. The first of these is the progressive expropriation and degradation of land areas and their ecosystems by the voracious demands of expanding populations, most especially in fragile tropical regions. The alternative to this threat is the intensification of production via sustainable resource management of favorable lands, coupled with the release of degradable lands and restoration of their naturally functioning ecosystems. The necessary intensification of land use must be based on the protection of soil and water resources against abuse and degradation by means of effective methods of conservation and quality enhancement.

Important advances have been made in recent years in the development of efficient soil management, including conservation tillage (minimum tillage, or even zero-tillage), precision application of nutrients to prevent contamination and eutrophication of the environment, maintenance of protective mulch coverage over the land surface to minimize evaporation and erosion by wind and rain, and the practice of agroforestry to restore the biotic community and its ecosystem services.

Dramatic advances have been made in the practice of irrigation, including the high-frequency, low-volume application of water precisely calibrated to answer the time-variable and space-variable needs of growing crops while minimizing the waste of water by evaporation, runoff, and excessive seepage (as well as the restriction of root-zone aeration, leaching of nutrients, and the scourge of salination) which have beset irrigated agriculture throughout history.

Advances have also been made in the control of the aerial environment of crops, by means of plastic covers to control and optimize light intensity and composition, temperature, atmospheric humidity and composition (e.g., CO_2 concentration), as well as to control fungal and insect infestation. The objective of all such environmental measures, coupled with genetic improvement of the yield potential of crops, must be to greatly increase yields per unit of land area and of resource investment (including energy), while ensuring the integrity and sustainability of the larger environment.