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# 10 Sustainable Soil Water Management Systems

*G. Basch, A. Kassam, T. Friedrich, F.L. Santos, P.I. Gubiani, A. Calegari, J.M. Reichert, and D.R. dos Santos*

## CONTENTS

## 10.1 INTRODUCTION

During the twentieth century, global water withdrawal increased about sevenfold, from 579 to 3917/km³ year. In the same period, the share of total water use by agriculture declined from 91% to 66% and it is supposed to decrease to around 61% by 2025 (Ghassemi and White 2007). Over the last decades, there was a considerable decline in the ratio of water consumption (nonrecoverable withdrawn water, i.e., lost by evapotranspiration [ET]) to water withdrawal, from 66% in 1940 to 60% in 2000 (Shiklomanov and Rodda 2003), meaning that water was used more efficiently, especially in the agricultural sector.

Whereas irrigation water use represents almost 70% of total human "blue" water use (water withdrawn from water bodies such as river, lakes, and aquifers) (Rockstrom et al. 2009a), global agricultural blue water consumption, that is, the amount of water that transpires productively through crops or evaporates unproductively from soils, water bodies, and vegetation canopies, is estimated to be even higher (Rost et al. 2008). In addition, nonquantifiable amounts of fossil, nonrenewable groundwater resources, or nonlocal water resources from distant regions are used for irrigation (Vörösmarty et al. 2005). Table 10.1 summarizes the global freshwater pools based on the data compiled by Shiklomanov and Rodda (2003). Although 30% of the global freshwater resources are stored as groundwater, and less than 0.3% in rivers and lakes, the latter are the main sources of fresh water for human use as they represent the dynamic component of the earth's total water resources (Shiklomanov 1993). Whereas global groundwater withdrawals amount to around 20%–25% of the total water withdrawals (Shiklomanov and Rodda 2003; Rosegrant et al. 2002), irrigation in many countries relies heavily on groundwater, with 53% and 46% of irrigation water being pumped from aquifers in countries such as India and the United States, respectively (Shah et al. 2007). Locally, groundwater resources are already overexploited, with the rate of water withdrawal being faster than recharge, causing water tables to fall (Gleick et al. 2002). Globally, about 15%–35% of irrigation withdrawals are estimated to be unsustainable; many of these withdrawals are from groundwater sources (Rosegrant et al. 2009).

**TABLE 10.1**
**Global Distribution of Fresh Water**

| Global Pools of Freshwater | ($10^{12}$ m³) | (%) |
|---|---|---|
| Fresh groundwater | 10530 | 30.06 |
| Glaciers, permanent snow and permafrost | 24364 | 69.55 |
| Lakes (fresh water) | 91 | 0.26 |
| Marshes and swamps | 11.5 | 0.03 |
| River water | 2.12 | 0.01 |
| Biological water | 1.12 | 0.00 |
| Water in the atmosphere | 12.9 | 0.04 |
| Soil moisture | 16.5 | 0.05 |
| Total | 35029.14 | 100 |

In addition to the expected increase in agricultural water use to meet the demand for more food, the ongoing urbanization of the world's population will require an increased share of the fresh water available. Based on the estimation of a world population of 9.2 billion people by 2050 and a dietary change driven by higher incomes and urbanization, world food demand is supposed to increase by 70% (or by 100% in the developing world) within less than 50 years (Bruinsma 2009; Thompson 2007). There are only two ways to cope with this increased projected demand, not only for food and feed, but also for fiber and biofuel: by a substantial increase in cropland and/or a large improvement in productivity per unit of land cropped. Based on an optimistic scenario of water availability and management in which a theoretical maximum of 85% of the total ET from cropland and pasture was assumed to be available for plant transpiration and thus biomass production, Rockstrom et al. (2009a) suggested that without improvements in water productivity (WP), a horizontal cropland expansion by about 1000 Mha would be required to produce the food for >10 billion people, which is two-thirds of today's cropland (Ramankutty et al. 2008). In fact, regarding this option, Thompson (2007) considers the possibility of the area of land in farm production being doubled, but only with the massive destruction of forests and the loss of wildlife habitat, biodiversity, and carbon sequestration capacity.

Several authors consider a potential increase in cropland of around 9%–12% as realistic and feasible (Bruinsma 2009; Molden 2007; Thompson 2007), not taking into account that around 10 Mha may be lost every year due to soil erosion, other forms of degradation, and conversion to nonfarm uses (Leach 1995; Pimentel et al. 1995), indicating that cropland expansion could be close to zero (Postel 1998) and that the increasing demand has to be satisfied by higher crop productivities. However, with the exception of sub-Saharan Africa, most of the productivity enhancement potential of the "Green Revolution" technologies has already been exploited (Molden 2007). This means that the gains in agricultural productivity must be achieved through advances in other areas, such as the improvement in soil fertility and water-use efficiency (WUE), and the use of biotechnological innovations to further enhance the efficiency of the already applied inputs and to improve crop performance under stress conditions.

Although water is considered a renewable resource because it depends on rainfall, its availability is finite in terms of the amount available per unit time in any one region (Pimentel et al. 2004). Considering an optimistic scenario, Molden (2007) estimates the agricultural water withdrawal to increase by only 13% by the year 2050. Therefore, and bearing in mind the limited blue water resources and the rapidly increasing competition of other sectors for this resource, the necessary gains in agricultural productivity will depend strongly on improvements in the use of "green" water (precipitation or water that is stored in the root zone) (Rockstrom 2009a). Rost et al. (2008) consider it a misconception to regard agricultural water consumption as dependent primarily on blue water withdrawals. In fact, around 80% of global cropland is rainfed, and 60%–70% of the world's food is produced on rainfed land, that is, by the consumption of precipitation water infiltrated into the soil (Falkenmark and Rockstrom 2004). Further, green water also plays an important role on irrigated land in situations where blue water is only used to supplement the crop water requirement for optimal growth and production. Based on the application of different models, Rost et al. (2008) estimated that a share of over 85% of green water was being consumed on the global cropland. This underpins the statement made by Hoff et al. (2010) that an integrated water resources management (IWRM) relying on blue water only can no longer provide complete sustainable solutions. These authors also refer to the increasing interest in the potential of the "invisible" green water resource for additional crop production.

Managing precipitation as a key resource for production intensification, through integrating green and blue water, has been postulated as the basis of a new paradigm to help close the water gap (Falkenmark and Rockstrom 2004). From a hydrological perspective, in many regions, including those in the semiarid areas, there is enough rainfall to increase crop yields considerably without recourse to the development of large-scale irrigation schemes (Rockstrom et al. 2007). Rockstrom (2000) has recorded estimates of rainfall losses due to unproductive soil evaporation, surface runoff, deep percolation and interception losses of up to 70%–85%. Irrigation plays and will continue to play an important role in feeding the growing world population, and there still exist a need and opportunities for an expansion of the irrigated cropland. However, to avoid at least half of the additional water requirements in agriculture, Rockstrom et al. (2007) have suggested two possibilities: (i) reduction of green water losses, that is, WP improvements in irrigated and rainfed agriculture, and (ii) better use of the local rainfall water.

In this context, soil quality and its management must be considered as key elements for the effective management of water resources, given that the hydrological cycle and land management are intimately linked (Bossio et al. 2007). Bossio et al. (2010) have described soil degradation as the starting point of a negative cycle of soil–water relationships, creating a positive, self-accelerating feedback loop with important negative impacts on water cycling and WP. Therefore, sustainable soil management corresponds to sustainable water management through the improvement of soil water management.

The purpose of this chapter is to review the existing options of soil water management systems and their potential contribution to the improvement of the available soil water in the root zone, WUE, and WP. Ultimately, these water-related aspects seem to be the only solution to producing enough food, feed, fiber, and biofuels for 1.5 times today's world population, without competing excessively with the existing natural ecosystems and their services and the water resources allocated to them and to other human activities.

## 10.2 PROCESSES AFFECTING SOIL WATER DYNAMICS

Although the earth's land surface (29.2% of total surface) contributes only 14% to total evaporation, it receives around 20% of the precipitation falling on earth (Pimentel et al. 2004). About $115 \times 10^{12}$ $m^3$ of precipitation corresponds to about 780 mm of the land surface, on an average (Table 10.2). The transfer of this significant portion of water from oceans to land surface is of vital importance not only to agriculture but also to human life and natural ecosystems. Equally important is the fact that soils are able to store around 20% of the water annually transferred from the land surface to the atmosphere by evapotranspiration.

Globally, it is estimated that out of the total precipitation over the continents, one-third becomes blue water, that is, runoff into rivers and aquifer recharge, and two-thirds infiltrate the soil, forming the so-called "green water" that supports, productively or unproductively, biomass production and returns to the atmosphere as vapor (Hoff 2010). Numerous hydrological models can be found in the literature that attempt to describe water partitioning at different scales, depending on the pretended objectives. Lal (2008b), for example, described the processes of water loss from agricultural watersheds using the equation:

$$P = R + I + D + \Delta\theta + \int Edt + \int Tdt, \qquad (10.1)$$

where P is the precipitation, I is the infiltration, R is the runoff, D is the deep drainage, Δθ is the change in soil water storage, T is the transpiration, E is the soil evaporation, and t is the time.

Lal (2008b) considered the sum of the runoff and deep drainage as blue water and the consumptive transpiration water as green water. Ngigi et al. (2006) used the same partitioning components to characterize the available crop water over a season and to describe the aspects of in situ rainwater harvesting and management systems. Still other components are used in water balance equations. For example, to model soil water storage, Makurira et al. (2010) used Equation 10.2, based on a water balance model from Savenije (1997).

$$\frac{dS_s}{dt} + \frac{dS_u}{dt} + \frac{dS_g}{dt} = P - E_T - E_I - E_s - Q_g - Q_s, \qquad (10.2)$$

where (all terms in mm/day) P is the precipitation received in the system, $E_T$ is the transpiration, $E_I$ is the evaporation from interception, that is, from the canopy cover and the soil surface, $E_s$ is the evaporation from the soil, $Q_s$ is the net surface runoff, $Q_g$ is the groundwater run off, $dS_s/dt$ is the rate of change of surface water storage, $dS_u/dt$ is the rate of change of water storage in the root zone, and $dS_g/dt$ is the rate of change of groundwater storage.

Compared with Equation 10.1, Equation 10.2, in addition to introducing the component groundwater runoff, considers the evaporation of canopy-intercepted rainwater and the wet soil surface ($E_I$). According to Savenije (2004), depending on the local conditions, the latter can amount to 40%–50% of the total precipitation. Therefore, this author advocates the abandonment of the term "evapotranspiration" as it only reflects the incapacity to separate the different evaporative processes, that is, evaporation from interception, transpiration, soil evaporation, wet surface, and open-water evaporation, such as water retained at the soil surface or flooded rice fields. Although classified as unproductive flux, evaporation through interception is not regarded as a loss to the water system because it is responsible for the moisture recycling that sustains continental rainfall. Hence, this component cannot be included in the green or blue water fraction.

On cropland, the partitioning of the precipitation into the different components of the water balance (runoff, soil and plant [interception] evaporation, transpiration, deep percolation) may vary tremendously, depending on the agroecological characteristics of the site, mainly the soil type and management, slope, plant cover, and rainfall characteristics. On two different soils in Central India, Laryea et al. (1991) determined over a period of 4 years a blue water share (runoff and percolation) of total rainfall of 37% and 59%. Whereas runoff was similar at both sites (28% and 26%), deep percolation differed considerably, reaching 9% and 33%, respectively. Modeling water partitioning at field scale based on onsite observations at two sites in northern Tanzania, Makurira et al. (2010) also observed big differences in the water partitioning when comparing the traditional and the innovative farming practices, using the runoff diversion to crop plots. They found that the slope of the field and the soil depth contributed decisively to the partitioning of both the rainwater and the diverted runoff and that interception accounted for one-fourth and one-third of the total precipitation for the two sites, respectively. Figure 10.1 gives an overview of the components of the water balance over a landscape or watershed.

Considering the limited land and water resources suitable to produce enough commodities for the growing world population, while sustaining other ecosystem services provided by agriculture, one of the main strategies by which agricultural water management can deal with the large tradeoffs between water uses is improving water management practices on agricultural lands (Gordon

**TABLE 10.2**
**Global Fluxes of Fresh Water (Annual)**

| Water Flux Component | Units | Amount |
|---|---|---|
| Total earth's evapotranspiration | $10^{12}$ $m^3$ | 577 |
| Evapotranspiration from oceans (86%) | $10^{12}$ $m^3$ | 496.2 |
| Evapotranspiration from land (14%) | $10^{12}$ $m^3$ | 80.8 |
| Average rainfall on land surface (20% of global ETP) | mm | 780 |
| River runoff (into oceans) | $10^{12}$ $m^3$ | 42.8 |

*Source:* Shiklomanov, I.A. and Rodda, J.C., *World Water Resources at the Beginning of the Twenty-First Century*, Cambridge University Press, New York, 2003; Shiklomanov, I.A., World freshwater resources. In *Water in Crisis: A Guide to the World's Freshwater Resources*, edited by P. Gleick, pp. 13–24, Oxford University Press, New York, 1993.

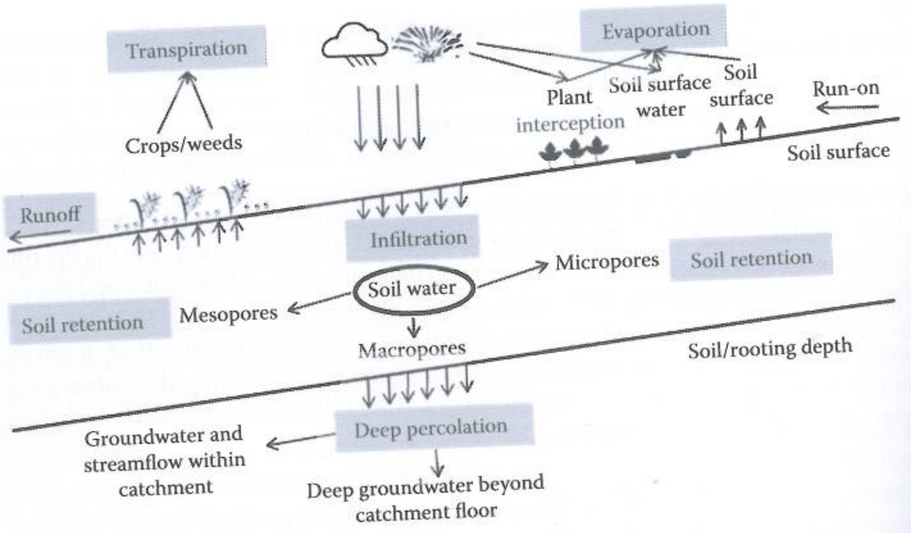

**FIGURE 10.1** Water fluxes over a landscape or watershed and the destinations of rain and irrigation water.

et al. 2010). This requires a careful look at the water fluxes described in Figure 10.1 and examining the processes affecting the soil water, which is ultimately the water source for plant growth and biomass production.

Although WP and WUE have been questioned as useful concepts in agricultural water management (Blum 2009; Zoebl 2006), they are the terms commonly used to evaluate the efficiency with which rain and/or irrigation water is transformed into grain yield or biomass production. Without always having the same concept in mind (Ali and Talukder 2008), much has been written in recent years about the ways to improve agricultural WP or WUE (Bossio et al. 2010; Fang et al. 2010b; Liu et al. 2010; Molden et al. 2010; Shaheen et al. 2010; Alvaro-Fuentes et al. 2009; Kang et al. 2009; Katerji and Mastrorilli 2009; Rockstrom et al. 2009b; Evans and Sadler 2008; Khan et al. 2008; Ritchie and Basso 2008; Bluemling et al. 2007; Bouman 2007; Molden et al. 2007; Rockstrom and Barron 2007; Steduto et al. 2007; Adekalu and Okunade 2006; Singh et al. 2006; Zhang et al. 2005).

Regardless of the discussion about terms and definitions, the fundamental question remains: How to produce more with the same or even less amount of water available from rainfall and irrigation? This question is undoubtedly linked to the possibilities of minimizing, at least at field level, unproductive water losses, namely, runoff, evaporation, and deep percolation. Whereas from a water cycle perspective, all these components are also important to replenish the blue water resources, from an agronomist viewpoint, a reduction of these losses must occur, not only to achieve the goal set above of a higher WP, WUE, or, as suggested by Blum (2009), efficient water use (EWU), but also because runoff losses, if uncontrolled, can have other severe and harmful consequences. Albeit the shift from unproductive evaporation losses to an increase in crop transpiration is not expected to alter significantly the return of water vapor to the atmosphere, a considerable blue-to-green water redirection, through either reduced runoff and deep percolation or water withdrawal for irrigation, could involve a corresponding depletion of the stream flow (Falkenmark 2007). These trade-offs should be kept in mind when searching for improved agricultural water resource management systems. They also point, in the first place, at soil and soil water management practices to achieve a sustainable combination of maximizing transpiration and soil water storage and minimizing runoff and evaporation. Technically feasible and cost-effective solutions for this achievement are a high priority (Rockstrom et al. 2002) and form a basis for sustainable soil water management systems. These have to consider the different processes that affect the soil water, as indicated in Figure 10.1, and the parameters that influence these processes (Figure 10.2).

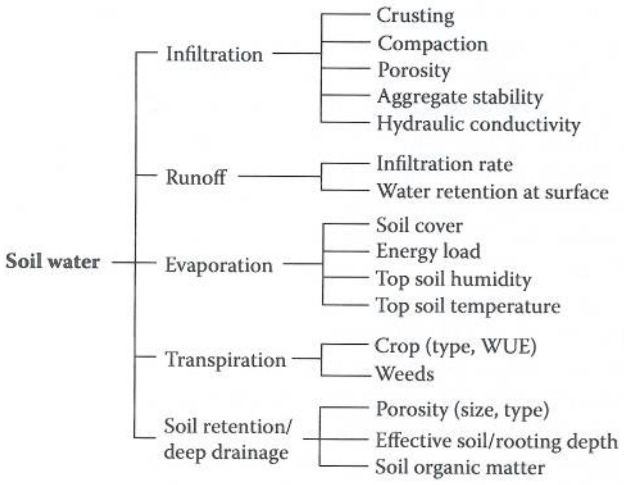

**FIGURE 10.2** The processes and parameters affecting soil water.

### 10.2.1 INFILTRATION

A first step in converting blue water to green water is to maximize water infiltration into the soil. This process and its variation with time are mainly governed by the initial wetness and suction of the soil, as well as its texture, structure, and the uniformity of its profile. While the soil texture and the initial moisture content can hardly be changed, an enhancement of the amount and the stability of the structural soil aggregates, total porosity and macroporosity, and thus hydraulic conductivity, and a decrease in the surface crusting and compaction are achievable through management practices.

Numerous attempts have been made to describe thoroughly the process of infiltration and many models and equations are used to express infiltrability as a function of time or of the total quantity of water infiltrated into the soil (Hillel 1980). However, beyond the understanding of the process itself, which has been subject to many studies, it is of crucial importance to identify the management practices that are able to enhance the infiltration flux, that is, to act on the factors that can be influenced in a technically feasible and cost-effective way. For that purpose, it is useful to distinguish whether infiltration is supply-, surface-, or profile-controlled. Whereas supply control (amount and intensity) is possible only under irrigated conditions, infiltrability of the soil surface layer (surface controlled) and the subsurface hydraulic conductivity (profile controlled) are manageable conditions, even under a rainfed situation.

Increasing the share of rainfall or irrigation water that infiltrates the soil can be achieved through either an improved infiltrability or an extension of the time period during which water is capable of infiltrating into the soil (surface retention or ponding). Whereas the former is strongly enhanced in the presence of continuous macroporosity (mainly biopores created by macrofauna activity and former root channels), the latter depends on the soil surface roughness and the overall slope of the land, which determine the so-called surface storage capacity. An increase in the surface roughness is often unintentionally attained through any form of soil tillage, or it is intentionally achieved through tillage operations along contour lines or by creating "pockets" or "basins" over the soil surface, especially with row crops.

At the soil surface, the processes defined as particle detachment, sealing, and crusting are strongly influenced by the vulnerability of the soil aggregates to breakdown, which is caused by the kinetic impact of raindrops or the surface irrigation water flow or the mechanical impact through tillage implements or wheeling (Li et al. 2009). Soils prone to crusting and sealing usually show reduced infiltration rates (Ben-Hur and Lado 2008; Lal 2008b; Ramos et al. 2003).

This suggests that either the enhancement of the aggregate stability or the protection of the soil through any form of surface cover could help diminish the extent and impact of these processes on infiltration. Thus, measures that increase the soil organic matter (SOM) content or the application of soil amendments that enhance the aggregate stability contribute to improving the infiltrability of agricultural soils (Lado et al. 2004). In addition to the existing possibilities of reducing the kinetic energy of water applied through overhead irrigation, it is mainly the soil cover, that dissipates the energy load of raindrops before they reach the soil surface. Although a large majority of studies on the effect of mulching report improvements in water infiltration (Hula et al. 2010; Jordan et al. 2010; Roth 1985), some did not find a response of water infiltration to mulching, because of the variability in the soil and subsurface conditions (Blanco-Canqui and Lal 2007a; Singh and Malhi 2006).

In many situations, the subsurface properties, such as the underlying, less conductive, fine-textured layers, may restrict infiltration, meaning that the hydraulic conductivity of the subsurface soil is lower than that of the soil at the surface, which occurs frequently in layered soil profiles or through compacted layers. Subsoiling to break the restrictive soil layers as an emergency repair measure and promoting the development of vertically oriented macropores through earthworm and other macrofauna activities and/or the maintenance of former root channels, both achieved through the absence of soil disturbance as a long-term strategy, are the recommended measures to improve profile-controlled infiltration rates (Tebrugge and During 1999).

### 10.2.2 RUNOFF

Surface runoff occurs when the water supply to the soil surface exceeds the rate of infiltration and after the surface storage capacity has reached its upper limit. Two basic types of runoff are normally distinguished: (1) laminar or "sheet" overland flow covering the whole soil surface of areas with little topographic relief and (2) stream flow in channels, also called rills or gullies, which receive the overland flow, generally forming a tree-like pattern down the slope.

Although surface runoff contributes to the recharge of the surface water bodies (blue water), capable of being potentially reused for irrigation, uncontrolled runoff from the land is not desirable as it is strongly associated with soil erosion and the transport of potential water pollutants. Especially in regions where the amount of rainfall is at the margin of being insufficient for crop production, it is of particular importance that as much of the rainfall as possible infiltrates the soil and is held in the root zone.

As mentioned in the previous section, the reduction of the runoff depends essentially on the infiltrability of the soil and its capacity to retain excess water on the surface, thereby reducing the velocity of the runoff and transforming the potential runoff into run-on by increasing the time available for infiltration. Several surface shaping and land configuration techniques, such as tied ridges, contour ridges, flat bed or pit planting (Chiroma et al. 2008; Jadhav et al. 2008), vegetation buffers or hedges (Cullum et al. 2007; Blanco-Canqui et al. 2004), or different types of vegetation cover (Mohammad and Adam 2010) have been found to considerably reduce the surface runoff. On the contrary, Gomez and Nearing (2005), based on rainfall simulation trials, attribute only a temporary effect of the initial surface roughness to the reduction of runoff. Other researchers also report a high variability in the effects of the soil surface characteristics and the conditions on the generation of runoff (Armand et al. 2009; Seeger 2007).

Whereas runoff is generally considered as prejudicial from the viewpoint of soil and water conservation, as it always carries the risk of soil erosion, gully formation, and off-site transport of nutrients and chemicals, in some situations it may be desirable to withdraw excess rainwater from arable land to avoid prolonged waterlogging of the crops (Basch 1988) or to supply adjacent cropping areas with additional water, also designated as runoff diversion (Makurira et al. 2009). The deliberate inducement of runoff through manifold means has been practiced since antiquity in order to increase water availability in designated areas (Hillel 1980).

### 10.2.3 SOIL WATER RETENTION AND DEEP DRAINAGE

After water infiltrates the soil, its movement in or through the soil is mainly influenced by gravitational forces and suction gradients. Depending on whether these processes start from initially saturated conditions or an unsaturated state, they are called either internal drainages or redistributions (Hillel 1980), and the rate at which they occur are normally described by the saturated and unsaturated hydraulic conductivities of the respective soil. Internal drainage or even unsaturated water flow beyond the effective rooting depth is referred to as deep drainage or deep percolation. The amount of water that is retained in a soil against gravity and does not leave the root zone determines the soil water storage capacity.

Although deep drainage is an important process to allow excess water to drain and avoid waterlogging, and to recharge the groundwater, from an agronomic point of view and especially in regions with a low and erratic rainfall, but even in relatively humid regions, soil water storage is of vital importance for crops to overcome periods without insufficient precipitation. Effective plant-available soil water depends, in the first place, on the porosity (amount and pore size distribution) of a soil. While pore size distribution is strongly affected by the soil properties, such as texture, structure, and SOM, the total pore volume from which plants may extract water depends also on the soil volume that the roots are able to explore. Thus, efforts to increase the amount of plant-available soil water involve the adoption of soil management practices that increase the rooting depth and/or the volume of the pore size range from which plants are able to withdraw water, often referred to as mesopores.

Physical and chemical subsoil constraints may severely affect the rooting depth and restrict water uptake from deeper soil layers (Dang et al. 2010; MacEwan et al. 2010; Passioura and Angus 2010; Rodriguez et al. 2006). Access to and uptake of water from the subsoil can improve crop yields considerably (Kirkegaard et al. 2007), and improving subsoil conditions was found to be justified by higher returns under Mediterranean conditions (Wong and Asseng 2007). Numerous approaches have been suggested to overcome these constraints, which were categorized by Adcock et al. (2007) into three groups: (1) amelioration strategies including any type of deep soil loosening and the application soil amendments, (2) breeding efforts, and (3) avoidance strategies such as raised beds or crop management practices. However, they may be of only temporary effect and limited to the possible depth of intervention (Lopez-Fando et al. 2007).

Changes in the soil porosity to increase the amount of plant-available water will depend on the improvement of the soil structure and aggregation (Horn and Smucker 2005) and the SOM (Abid and Lal 2009; Hudson 1994). However, the relationship of the soil water retention to the organic carbon content is affected by proportions of textural components and is more pronounced at lower matric suctions (Rawls et al. 2003). In particular, coarse-textured soils and soils with low organic carbon contents benefit in their water-holding capacity from increases in organic matter (Rawls et al. 2003).

As previously mentioned, deep drainage must not be considered as a permanent "loss" of water from the root zone once the soil profile is replenished with water reaching the upper limit of the soil's water-holding capacity. The observation that higher infiltration rates where soil conservation measures are used did not result in a better crop performance in South East Queensland is explained by Bell et al. (2005), with the improved macroporosity that may enhance unsaturated flow through the soil profile and contribute to increased deep drainage "losses."

### 10.2.4 TRANSPIRATION

Transpiration by leaves and crop canopies is inseparable from the processes of carbon dioxide assimilation from the atmosphere and biomass production. Its efficiency is generally referred to as biomass transpiration efficiency (TE) or defined as the ratio of total plant biomass (above and below ground) to growing season transpiration (Suyker and Verma 2009), and it has to be distinguished from the terms WUE and WP. WUE is defined as water consumptively used in ET as a proportion of the water applied by either irrigation or rainfall. WP is defined biologically (or economically) in terms of economic yield or total biomass per unit of water consumptively used in ET (Fereres and Kassam, 2003; Sadras and Angus 2006). It is the job of crop management to ensure that WUE and WP are maintained as high as possible for each crop in the cropping system and for the cropping system as a whole within the prevailing agroecological and socioeconomic constraints. Many strategies have been identified to enhance WUE and WP (Bluemling et al. 2007), mainly involving appropriate tillage and soil management (Chiroma et al. 2008; Adekalu and Okunade 2006; Hatfield et al. 2001), irrigation management (amount, timing) (Fang et al. 2010a; Katerji et al. 2010; Liu et al. 2010; Buttar et al. 2007; Adekalu and Okunade 2006), and weed and crop management, including the choice of cultivars and breeding efforts (Fang et al. 2010b; Passioura 2006; Tennakoon and Hulugalle 2006; Zhang et al. 2005; Gregory et al. 2000). Although many authors continue using the concept of WUE to characterize the efficiency with which water is used to produce biomass or yield and to characterize how much biomass or yield is produced per unit of water used in ET, other authors question its usefulness (Zoebl 2006) or prefer alternative approaches such as the "effective use of water" (EUW) as a target for yield improvement in water-limited environments because high WUE, WP, or TE may be achieved at the expense of reduced EUW (Blum 2009). However, it would appear that all the indices have their values, depending on the purpose for which a particular index is being used.

To improve biomass production especially in water-limited environments, it is crucial to increase the total amount of water transpired and/or the TE (Bouman 2007). Whereas water available for transpiration depends on inflows, outflows, and storage capacity, the increase in efficiency with which transpired water is exchanged for $CO_2$ will require genetic improvements as the ratio of biomass production to transpiration has been shown to be fairly constant for a given species in a given climate (Ehlers and Goss 2003; Steduto et al. 2007). Bennett (2003) has summarized the breeding efforts and bioengineering opportunities to improve TE. Although genetic variations in carbon isotope discrimination as an indicator for differentiated TE have been found between cultivars (Passioura 2006; Richards 2006), most of the breeding efforts are directed toward the avoidance of dehydration, that is, adaptation of the crop cycle to the given hydrological environment (Blum 2009), and the genetic improvement of the harvest index (HI) (Passioura 2006).

The fact that $C_4$ crops have a more efficient photosynthetic pathway, and thus a higher TE than $C_3$ plants, has suggested the introduction of their photosynthetic pathway into $C_3$ plants through genetic engineering (Sheehy 2000), an approach that has been followed over the recent past (Furbank et al. 2009; Hibberd et al. 2008).

### 10.2.5 EVAPORATION

Evaporation is called the vaporization of a liquid that occurs at its surface. In a soil–plant–atmosphere system, evaporation occurs from each of the components. Although transpiration is a specific form of evaporation, it is referred to separately or in combination (ET) as it is the productive consumption of water in crop production. All other origins of evaporation, whether from the soil surface (wet soil or free water stored over it), the canopy, or from sprinkler droplets, are considered losses to the soil–plant–atmosphere system. Burt et al. (2005) carried out a comprehensive review of the different evaporative processes and their contribution to the overall evaporation losses. Although, as mentioned previously, the evaporation losses of canopy-intercepted rain or irrigation water can reach considerable percentages of the total water supply (Savenije 2004), they are difficult to be influenced unless through better timing of the overhead irrigation. Therefore, the first option to reduce unproductive evaporation losses is the understanding of the process of soil evaporation in order to minimize it through feasible management practices.

The most important factors that affect evaporation from the soil, apart from the conditions external to the evaporating body (evaporative demand), are its water content, texture, structure, and the degree to which it is covered either by growing vegetation or any form of surface mulch. With regard to the soil water content, three evaporation stages are distinguished: the first stage is when the water supply at/to the surface is sufficient to allow a more or less constant evaporation rate as a function of the evaporative demand; the second stage, the falling-rate stage, depends on the soil properties that are responsible for the delivery of moisture to the evaporation zone; and the third stage depends mainly on the rate of vapor diffusion. Both the soil texture and the structure may affect evaporation due to their influence on the soil hydraulic properties (Ndiaye et al. 2007; Jalota and Arora 2002). Under similar soil structure conditions, finer-textured soils show higher evaporation losses than coarse-textured soils (Jalota and Prihar 1986; Prihar et al. 1996). At low moisture levels when the water is held in coarse-textured soils between soil particles rather than in continuous pores, evaporation occurs mainly through the slower process of diffusion instead of conductance in water-filled pores to reach the zone of evaporation (Ward et al. 2009).

The most notable reduction of evaporation losses and the most easily attained through management practices is through the cover of the soil by vegetation or any form of stubble and mulch, whether of organic (crop residues, waste products, cover crop, etc.) or inorganic (stones, plastic films, etc.) origin. Soil cover interferes with the evaporation process mainly by providing a mechanical barrier or resistance to the removal of moisture over the soil, reducing the energy supply (heat flux) to the zone of evaporation (both lowering the evaporative demand), and decreasing the conductivity or diffusivity of the topsoil layer if superficially incorporated. Numerous studies have been conducted to evaluate the effectiveness of different mulching types and practices (Yuan et al. 2009; Ward et al. 2009; Monzon et al. 2006; Burt 2005; Sauer et al. 1996), and they generally agree that the soil cover is especially effective in reducing the evaporation losses at the first evaporation stage, thereby contributing to a more favorable soil water status. However, under relatively dry soil conditions, a soil cover in the form of standing stubble may sometimes enhance evaporation, which is attributed to the hydraulic redistribution along the senesced roots and stems (Ward et al. 2009; Leffler et al. 2005).

## 10.3 MANAGEMENT PRACTICES THAT AFFECT SOIL WATER AVAILABILITY

The objectives and arguments for soil tillage are many, including weed control, soil decompaction, crop residue management, and adequate seedbed preparation. However, the results in the literature on the effects of tillage operations on the soil water and its use through crops are highly variable and contradictory. The inconsistency of the effects of different tillage systems on the soil's physical and hydraulic properties is attributed to the transitory nature of the soil structure after tillage, the site history, the initial and the final water contents, the time of sampling, and the extent of soil disturbances (Azooz and Arshad 1996).

Based on the processes that affect soil water (outlined in Figure 10.2), this section reviews the effects of soil tillage practices on these processes and the consequences on crop-available soil water and its use efficiency.

### 10.3.1 SOIL TILLAGE

#### 10.3.1.1 Effects on Infiltration and Runoff

Tillage practices change the infiltration and runoff components, basically by modifying the soil properties such as the stability of the structural soil aggregates, the total porosity and macroporosity, the hydraulic conductivity, the surface crusting and compaction, and the SOM. Generally, soil aggregation improves with the conversion from conventional soil tillage to no-till (NT) soil management. As a result, pore connectivity takes place, enhancing the soil quality and the water transmission properties.

In the literature, the effect of tillage on infiltration is ambiguous. Reviewing the state-of-science to quantify the agricultural management effects on the soil hydraulic properties, Strudley et al.

(2008) showed that there is a trend of NT systems to promote an increase in the macropore connectivity and the infiltration rate; however, because of the differences in soils, climates, and specific practices of tillage, it is not possible to generalize these results without a detailed knowledge of all the controlling factors. As related to water infiltration, several researches have highlighted the great advantages of the NT systems over conventional tillage (CT) practices. However, the site-specific conditions could indicate the need for a surface, shallow soil disturbance to destroy the surface crust or compacted layers, which can occur as a consequence of little crop residue on the soil surface (Thierfelder and Wall 2009; Singh et al. 2005) or intense tillage and machinery traffic (Reichert et al. 2009b; Mary and Changying 2008; Sasal et al. 2006; Hamza and Anderson 2005). Even considering that this surface disturbance may promote some increase in water evaporation, probably the gain in water infiltration due to the runoff reduction will surpass the aforementioned effect. However, tillage seems to have only a short-lasting effect on the improvement of the infiltration rate (Freese et al. 1993).

Experiments performed in several regions of the world show that NT systems promote soil aggregation (Stone and Schlegel 2010; Rhoton et al. 2002) and water infiltration. One study carried out in southern Brazil showed that rainwater infiltration increased from 20 mm/h under CT to 45 mm/h under NT (which included cover crops and crop rotation) (Calegari et al. 1998). In Kansas, Texas, on a silt loam soil, Stone and Schlegel (2010) observed that the infiltration rate under NT (30.56 mm/h) was 1.99-fold and 2.67-fold greater than in reduced tillage (RT) and in CT, respectively. The infiltration rate was positively correlated with the mean weight diameter (MWD) of the water-stable aggregates (WSA), which, in turn, was also positively correlated with the total soil organic carbon (SOC). The authors attributed this greater steady-state infiltration rate in the NT system to the presence and stability of the surface-connected macropores, the greater concentration of larger, water-stable aggregates in the surface layer, and the reduced surface sealing due to the protection from raindrop impact promoted by the residues. In their review of the effects of tillage systems on the physical properties of the soil and the water content in the Argentine Pampas, Alvarez and Steinbach (2009) clearly document the higher infiltration rates under NT when compared with limited tillage, especially plow tillage (Figure 10.3).

Soil disturbance caused by many tillage practices increases the surface roughness, the macroporosity, and the initial infiltrability, although the infiltration rapidly declines with time as a consequence of aggregate collapse (Guzha 2004). On a silt loam, Wahl et al. (2004) also observed a high infiltration dependence on macroporosity. Their results showed that the infiltration rates measured with a tension infiltrometer were higher in the soil surface layer in CT than in conservation tillage.

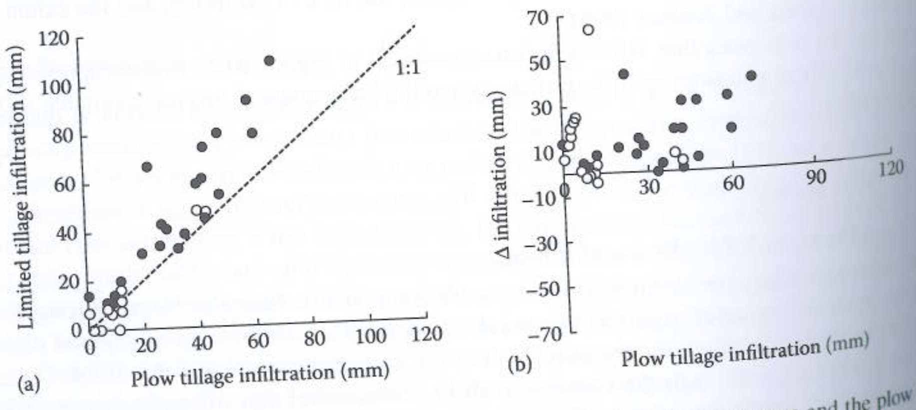

**FIGURE 10.3** The relationship between soil infiltration under limited tillage systems and the plow tillage systems (a). The change in soil infiltration (limited tillage–plow tillage) in relation to plow tillage infiltration (b). Full circles—no tillage; empty circles—chisel or disk tillage. (From Alvarez, R. and Steinbach, H.S., *Soil Till. Res.*, 104, 1, 2009.)

At depths greater than 50 cm, the water intake in conservation tillage was higher than in CT and even higher than in the topsoil for both tillage types. The authors attribute these findings to a higher macroporosity under conservation tillage at 20 cm and below and to a much better macropore continuity promoted by the soil fauna activity in the soil profile.

In addition to the importance of macroporosity and its geometry for infiltration and redistribution of the soil water in depth, Sasal et al. (2006) emphasized the importance of the stability of the soil structure and the need for a complete characterization of the soil porosity as essential information to assess the effect of the structural conditions on the soil water dynamics. At two of three study sites, these authors observed a more horizontal orientation of the macropores under zero tillage when compared with the chisel plough, which they ascribe mainly to the pressures generated by repeated traffic and a low volume of crop residues in the soybean-dominated crop rotations. At the same time, they found a very good relationship between the vertically oriented macropores and the infiltration rate, an observation frequently shared by other authors (Imhoff et al. 2010; Buczko et al. 2003; Tebrugge and Abelsova 1999).

An enhanced soil bioporosity through macrofauna, mainly earthworm activity, or created by roots after their decomposition, could compensate for the effect of reduced total porosity or even soil compaction on the water flux within the soil. Although Abreu et al. (2004) could not find an increase in the water infiltration under minimum tillage (MT), they were able to show that saturated hydraulic conductivity measured in the field increased in the soil cultivated with showy crotalaria (*Crotalaria spectabilis* Roth) under MT (Crotalaria), even when the soil mechanical resistance was greater than in other tillage-based systems (Figure 10.4). This result was due to the better pore continuity promoted by the deep root growth of *Crotalaria*, since the total porosity, macroporosity, and bulk density were not different among the tillage systems. Thus, the tillage and cropping systems that enhance vertically oriented bioporosity are likely to increase the amount of water captured and redistributed in the soil. Hartge and Bohne (1983) reported that repacked soil with artificial vertical macropores was more stable than repacked soil with artificial horizontal macropores.

Runoff is the direct consequence of the precipitation intensity being higher than the infiltration rate and the soil surface water storage capacity. Especially in regions where rainfall is low and erratic, runoff is always undesirable as it reduces the amount of soil water available for productive transpiration (Guzha 2004). Soil tillage normally increases the soil surface roughness and the residence time of the water on the soil surface, but the continuous production of earthworm casts on untilled land has also been found to induce a marked surface roughness and to reduce runoff

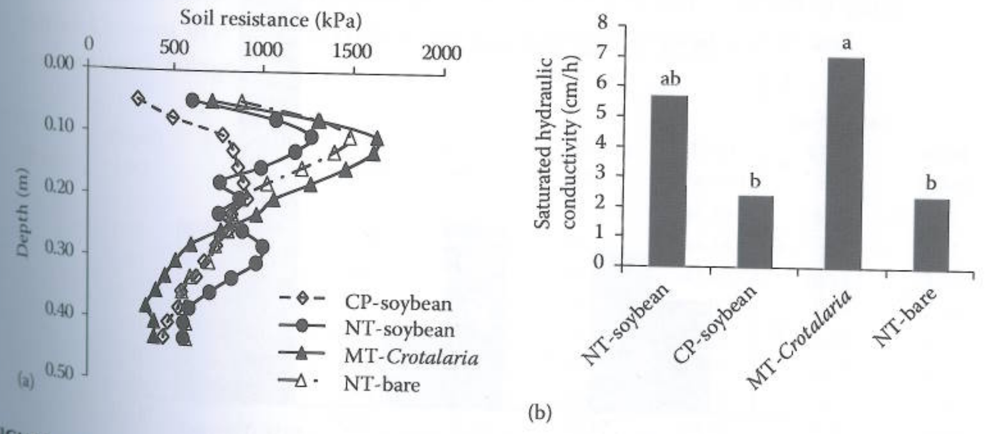

**FIGURE 10.4** The soil penetration resistance (a) and the saturated hydraulic conductivity (b) measured at 0.02–0.12 m layer in soils under different management systems. Bars with the same letter are not significantly different ($P = 0.5$), as determined by a DMS test. CP: chisel plow; NT: no-tillage; MT: minimum tillage. (Adapted from Abreu, S.L., et al., *Rev. Bras. Cienc. Solo*, 28, 519, 2004.)

(Podwojewski et al. 2008). Although soil roughness may play a key role in retaining precipitation in situ and retarding runoff, in warm and dry environments, the soil surface sealing that follows tillage is critical, since the water that ponds on the soil surface for even a short time quickly evaporates, thereby reducing the infiltration and the effective rainfall (Peterson and Westfall 2004).

Rhoton et al. (2002) have comprehensively described the importance of the effects induced by tillage systems on the soil properties and the surface runoff. Based on long-term studies of a silt loam in the southeast of the United States, they correlated the soil properties such as SOM, aggregate stability, total and dispersible clay content, and bulk density to surface runoff. From single, two-, and three-variable regression models performed for depths of 0–1 cm and 1–3 cm, the authors concluded that the most important soil property explaining runoff was bulk density under NT and aggregate stability under CT (chisel plough and disk harrow). Further, they concluded that bulk density is a measure of the surface porosity that is stabilized by a higher SOM content under NT, making other soil properties relatively unimportant. This was not the same for the soil under CT, where the aggregate stability and the water dispersible clay content were identified as the most important properties for controlling runoff.

A reduced aggregate stability and a less favorable soil structure through soil tillage are the most frequent arguments to explain a higher surface runoff when compared with the MT or NT systems. Although tillage temporarily creates more favorable conditions initially for infiltration and less runoff through higher macroporosity and surface retention, soil sealing through the particle detachment of the disturbed soil surfaces contributes to a rapid change in the infiltration conditions (Teixeira et al. 2000, Azooz and Arshad 1996) and to the overall higher runoff and less infiltration of the tilled soil. For example, Castro et al. (1993) observed that NT reduced the runoff water losses by 88% when compared with heavy-disc harrowing, with losses of 13.1, 35.7, and 93 mm/year for NT, the chisel plough, and the disc plough, respectively. Kosgei et al. (2007) evaluated the effects of CT (moldboard plough) and NT on the water losses, infiltration, and rain use efficiency of maize in the 2005/2006 season (Figure 10.5), in a highly diverse catchment in South Africa. NT treatment generated less runoff (22 mm) than CT (37 mm), corresponding to 6% and 8% of the seasonal rainfall (463 mm), respectively. Despite the small difference in the cumulative water intake, the authors ascribe the large differences in the yield to the higher soil water availability under NT throughout the growing season.

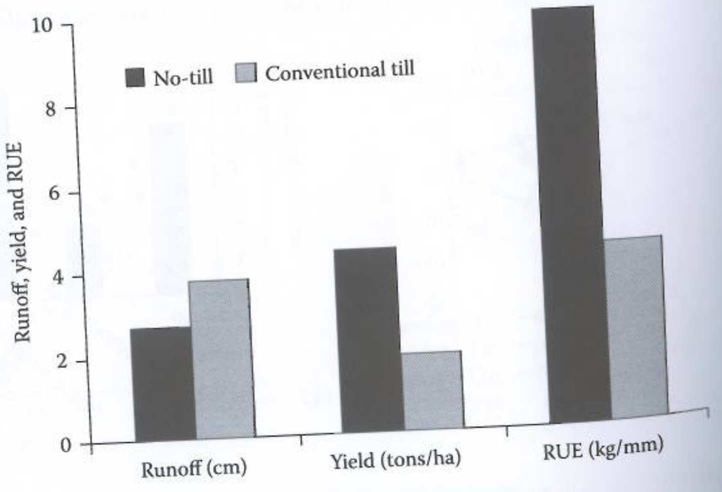

**FIGURE 10.5** The seasonal average runoff depths (cm), the maize yields (ton/ha), and the "effective" rain use efficiency (RUE) (kg/mm) in no-tillage and conventional tillage plots in Potshini catchment in the 2005/2006 season. (From Kosgei, J.R., et al., *Phys. Chem. Earth*, 32, 1117, 2007.)

### 10.3.1.2 Effects on Water Retention Capacity and Deep Drainage

As previously outlined in Section 10.2, plant-available water in a given volume of soil depends on the amount of mesopores that are able to retain water against gravitational forces and to deliver it to the roots on demand. Second, the total soil volume that the roots are able to explore (rooting depth) is equally important as plants can compensate for water stress in the upper, more densely rooted, soil layers by increasing the water uptake from deeper layers (Teuling et al. 2006). Thus, tillage management may directly or indirectly affect the pore size distribution, the pore geometry, and the hydraulic properties of the soil and hence, the plant-available soil water.

Today, it is widely recognized that the absence of soil disturbance improves aggregate stability and promotes SOM accumulation and stabilization. Through the buildup of SOM and the consequent promotion of soil aggregation and structure stabilization, the reduction of tillage intensity contributes to a higher percentage of intermediate pores in relation to the total porosity (Fernandez-Ugalde et al. 2009; da Veiga et al. 2008; Bescansa et al. 2006). Many researchers have found a high correlation between the structural quality of the soil and the SOM content with plant-available water (Imhoff et al. 2010; Abid and Lal 2009; So et al. 2009; Mrabet et al. 2001). Despite a frequently observed reduction of the total porosity in the surface soil layer under NT, the total volume of mesopores is increased in the absence of soil disturbance. After 6 years of differentiated tillage (NT and moldboard plough), Carvalho and Basch (1995) found a lower total and medium-size porosity under NT in the 0–0.1 m soil layer; however, in the 0.1 and 0.3 m soil layers, the total porosity and especially the pore space referring to plant-available water were considerably increased (Table 10.3). There was also a close correspondence to bulk density and the SOM content. Results obtained by other authors corroborate these findings (Fernandez-Ugalde et al. 2009; Bescansa et al. 2006; Bhattacharyya et al. 2006; Rasmussen 1999; Hussain et al. 1998), although, in their review on conservation tillage and the depth stratification of porosity and SOM, Kay and VandenBygaart (2002) identified some cases where tillage-induced changes in mesoporosity did not occur. According to their interpretation, only long-term studies are able to provide consistent information especially with regard to the changes in the SOM and the changes in the pore size fractions.

Chemical and physical subsoil constraints frequently limit the water uptake from the deeper soil layers (Dang et al. 2010; MacEwan et al. 2010; Nuttall and Armstrong 2010). Water that is stored deep

**TABLE 10.3**
**Total Porosity, Pore Size Distribution, Plant-Available Water, and Soil Organic Matter Content in a Vertic Cambisol after 6 Years under No-Till (NT) and Conventional Tillage (CT)**

| Tillage | Depth (cm) | >50 µm (%) | 50–10 µm (%) | 10–0.2 µm (%) | <0.2 µm (%) | Total Porosity | Available Water (%) | SOM (g/kg) |
|---|---|---|---|---|---|---|---|---|
| NT | 10 | 3.20 | 2.22 | 2.7 | 38.37 | 46.52 | 4.92 | 2.53 |
| | 20 | 0.86 | 3.91 | 5.22 | 36.16 | 46.15 | 9.13 | 2.15 |
| | 30 | 1.86 | 2.63 | 11.48 | 29.44 | 45.40 | 14.11 | 2.25 |
| | 0–30 | 1.97 | 2.92 | 6.47 | 34.66 | 46.02 | 9.39 | 2.31 |
| CT | 10 | 15.08 | 2.34 | 4.36 | 29.95 | 51.73 | 6.71 | 1.58 |
| | 20 | 2.67 | 1.32 | 2.31 | 39.95 | 42.25 | 3.63 | 1.7 |
| | 30 | 1.47 | 1.56 | 3.29 | 35.62 | 41.94 | 4.85 | 1.66 |
| | 0–30 | 6.41 | 1.74 | 3.32 | 35.17 | 45.31 | 5.06 | 1.65 |

*Source:* Carvalho, M. and Basch, G., Experience with the applicability of no-tillage crop production in the West-European countries. *Proceedings of the EC-Workshop II.* Wissenschaftlicher Fachverlag, Langgöns, Germany, 1995.

in the soil profile is considered especially valuable to crop yield because it becomes available during grain filling (Passioura and Angus 2010; Kirkegaard et al. 2007). With regard to the physical subsoil constraints, whether of natural or anthropogenic origin (hard setting soils or hard pans), deep soil loosening has become a widely used soil management practice where powerful tractors and subsoiling equipment are available (Hamza and Anderson 2005). Deep ripping and slotting are frequently proposed operations to overcome these constraints and to improve the access of roots to additional soil water and nutrients (MacEwan et al. 2010; Hartmann et al. 2008; Adcock et al. 2007; Sadras et al. 2005; Hamza and Anderson 2003). However, the documented results have been variable and the benefits of deep soil loosening and the consequent crop response may differ from one year to another and from one place to another. Wetter locations and coarser-textured soils are more likely to benefit from subsoiling than fine-textured soils and drier locations (Wong and Asseng 2007). Negative results from deep soil loosening were obtained in dry years or when deep drainage losses occurred (Wong and Asseng 2007). Further, the deep loosening effects are often of short duration, especially if not accompanied by additional measures, such as subsoil conditioners (i.e., gypsum), the installation of primer crops, or reduced or controlled traffic (Lopez-Fando et al. 2007; Hamza and Anderson 2003, 2005; Yunusa and Newton 2003). Adcock et al. (2007) also highlight the need for a careful balance between the expectable increase in economic returns and the costs and duration of any amelioration measure.

In order to establish a relationship between the soil physical constraints, the root growth, and the soil-available water, the use of indicators such as growth-limiting bulk density (GLBD), least-limiting water range (LLWR), and integrated water capacity (IWC) has been proposed. The first one, based on the work of Pierce et al. (1983), provides threshold bulk densities for a given soil texture at which water availability becomes excessively restricted. LLWR serves as an index of the soil structural quality, integrating values of the soil matrix potential, aeration, and the soil strength (Dasilva et al. 1994). The concept of IWC has been proposed as a flexible method to quantify various soil physical limitations when calculating the available water in nonswelling soils and then extended to swelling soils, introducing overburden pressures (Groenevelt et al. 2001). Although considered as useful indicators of soil physical quality for crop production (Leao et al. 2006; Lapen et al. 2004), the applicability of the most widely used LLWR indicator has been questioned by several authors (Asgarzadeh et al. 2010; Kaufmann et al. 2010; Reichert et al. 2009b; Benjamin et al. 2003), disagreeing mainly on the critical values used for some of the soil characteristics, based on bulk soil conditions. Especially under NT, the critical bulk densities do not reveal the pore geometry and continuity and may not necessarily restrict root growth (Reichert et al. 2009b; Bolliger et al. 2006).

Deep drainage, defined as water passing below the potential maximum rooting depth, occurs when the soil volume above is saturated and the wetting front reaches the lower limit of the rooting zone or through preferential pathways even if the soil profile is not saturated. It is an important process to recharge the groundwater and to conduct excess water from the soil profile to the deeper soil layers, thus contributing to reduced surface runoff. In regions with water scarcity, however, deep drainage is often considered to correspond to a loss in the potential crop growth, although for dry environments, deep drainage losses are usually much smaller than the losses through evaporation (Passioura and Angus 2010), except in very sandy soils (Passioura 2006). In some regions, deep drainage is also associated with the problems with secondary salinity (Asseng et al. 2001; Ridley et al. 2001).

According to Strudley (2008), the drainage effects on soils subsequent to tillage have not been studied very extensively, due to their high temporal and spatial variability. In addition to the above-mentioned effects on water retention, tillage may affect deep drainage either through its negative impact on the rooting depth or on the creation and longevity of macropores. It is widely recognized that in the absence of soil disturbance, as is the case in NT systems, biological macropores, earthworm tubes, former root channels, and voids between the soil structural units are preserved, thereby forming preferential pathways for rapid and deep percolation (Verhulst et al. 2010; Cullum 2009; Strudley et al. 2008; Shipitalo et al. 2000; Tebrugge and During 1999). Although Diaz-Ambrona et al. (2005) found that tillage treatments alone made little difference to deep drainage; they highlight the greater soil water storage where residues were maintained, which led to higher drainage losses.

After 18 years of NT and CT on a Vertisol, McGarry et al. (2000) found that in addition to taking a longer time to ponding, final infiltration rate, total infiltration and deep drainage were also enhanced. Through a higher water intake, less evaporation losses in the case of residue maintenance, and a better pore connectivity, deep drainage is more likely to occur under NT than under CT. However, the withdrawal of excess water from the saturated topsoil through deep drainage provides a basis for a positive trade-off between the consequent increase in infiltration and the reduction in runoff.

### 10.3.1.3 Effects on Soil Evaporation

In arid and semiarid regions, the main unproductive water loss is caused by direct evaporation, especially if there are many low-intensity rainfall events (Lampurlanés and Cantero-Martínez 2006; Passioura 2006). Reducing the evaporation losses is a major challenge for farmers, especially in water-scarce regions where fallow periods are used to accumulate additional soil water. Under rainfed Mediterranean conditions in central Aragon (northeast Spain), based on field measurements and model simulations, Moret et al. (2007) obtained evaporation losses during the fallow period in the range of 55%–91%, whereas deep drainage losses were in the range of 5%–28%. Thus, comparing continuous barley and a barley–fallow crop rotation, Moret et al. (2006) measured only an additional 20 mm of soil water storage through the fallow period.

Evaporation reduction from a bare soil surface during the initial evaporation stage can be attained through a coarse or disturbed layer (or mulch) overlying the wet subsoil. In a conventional system, however, tillage operations with the purpose of reducing evaporation are carried out with the soil at favorable moisture conditions, which is almost at the end of the initial evaporation stage. In addition, soil loosening and exposure boosts water losses from the cultivated soil layer as tillage operations favor heating and the formation of air pockets in which evaporation occurs (Licht and Al-Kaisi 2005). Within 24 h after the primary soil tillage, Moret et al. (2006) measured up to 16 mm of evaporation losses against 2 mm under NT. After the secondary tillage, they still obtained differences of up to 3 mm of water losses between the tilled and the untilled treatments. Therefore, the performance of tillage with the objective of reducing evaporation is the result of a balance between the short-term evaporation losses through enhanced drying of the soil layer disturbed by any form of tillage and the possible long-term gains through the breakup of a faster upward capillary movement in the undisturbed soil.

Tillage may also affect soil evaporation through increased surface roughness, exposing a greater surface to the overlying atmosphere and winds and through a change in the soil surface temperature and albedo. Despite a higher surface albedo on a smooth bare soil when compared with moldboard ploughed soil or CT, Oguntunde et al. (2006) found only small differences in the soil moisture content of the surface layer. On swelling and shrinking soils, evaporation losses may be considerable. According to Ritchie and Adams (1974), evaporation from the cracks near the end of the sorghum growing season was 0.6 mm/day and an additional 15 mm of soil water is lost by evaporation before the soil swells and cracks close from the rains. Mulching or superficial soil tillage could prevent the formation of cracks or at least obliterate them after they have begun to form.

Although the absence of soil disturbance through the practice of NT has been viewed as a method that reduces evaporation losses (Kosgei et al. 2007; Fowler and Rockstrom 2001), information on the tillage-induced effects on water evaporation from bare soils is scarce, as NT treatments are usually associated with the maintenance of some form of residues over the soil surface. The effects of residues on the soil water and especially evaporation, whether in combination with NT practices or not, have been the subject of extensive studies and will be discussed in the following section.

### 10.3.2 SOIL COVER AND RESIDUE MANAGEMENT

In natural ecosystems with some minimum rainfall for the growth of vegetation, the soil surface develops some form of organic cover consisting of plants and their residues after senescence. The soil cover controls the flux of energy and water by interacting with components of the atmosphere, the hydrosphere, the biosphere, and the pedosphere (Lal 2009). The conversion of natural environments into agricultural areas leads to a significant change in the partitioning of the water, nutrient, carbon, and energy flow. During and after a rainfall event, rainwater may infiltrate into the soil to replenish the soil water or flow through it to recharge the groundwater, and some may run off as overland flow and evaporate back into the atmosphere (directly from an unprotected soil surface and from plant leaves) (Bot and Benites 2005). The soil cover and residues directly affect the runoff and soil evaporation and indirectly affect deep percolation, all of them representing unproductive water losses. The objectives of sustainable soil and soil water management are to redirect these losses into an increase of soil water storage and availability to plants.

In this section, we address the influence of the soil cover, including the application of organic and inorganic mulching material, cover crops, and crop residues on the soil water, either through their direct impact on infiltration/runoff and evaporation or their indirect effects on the SOM content and macrofauna activity. Additionally, we present evidence on how the soil cover type (including cover crops) and the residue characteristics and their management affect the soil water conservation and the soil productivity.

### 10.3.2.1 Effects on Infiltration and Runoff

Soil macroaggregate breakdown is seen as the major factor leading to surface pore clogging by primary particles and microaggregates and thus to the formation of surface seals or crusts (Lal and Shukla 2004). The soil cover prevents this breakdown by reducing the kinetic energy with which raindrops reach the soil surface (Ben-Hur and Lado 2008). In addition to the detachment of the soil aggregates through direct raindrop impact and the physicochemical dispersion of the clays, slaking is considered another important process in the disintegration of the aggregates and the consequent seal formation (Lado et al. 2004). The faster the wetting rate of the dry soil, the higher are the slaking forces. As the aggregate breakdown due to slaking is inversely related to the antecedent water content (Haynes 2000), the higher topsoil moisture of the covered soil reduces the slaking forces.

The tendency of a soil to form a surface seal, the resulting decrease in infiltration, and the amount of the resulting runoff and soil loss depend on the aggregate stability (Ben-Hur and Lado 2008). Many reviews have been published on the effects of the soil properties, such as texture, organic matter content, soil mineralogy, and soil salinity and sodicity, on aggregate stability (e.g., Lado and Ben-Hur 2004; Kay and Angers 1999). The amount of crop residues and their management, however, can have a decisive effect on the resilience of the aggregate breakdown. After applying different amounts of wheat straw on an untilled loamy Fluvisol in the southwest of Spain over a period of 3 years, Jordan et al. (2010), using the water-drop test and ultrasonic disruption methods, found a clearly improved aggregate stability with an increase in the amount of straw residues ranging from 0 to 15 Mg/ha (Figure 10.6). However, only the two highest mulching rates provided a significantly better aggregate stability after 3 years. A more linear and positive correlation between the amount of wheat straw and the percentage of WSA and the MWD was found by Mulumba and Lal (2008) after 11 years on a stagnic Luvisol in central Ohio. Yet, it seems that crop residues alone are not effective in improving the soil aggregate stability. After 7 years of different residue management, which included NT with residues, residue incorporation through chisel/disk tillage, and residue removal before and replacement after tillage, Wuest (2007) found no differences in the MWD of the aggregates in the 0–5 cm layer between the straw mixed and surface-applied in the tilled treatments; however, under NT, the MWD was more than two times greater. This significant improvement of the aggregate stability under NT, when compared with the mixed treatment, was also expressed in the 5–10 cm soil layer. According to the author, an improved fungal activity might explain the observation of a better aggregate stability in the 5–10 cm layer when the straw was surface-applied after tillage instead of being incorporated into the surface soil. Under NT, this effect would also add to other changes such as an increase in the SOM.

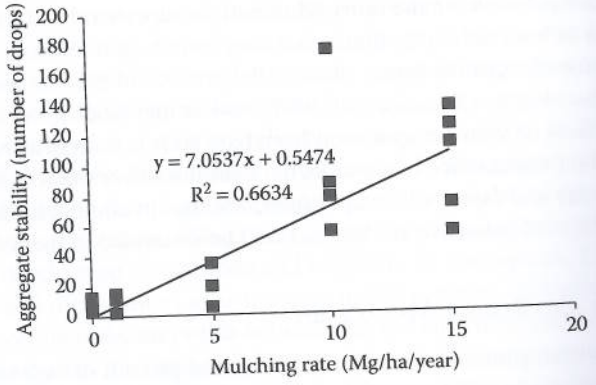

**FIGURE 10.6** The relationship between the aggregate stability and the mulching rate. (From Jordan, A., Zavala, L.M., and Gil, J., *Catena*, 81, 77, 2010.)

Soil cover with crop residue also promotes topsoil porosity, improving the water entry and transmission into the soil. The continuity of the pores left by decayed roots plays an important role in improving the infiltration rate, particularly in a very fine textured soil.

It is widely accepted that the random roughness of the soil surface created by tillage may contribute to the temporary retardation of the runoff, mainly through an increased depressional storage capacity. However, depending on several soil properties, there is a more or less sharp decline in the depressional storage with the progressive impact of the raindrops (Gomez and Nearing 2005; Guzha 2004). If crop residues are left on the soil surface, or are partially incorporated in the upper soil layer through mesofauna, not only is the impact of the raindrops reduced, but also the stream velocity, as the residues act as a succession of physical barriers (Verhulst et al. 2010; Jin et al. 2009). The residues play a role similar to that of surface roughness, that is, increasing the time for infiltration to take place (Blevins and Frye 1993), with the difference that their effect lasts longer. Therefore, the time lag for runoff generation is also greater when the crop residue is left on the soil surface (Jordan et al. 2010) and the transmission losses (turning small-scale runoff into large-scale runoff) decrease with the increasing vegetation or residue cover (Leys et al. 2010).

When incorporated into the surface soil, the amount of residues also seems to affect the infiltration and runoff. Gimenez and Govers (2008) measured an extra shear stress created by the freshly surface-incorporated residues and a reduced flow velocity, both of which were well correlated with the quantity of residues incorporated. However, at high runoff rates, their effect on reducing the flow hydraulics and erosivity is decreased. Studying the effect of shredded and spring-incorporated corn stalks of different plant populations (0%, 50%, and 100%) on runoff and erosion, Wilson et al. (2008) found a reduction in the average annual soil loss of around 50% for the 50% and 100% plant densities compared with the 0% population with no residues (bare soil), but a very small reduction in the surface runoff of 6.5% and 10.8%, respectively. The 50% and 100% population did not differ in the yield or in the amount of residues left, which was around 7 Mg/ha.

Thus, soil cover and crop residues left at the soil surface seem to be effective in improving infiltration and in reducing the surface runoff and soil loss. It also appears that the amount of residues is closely related to the degree to which the runoff is decreased. After 3 years under different mulching rates of wheat straw, rainfall simulation measurements at intensities of 65 mm/h provided clear differences in the surface runoff between mulching rates (Jordan et al. 2010) (Figure 10.7). In this study, the highest rates of 10 and 15 Mg/ha were necessary to almost completely avoid runoff.

A big difference between high and low standing, surface cut and removed stubbles has been found in regions where the retention of snow is crucial for supplying water to the following crop. Sharratt (2002) reported that taller stubble trapped more snow, reduced the depth of frost penetration, and hastened thawing of the soil profile by at least 25 days, when compared with short stubble or residue removal. Further, the variability in the soil water recharge was closely related to the amount of snow cover.

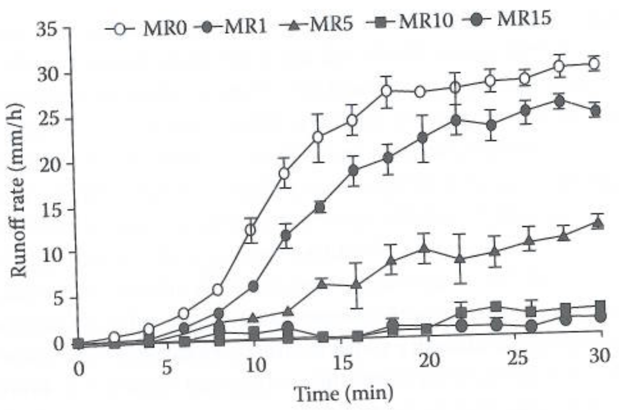

**FIGURE 10.7** The variation of the mean runoff rates under different mulching rates. MR0 = control; MR1 = 1 Mg/(ha year); MR5 = 5 Mg/(ha year); MR10 = 10 Mg/(ha year); MR15 = 15 Mg/(ha year). N = 5 for each mulching rate treatment. Vertical bars indicate ± standard deviation. (From Jordan, A., Zavala, L.M., and Gil, J., *Catena*, 81, 77, 2010.)

### 10.3.2.2 Effects on Evaporation

The transfer of water from the liquid phase to the vapor phase occurs at the expense of the absorbed heat energy and depends on the occurrence of the water vapor deficit in the air above the soil surface and the diffusion resistance along the pathway. The amount of heat energy and the water vapor deficit are increased proportionally due to the absorption of the incident radiant energy from the sun by the soil surface and the resulting increase in the temperature. Furthermore, the evaporation vapor flux from the soil is increased by the wind. Thus, the main approach for reducing water evaporation is by reflecting the incident energy to reduce the energy absorption by the surface, reducing the wind speed at the soil surface, and impeding or reducing the vapor flux from the soil into the atmosphere. The soil cover and residues act on all these processes, but it has been difficult to quantify their effects on the processes separately.

Soils mulched with crop residues or cover crops have a reduced maximum soil temperature and a lower amplitude (Zhang et al. 2009; da Silva et al. 2006; Fabrizzi et al. 2005). The high solar reflectivity and low thermal conductivity of the crop residues prevent an increase in temperature (Shinners et al. 1994; Hillel 1980). On submitting a long-term NT area after a winter cover crop (black oats) to different tillage practices (NT, mouldboard plough, and chisel), da Silva et al. (2006) found that the cover crop residues on the soil surface under NT reduced both the maximum soil temperature and the daily amplitudes. Trevisan et al. (2002) showed a reduction in the soil temperature amplitude down to 20 cm in depth with an oat straw cover throughout the year, compared with soil without a straw cover. Thus, a lower portion of the surface energy balance will be used as latent heat in the system, reducing the evaporation of water from the soil.

Both transpiration and soil evaporation depend on the evaporative demand of the environment. In order to study the interaction between the soil type, the residue cover, and the evaporative demand, Freitas et al. (2006) treated a loamy sand and a heavy clay soil covered with different types and amounts of residues to three different evaporative demands of around 3, 5.2–6, and 7–8 mm/day (Table 10.4).

Whereas the uncovered soil remained in the first evaporation stage only at the evaporative demand of 3 mm/day, both residue-covered treatments maintained this stage over the 21-day trial period for the medium and highest evaporative demands. On average, over both soil and residue types, the highest amounts of residues resulted in total evaporation, which was around 30% of that measured in the treatment without residues. Especially on the loamy sand, evaporation reduction under the highest amount of residues was almost independent of the evaporative demand.

**TABLE 10.4**
**Total Soil Evaporation during 21 Days (after Reaching Field Capacity) for Two Different Soils under Different Types and Amounts of Residues and Different Evaporative Demands**

| | | | Evaporative Demand (mm/day) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Residues (kg/ha) | | | Corn | | | Wheat | | |
| Soil type | Corn | Wheat | 8 | 6 | 3 | 7 | 5.2 | 3 |
| Loamy sand | 0 | 0 | 74.2 | 82 | 57.2 | 59.2 | 68 | 47.9 |
| Heavy clay | 0 | 0 | 56.4 | 74.2 | 56.4 | 54.7 | 59 | 46.9 |
| Loamy sand | 5000 | 3500 | 40.2 | 28.9 | 19 | 38 | 28.4 | 18.5 |
| Heavy clay | 5000 | 3500 | 35.7 | 30.1 | 22.2 | 35.2 | 32 | 22.8 |
| Loamy sand | 10000 | 7000 | 20.4 | 19.8 | 18.6 | 20.6 | 20 | 16.5 |
| Heavy clay | 10000 | 7000 | 21.1 | 18.1 | 13.6 | 20.3 | 17.1 | 13.1 |

*Source:* Adapted from Freitas, P.S.L., et al., *Rev. Bras. Eng. Agr. Ambient.* 10, 104, 2006.

The contribution of residues, whether alone or in combination with NT, to reducing the evaporation component of total ET has been confirmed by numerous studies and under many different conditions. In Punjab, India, Jalota and Arora (2002) observed that straw mulching (6 Mg/ha) substantially reduced the soil water evaporation under medium-textured and coarse-textured soils by 18.5 and 13.1 cm in maize, 23.8 and 16.6 cm in cotton, and 23.6 and 17.6 cm in sugarcane crops, respectively. They concluded that the irrigation requirements of summer crops can be reduced further by mulching with crop residues. Lamm et al. (2009) also suggest that strip tillage and NT, due to the maintenance of the crop residues, should be considered as improved alternatives to CT, particularly when the irrigation capacity is limited. In Texas, Lascano et al. (1994) found in cotton production that the total ET was similar between a conventional and a wheat straw residue–based strip-tillage system. However, they found large differences in the components of ET, with a share of the transpiration of 50% with CT with no residue against 69% under straw mulch, which resulted in a 35% increase in the lint yield. In a recent study using undisturbed mini-lysimeters, Klocke et al. (2009) compared the effect of bare soil with the soil partially or completely covered with wheat stubble and corn stover and with and without the effect of the corn canopy. On average over 3 years, the evaporation in the field study (with canopy and full residue cover) was reduced by almost a half through both types of residues. Even with a surface coverage between 91% and 100%, the higher the amount of residues, the more pronounced was the reduction in evaporation. In the trial without a canopy, evaporation compared with bare soil was reduced by 20% or less by residue treatments with partial cover, but significantly more by the full cover of both wheat and corn residues. Standing wheat stubble surpassed the evaporation reduction effect of the flat corn residue, an observation that the authors attribute to the possible aerodynamic effects of standing straw.

However, the residue management effects on the evaporative water losses may vary with different climatic conditions. For example, in contrast to a possible reduction of the convective component of evaporation through standing wheat stems, advanced by Aiken et al. (2003), Ward et al. (2009), under sandy topsoil conditions, observed an increased evaporation in the presence of standing stubble when compared with cut and removed stems or slightly buried stems. A possible capillary upward movement of water through the senesced roots is provided as a possible explanation. It has also been concluded that residue thickness (volume) is more important than mass per unit area for controlling evaporation (Steiner 1989).

Although high porosity and pore continuity are favorable characteristics for increasing the soil water storage capacity and deep infiltration, they also enhance the upward water movement from the deeper soil layers (Lampurlanes and Cantero-Martínez 2006). Therefore, compared with the retention of a sufficient amount of residues at the soil surface to reduce evaporation effectively, some authors found better results with a very shallow surface incorporation of residues because this is best at breaking the unsaturated hydraulic conductivity, a process that, for Sillon et al. (2003), seems to be more important for evaporation reduction than the differences in albedo and surface roughness. Prihar et al. (1996) found that the benefits of the residue management treatments followed the order of residue-undercut > residue-mulch > residue-incorporated. According to Gill and Jalota (1996), incorporating lower rates of straw mulch into the top few centimeters can be as efficient or more efficient than higher mulch rates at reducing evaporation.

Other types of surface covers have been proposed to reduce unproductive evaporation losses, such as plastic films or sand or gravel mulch (Liu et al. 2009; Yuan et al. 2009; Tao et al. 2006). Despite some positive results with regard to reduced evaporation and improved water storage and productivity, labor and capital investment are clearly the major constraints to the widespread use of these materials, at least with the objective of evaporation reduction.

The process of evaporation and its control remain a complex issue as they strongly depend on the soil and climate conditions and the length of time over which treatments or practices are applied. Nonetheless, it is widely agreed that an increase in the rate of the soil surface mulch can reduce the amount of short-term and probably long-term soil evaporation (Verhulst et al. 2010; Blanco-Canqui and Lal 2009; Singh et al. 2006; Burt et al. 2005). Occasionally, under dry rainfed conditions and on sandy soils, surface mulch may not be effective for evaporation reduction (Ward et al. 2009; Burt et al. 2005). However, under these conditions, the response of the soil evaporation and that of the soil water storage to rainfall are in a phase where all rainfall is evaporated, irrespective of the soil cover (Monzon 2006).

### 10.3.2.3 Effects on Soil Water through the Increase in Soil Organic Matter and Macrofauna Activity

The removal of crop residues through burning or for fodder and biofuel purposes is considered to be a major threat to soil productivity, environmental quality, and overall sustainable development (Blanco-Canqui and Lal 2009; Hakala et al. 2009; Lal 2009). In addition to the physical protection of the surface soil layer and its impact on infiltration and evaporation, organic residues enhance the buildup of SOM and soil fauna activity, which contribute to improve the soil porosity, soil particle aggregation, soil moisture storage, and deep water infiltration (Lal 2009; Wuest et al. 2005).

The improved pore space is a consequence of the bioturbation activities of earthworms and other macroorganisms and the channels left in the soil by decayed plant roots. Studying the effects of earthworms in Germany, Ernst et al. (2009) found that the soil water was strongly affected by the activity of ecologically different earthworm species. The epigeic *Lumbricus rubellus* tended to enhance the storage of soil moisture in the topsoil, and the endogeic *Aporrectodea caliginosa* strongly improved the water infiltration and hastened the water discharge through the soil. Although the benefits of increased earthworm populations are mainly attributed to the absence of soil disturbance (two to nine times more in NT than under CT [Chan 2001] and relatively less than the amount of residues retained at the soil surface [Eriksen-Hamel et al. 2009]), Blanco-Canqui and Lal (2007b) found a strong effect of corn stover removal on the reduction in the number of earthworms. On all three soils studied, stover removal at rates above 25% drastically reduced the number of earthworms and, on the occasionally anaerobic clayey soil, stover removal above 50% eliminated the earthworms. At a different site after 10 years of applying 0, 8, and 16 Mg/ha year of wheat straw without crop and cultural operations, Blanco-Canqui and Lal (2007a) found 158 ± 52 earthworms per square meter in the medium and 267 ± 58 earthworms per square meter in the highest mulching treatment, whereas no earthworms were present in the zero mulch level.

Whereas the authors associate the higher water infiltration rates obtained with less or no stover removal in the study under three different soils (Blanco-Canqui and Lal 2007b) to the greater number of surface-connected earthworm burrows and other biopores, they found no difference in the infiltration rates between the residue levels at the other site (Blanco-Canqui and Lal 2007a). In both studies, however, they measured significantly higher soil water retention under the higher amount of residues, although this was confined to the surface soil layer. While some reports indicate that an abundance of earthworms has a strong influence on the soil porosity and the consequent water infiltration in mulched NT soils, Bottinelli et al. (2010), Kladivko et al. (1997), and Blanco-Canqui and Lal (2007a) concluded that increases in the earthworm population by mulching does not always increase the water infiltration rate in all soils, depending on the dominating type of earthworms.

Increases in the surface mulch or the residues incorporated into the soil tend to increase the SOM (Wuest et al. 2005; Sharma and Acharya 2000). Even under NT, the amount, type, and management of the residues play an important role in the evolution of the SOM. Basch et al. (2010) compared the residues of chickpea and the different amounts and management of wheat straw with regard to the changes in the SOM under Mediterranean conditions. After 3 years, they had already found significant differences in the SOM in the following order (letters indicate differences $P \leq 0.05$): chickpea residues (c) >stubble only (bc) >in-field grazing of straw and stubble (b) >>straw retained (a) >2 × straw retained (a).

SOM promotes soil biological activities and processes, resulting in more bacterial waste products, organic gels, fungal hyphae (polysaccharides), and worm secretions and casts (Wuest et al. 2005), which improve the aggregate stability and porosity. Directly or indirectly, these organic compounds are related to the water-holding capacity, although it is the total SOC or organic matter that is usually considered as an important aggregate indicator in a discussion on water retention pedofunctions (Rawls et al. 2003). Evaluating the efficiency of the pedotransfer functions to estimate water retention in 725 soil samples from the state of Rio Grande do Sul, Brazil, covering all types of soil textures, Reichert et al. (2009a) concluded that organic matter must be included as an independent variable, because it had an individual positive effect on the field capacity and the plant-available water. Sharma and Acharya (2000) found that the application of fresh lantana (*Lantana camara* L.) at a rate of 8 Mg DM/ha either as a surface mulch or incorporated over 4 years significantly increased the SOM content in the layer 0–15 cm. At the different sowing dates, the mulched treatments compared with the unmulched treatment showed a higher amount of stored soil water (between 15.1 and 22 mm) in the 0–45 cm layer. From the third year onward, both mulch treatments yielded significantly higher than the unmulched treatment, and in the fourth year the yield in the surface-applied mulch surpassed those in the incorporated mulch.

Crop residue incorporation is not the best residue management practice because it implies soil disruption and eliminates the beneficial effects of the residues retained on the soil surface. Even so, in a long-term experiment, Singh et al. (2005) found that rice straw incorporation was less detrimental to the soil physical and hydraulic properties than the burned or removed rice straw. Whereas straw removal compared with the other residue management systems performed worst with regard to SOM and soil aggregation, straw burning led to reduced water retention due to an increased water repellency of the soil surfaces. Comparing the effect of rice straw incorporation plus 60% of the mineral fertilizer–only treatment over 8 years in a sweet potato–rapeseed rotation, Zhu et al. (2010) found a 13% increase in the SOM with the rice straw application and a significant increase in the water-holding capacity. The correlation between these two parameters was highly significant.

### 10.3.2.4 Influence of Type of Soil Cover and Residues and Their Management on Soil Water and Crop Productivity

As shown in the previous sections, the soil cover has a decisive effect on the soil water dynamics and contributes to enhancing the green water component and promoting WP. The possibilities and the choice of the soil cover and its impact depend, in addition to the main objective behind it, on the climate, the soil properties, the management and cropping system (Wilhelm et al. 2004), and the alternative uses of biomass (Lal 2009), among others.

Whereas the use of cover crops is mainly restricted to humid or subhumid regions, in semiarid environments, soil cover through crop residues is the most commonly used option to improve the use efficiency of the main limiting factor to crop productivity. On a very limited scale, other materials such as plastic films, gravel or sand, or organic waste products are used for mulching to protect the soil and enhance the green water component. The use and the effectiveness of these materials have been reported mainly from Asian countries and are considered an option for reducing the soil evaporation, thereby increasing the infiltration of rainwater and soil water retention (Liu et al. 2010; Ghosh et al. 2006; Ramakrishna et al. 2006). In studies using soil cover with plastic film, Wang et al. (2009) found that transpiration was the main component of total ET. From a 2-year study, Liu et al. (2010) reported an increase of 19%–24% in maize yield and 23%–25% in WUE in soil covered with plastic film compared with rainfed bare soil. Total and partial covers of plain soil or ridges and furrows with different materials (straw, plastic film, gravel-sand) and their combinations have been proposed and studied with regard to WUE and crop performance (Liu et al. 2010; Wang et al. 2009; Yuan et al. 2009; Zhou et al. 2009). Although these techniques have been found to be more or less effective in reducing evaporation and runoff, improving infiltration and soil temperature, halting wind and water erosion, and enhancing biological activity and soil fertility (Li 2003), their use on extensive agricultural land can be seriously questioned for several reasons.

Therefore, in large-scale agriculture under semiarid conditions, crop residues, including those from cover crops, seem to be the only technically feasible and economically viable option to cover and protect the soil, while improving the soil water and WUE. Conservation of the soil moisture is one of the major advantages of the mulch farming systems (Mulumba and Lal 2008; Baumhardt and Jones 2002). In semiarid environments with rainfall above the minimum threshold for a benefit in terms of water storage, straw mulching generally increases yields by enhancing the soil water storage (Bescansa et al. 2006; Monzon et al. 2006), but in poorly drained soils or in temperate climates with suboptimal springtime temperatures, residue retention may sometimes reduce yield below optimal levels due to the decreases in the soil temperature (Lal 2008a; Fabrizzi et al. 2005; Anken et al. 2004) and the soil nitrogen (Gao and Li 2005).

As already discussed, the impact of the residues on soil water conservation may depend on their composition, management, and amount (Leys et al. 2010; Ward et al. 2009; Blanco-Canqui and Lal 2007b; Sauer et al. 1996; Steiner 1989). Although the possible impacts of the crop residues on the hydrophysical characteristics of the soil are well studied and it is widely recognized that the management systems that retain crop residues at the surface deliver the highest benefit in terms of soil water availability (Coppens et al. 2006; Burt et al. 2005), studies that relate long-term residue cover to soil water availability and crop productivity under field conditions are scarce and are sometimes inconclusive or contradictory (Blanco-Canqui et al. 2006) as the benefits of the residue cover in terms of soil fertility and water availability might be offset mainly by lower soil temperatures during the initial crop stages and weed and pest problems (Liu et al. 2004; Mann et al. 2002). The increasing demand for residues for biofuel production (Graham et al. 2007; Wilhelm et al. 2004) is raising concerns regarding excessive residue removal (Lal 2009) and that the benefits of long-term NT management may be lost by removing the crop residues (Dabney et al. 2004). Studying the different percentages of corn stover removal over 2 years on three long-term NT sites in Ohio, Blanco-Canqui and Lal (2007b) found a decrease in the plant-available water with an increase in the percentage of stover removal. However, this was reflected in higher crop yields only at one site, well-drained but erosion-prone. They concluded that soils with different characteristics might reveal yield effects if stover removal above a certain threshold level was continued over a longer time period and that site-specific determination of these threshold levels was urgently needed. However, these thresholds should also be assessed with regard to other ecosystem services provided by retaining crop residues, such as offsetting $CO_2$ emissions and maintaining the overall soil quality (Lal 2005).

Cover crops are grown for multiple reasons and their use may present advantages and disadvantages, as comprehensively reviewed by Dabney et al. (2001). With regard to soil moisture conditions for the main crop, the benefits may derive from higher water infiltration, less evaporation losses through an increased residue cover, an increase in SOC, improved soil physical properties (Lu et al. 2000), or removal of the excess water from a wet soil to allow timely establishment of the next crop (Unger and Vigil 1998). However, the reduction in soil moisture is the main reason why cover crops are more suited to subhumid and humid regions, unless irrigation is available to compensate for the extra water consumption by the cover crop. The use and the choice of cover crop species are highly site-specific and depend on the main objective to be achieved. Short-cycle and early maturing species or a premature interruption of the cover crop cycle have been proposed to reduce competition with the main crop (Whish et al. 2009; Salako and Tian 2003; Zhu et al. 1991). In semiarid regions with summer or winter rainfall, normally a single cash or food crop is produced during the growing season, often followed by fallow. In some regions, more than one-third of the agricultural land may be under fallow. With the NT system of soil and crop management, it has been shown that introducing cover crops (for forage or grain) in rotation can reduce the fallow land and simultaneously improve the soil cover, rainwater infiltration, soil water storage, biological nitrogen fixation (in case of legumes), and SOM and fertility (Goddard et al. 2008; Crabtree 2010), while reducing the soil evaporation as already indicated from crop residues (Jalota and Arora 2002). This has been shown to work in semiarid regions in many parts of the world, including North Africa (Mrabet 2008), Canada (Baig and Gamache 2009; Lindwall and Sonntag 2010), the United States (Ransom et al. 2007), Australia (Flower et al. 2008), and Eurasia (Gan et al. 2008). Similarly, with irrigated systems, off-season cover crops provide similar advantages.

## 10.4 PRODUCTION SYSTEM MANAGEMENT

### 10.4.1 Crop Management

This section focuses on the different ways that crops can be managed within production systems to improve the soil water availability, WUE, and WP, apart for cultural practices related to soil tillage, residue management, and soil cover, which were dealt with in the earlier sections. These constitute a large range and include crop and cultivar choice, crop establishment and yield response to water, crop genetic improvement, pest management, fertilization and nutrient management, crop phenotypic expression, and crop rotation and intensification.

However, it must be stressed that individual practices that form a constituent part of good crop management and good production system management for optimizing the use of rainfall or irrigation water are often interrelated in terms of their effects on the final outcome. The interactions among practices can work synergistically to produce outcomes in terms of soil moisture availability, WUE, and WP, in which the "whole is larger than the sum of the parts." For example, for a given amount of rainfall, the soil moisture availability to plants depends on how the soil surface, the SOM, and the plant root systems are being managed. Also, high water productivities under a good soil moisture supply are only possible when plant nutrition is adequate. Similarly, no amount of fertilizer application and use of modern varieties will improve the WUE and the WP if the soil has a 20–30 cm hard plough pan 15–20 cm below the surface; and worse, if the soil has no organic matter and life in it to build and maintain a good soil structure and porosity for maximum moisture storage and root growth. Equally, without the maintenance of a good water infiltration status of the soil and without the soil cover to minimize soil evaporation, it is not possible to fully optimize and maximize water use and WP.

Thus, all else being equal, soils that are maintained in good health and quality will offer the possibility of making the maximum amount of soil moisture available for crop production and the possibility of optimal water-use efficiencies and water productivities through good agronomic manipulation or good crop management. However, good crop management is not an independent variable but a function of how sustainably the production system as a whole is managed in order to sustain or intensify production while harnessing the desired ecosystem services. It is with this concept in mind that the following sections discuss some of the key elements of crop and production system management in relation to soil water availability, WUE, and WP.

#### 10.4.1.1 Crop and Cultivar Choice

The choice of adapted crops and cultivars in irrigated or rainfed production systems, from a moisture viewpoint, is dictated primarily by the nature of the water supply (amount, frequency, and variability) and the type of production system deployed (tillage system or NT system; also generally known as the conservation agriculture [CA] system) (Friedrich et al. 2009; Kassam et al. 2009). Production systems define the possible biological space–time relationships with the prevailing environment and resource use and have an overriding influence on crop agronomy or crop management and cultivar choice, whereas the economic and environmental objectives of the producer will dictate which adapted crops and their cultivars can best fit into the cropping system in space and time. For example, relatively early sowing is possible with NT production system, with improved WUE and WP, compared with tillage systems. The NT system can also offer the opportunity to introduce crop cultivars of longer maturity and higher yield potential or to include a shorter maturity relay crop variety for food or as cover crop.

The water relationships of crops depend on many attributes of the crop and the soil, but they depend, in the case of rainfed crops, even more on the seasonal climate and the weather conditions of the place where it is grown—which determine how much water the crop will receive and when, and how fast the water will be used, and how much of water can be stored in the root zone. It is therefore important that the environmental physiology of the crops and the crop cultivars fit appropriately into the *time available* for crop growth and phenological development and that the crops and their cultivars participating in the cropping system are able to adjust their life cycles to match the unpredictable year-to-year variations in the length of the growing period and in the soil moisture balance. The ability to withstand diurnal water deficits and to survive dry periods in a state of physiological dormancy seems likely to be important during this stage under both rainfed and irrigated conditions (Blum 2009; Soriano et al. 2004; Bunting and Kassam 1988).

Within any irrigated or rainfed production system, only a portion of the soil-available water (between field capacity and wilting point) is *readily available* to crops, which is equal to the level of the maximum depletion of the soil water that a crop can tolerate without a decrease in the plant growth rate. This varies with the type of crop as well as the cultivar. The value of readily available water for production depends in part on the crop cultivar, the quality of the soil, and the evaporative demand of the atmosphere. All these factors, including the crop and the cultivar environmental adaptability requirements, and in combination with economic factors alongside the length of time that the water supply from irrigation or rainfall will be available and its reliability, will influence the choice of crops and cultivars that might be considered for the cropping system (Kassam et al. 2007; Gregory et al. 2000; Bunting and Kassam 1988; FAO 1978–1981; Doorenbos and Kassam 1979). Some crops, such as potato, onion, and strawberry, require the soil to be continuously moist if they are to produce good yields; others, such as cotton, wheat, sorghum, safflower, and olive, will tolerate drier soil conditions. However, the level of depletion that a crop will tolerate varies greatly with their stage of development; most grain crops are vulnerable at the time of germination or planting, particularly under rainfed conditions, and, once established, prefer a smaller depletion during changes from the vegetative to reproductive growth, or in the case of cereals, during the period of panicle initiation, heading, and flowering to fruit and seed setting.

Further, crops vary in the extent to which the leaf water potential can fall without interrupting transpiration or doing damage to the leaves or other parts of the plant. For a given soil type or quality and level of evaporative demand, differences in the root system properties, the leaf and tissue water relations, and the crop development characteristics are all important in determining the differences between crops and among cultivars in the magnitude and time course of the readily available soil water. Doorenbos and Pruitt (1977) have reviewed the general information for different crops on the rooting depth and on the readily available water for different soil types and evaporative demand. Such information together with the information on the yield response to water provides a basis for designing cropping systems that can optimize the available water and offer best water productivities, including under deficit irrigation (FAO 1992; Doorenbos and Kassam 1979).

The WUE and WP of rainfed crops can be improved through crop and cultivar choice by ensuring a good fit between the crop growth cycle and the length of the prevailing rainfed growing period across the different climatic zones and also ensuring that the chosen crop cultivars have access to adequate nutrients and pest control (including weeds) to offer best WUE and WP. For example, in the warm tropical climatic zones with rainfall between 400 and 600 mm, annual grain crops of similar maturity are selected to fit the moisture regime, but there are specific component crops included in the crop association that allow for fuller use of the end of wet season moisture. In areas of higher rainfall up to 1000 mm, crop mixtures of grain crops with some root and tuber crops, especially those involving different maturities, are common. In areas with above 1000 mm of rainfall, crops and their cultivars are selected to fit into multiple cropping systems that are based on both the simultaneous (intercropping) and sequential (relay cropping) principles to maximize the use of the available soil water (Bunting and Kassam 1988; Kowal and Kassam 1978; Andrews and Kassam 1976).

In warmer regions with a long wet season as in the humid tropics, or a shorter wet season as in the seasonally dry tropics, with irrigation facilities, crops can be grown year round. Once crop cultivars of a certain duration have been selected to match the prevailing moisture regime, and barring other constraints such as poor soil health, soil compaction, and limited soil rooting volume, WP improvement is a function of good crop nutrition and protection, and ensuring minimum soil evaporation losses and the maximum proportion of available water consumed as transpiration (Passioura and Angus 2010), aspects that are discussed later in this section. Under drought-prone environments, WP can be improved or maintained by selecting cultivars that have an effective dehydration avoidance ability (Blum 2009) so that they can endure or withstand a dry period. Usually, this is based on the cultivars' ability to extract more stored water from the soil profile, by developing a bigger working range in the water potential in leaves and other plant parts through osmotic adjustment and by storing water in their tissues so that wilting is delayed (Chimenti et al. 2006; Blum 2009; Sellin 2001; Ali et al. 1999; Ludlow and Muchow 1988; Kassam et al. 1979).

#### 10.4.1.2 Crop Establishment and Yield Response to Water

Good and timely crop establishment is essential for achieving high WUE and WP. However, crop establishment can be a precarious or a vulnerable stage in a crop's life, particularly if the crop must be established with soil moisture derived from rainfall. This is because not only must the soil moisture supply be adequate for the seed to germinate, but it must also continue to supply the seedling roots with water and nutrients for growth. Under rainfed conditions, in a seasonally dry climate, whether in the tropics, subtropics, or a temperate climate, every year the farmer and the crop must cope with the variability of the soil moisture supply around the onset of the rains, and therefore at the start of the growing period. Each year, the start of the growing period can be different. However, for the seasonally dry tropics, it has been shown that an adequate soil moisture supply for crop establishment is reached when the rainfall is around 0.5 ET, increasing subsequently to meet the actual crop water requirement of the growing crop as its leaf area increases (FAO 1978–1981; Kowal and Kassam 1978). The actual crop water requirement is dictated by the evaporative demand of the atmosphere and the crop growth stage, in particular the crop leaf area. Dry spells soon after germination can be harmful if the soil moisture supply drops below 0.5 ET.

It is possible to make practical estimates of actual evapotranspiration (ETa), and hence the crop water requirement, from computed ET using empirically derived crop coefficients (kc), such as Eta = kc ET. Values of kc for different crops at different growth stages are given in Doorenbos and Kassam (1979). As indicated, for many dryland crops, kc at the time of crop emergence and establishment is 0.4–0.6, increasing to a maximum of 1.0–1.3 when the crop canopy covers most or all of the ground and is able to intercept most or all of the incoming radiation. This occurs in many crops and environments when the leaf area index (LAI) is around 3 (Stewart 1991; Bunting and Kassam 1988; Kowal and Kassam 1978). The relationship between relative ET (ETa/ET) for several field crops shows that at a given LAI, crops of markedly different canopy structures (e.g., sorghum, cotton, groundnut, pearl millet, and maize) use water at very similar rates (Kowal and Kassam 1978). Thus, factors that control the leaf area, particularly the nutrient fertility and the plant population, will dictate the time course of ETa, or WUE, and yield or WP.

In general, the relationship between yield (Y) and ET is linear and that each cultivar has its own ration of yield decline to ET deficit, provided water is the only limiting factor (Stewart 1991) and the required inputs of nutrients were used and weeds were controlled, etc. However, a water deficit of a given magnitude may occur either continuously over the total growing period of the crop or it may occur during any one of the individual growth periods,that is, establishment, vegetative, flowering, yield formation, or ripening. The effects of a water shortage on yield at the different growth stages of a number of crops are reviewed in Doorenbos and Kassam (1979), where the response of the yield to the water supply was quantified through the yield response factor (ky), which relates the relative yield decrease to the relative ET deficit. In the case of deficits occurring continuously over the total growing period, the effects of increasing water deficits on yield were less (ky < 1) for alfalfa, groundnut, safflower, and sugar beet than for banana, maize, and sugarcane (ky > 1). In the case of deficits occurring during the individual growth periods, the effect on yield is relatively small for the vegetative and ripening periods and relatively large for the flowering and yield formation periods.

This means that when water and crop management are not limiting, an analysis of the crop water production functions when performed for a range of crops can serve to identify those crops and cultivars that are best suited ecologically to the prevailing or expected water regime from rainfall or irrigation. They also help identify what crops and cultivars should be selected for the different seasonal moisture expectations from rainfall or irrigation. When the effects of the management decisions (such as plant population and fertilizer application levels) are simulated in the analysis, optimal management practices for different types of rainfall and irrigated moisture regimes can be identified. They can thus provide the basis for an economic evaluation for better estimates of production capabilities (Stewart 1991).

For irrigated conditions, crop management for the optimal use of water (i.e., to achieve best WUE and WP) can be simulated against particular objective functions, and actual crop management can follow the planned simulations. In the case of rainfed conditions, the rainfall probability analysis and the associated soil water balance analysis are required to quantify the probabilities of different rainfall amounts in selected time periods. This also quantifies the dates when the rainy period may begin and end and reveals the probability of dry (or wet) spells in specific time periods. This provides a basis for broad-based planning, including an analysis of the risk, allowing reference crop and cultivar mix and cropping systems to be identified. Linking such an analysis to an additional analysis of rainfall predictions, as is done in the case of response farming, allows crop management decisions regarding crop and variety types, planting dates, plant densities, and fertilizer levels and application to be made in response to the upcoming season (Stewart 1991). Crop water management for improved WUE and WP based on response farming relies on the notion that just prior to the start of each season, it is possible to exclude a significant portion of the probabilities (from the total range of probabilities) and have new probabilities assigned to the remainder. The key principle of response farming, as elaborated by Stewart (1991), is the reduction of the effective variability through an improved rainfall prediction, which does not mean pinpointing what is to occur, but, rather, identifying a portion of the range of recorded happenings that should not need to be considered as possibilities in the current season. This concept is based on the findings in different locations that there is a relationship between the time the rainfall season begins (date at which a particular soil moisture supply may be reached) and the rainfall amount and duration thereafter (Stewart 1991; Stewart and Kashasha 1984; Kowal and Kassam 1978).

Thus, from the above, it is clear that the crop management strategy for improved or optimal WUE and WP requires attention to a whole suite of elements. There are additional factors that have a significant impact on the overall water-related performance. For example, with tillage-based sowing and crop establishment, time is required to prepare the seedbed at the start of the rains. Also, actual rainfall is needed for germination, since after preparation, the seedbed dries out and often loses its capillary contact to the deeper soil water. As a result, moisture and time are spent that can delay sowing and crop establishment, as well as expend energy that may be saved or spent on something more productive. Also, the effective rainfall is reduced, thereby decreasing the potential WP, as well as WUE or effective water use (Blum 2009; Soriano et al. 2004).

The key to the effective use of soil water under rainfed conditions is to be able to plant the crop as early as possible. Any delay in crop establishment usually leads to a loss in yield in the case of rainfed crops. Where the average length of the growing period is short, as in the case of the semiarid regions, early sowing reduces the chances of late season water deficit. Given the rainfall variability at the start of the rainy season, often it is not possible to take full advantage of early sowing with tillage-based approaches in which the soil moisture that is available at the beginning of the season is used unproductively in land preparation through tillage for subsequent sowing.

An alternate approach to sowing in tilled soil is the possibility of sowing early into dry soil or just at the time of the onset of rain, if the soil has some moisture. This is only feasible under CA, which involves direct seeding into a soil with an organic mulch cover that allows, as seen earlier, maximum infiltration and therefore maximum effective rainfall. Where the rainfall climate is semiarid savannah with less than 90–120 days or it is a dryland type with no humid period during the rainy season, an adaptation such as dry sowing in mulch-covered microbasins or pits (called *likoti*, *tassa*, and *zai*) help achieve maximum infiltration and early sowing and crop establishment (Marongwe et al. 2011; Owenya et al. 2011; Silici 2010). In undisturbed dry soils, germination can occur on the basis of the available humidity in the soil pores from subsoil moisture, even when the bulk soil is below the permanent witling point. Similarly, in rainfall climates that are humid, a mulch-covered NT permanent bed system provides a good basis for crop establishment and for achieving higher WUE and WP (Govaerts et al. 2007). This is because the soil moisture in undisturbed mulch-covered soils is still at much higher levels and closer to the seeding soil horizons than in fully tilled soils.

Where the rainfall season is longer, it is possible to increase the WUE and the WP through an increase in the cropping intensity as well. Early sowing and crop establishment of the first crop allows a second crop to be fitted into the cropping system more optimally, and in certain cases, can even create time for a third short-season crop to be fitted into the cropping system. This has happened in Brazil in the Cerrados with the maize–soybean cropping system (Landers 2007) and in the Indo-Gangetic Plains with the wheat–rice cropping system (Hobbs et al. 2008; Hobbs 2007).

### 10.4.1.3 Crop Genetic Improvement

Physiologically, an improvement of the genetic yield potential, and therefore WP, with modern cultivars has been achieved through improving the HI by improving the sink capacity. At the same time, to achieve higher WUE and WP, the root system must be able to exploit the largest possible soil rooting volume for available water. Also, key phenological and physiological processes that determine sink size and yield formation, for example, panicle initiation, flowering and seed setting in cereals or tuber initiation in tuber crops, and yield components such as the number of head-bearing tillers, seeds per spikelet, or seeds per cob, etc., are protected against drought or extreme temperatures as much as possible. Thus, the selection of improved WUE and WP has tended to lead to a larger root system and a higher HI, but also to physiological resilience to drought and temperature stress. The HI, WUE, and WP are indices and represent the outcomes of a series of crop ecophysiological processes operating in the right way under normal circumstances as well as under situations of stress causing water deficits and under situations of heat stress. Outcome-related indices are not helpful as explicit targets of breeding and genetic improvement programs. Instead, for water-limited and drought-prone environments to target plant adaptive characteristics including dehydration avoidance traits that can (1) enable the crop to establish as early as possible and reach and exploit the maximum amount of soil-available water for transpiration and the maximum photosynthesis and desired biomass partitioning and (2) help minimize the impact of dehydration under water deficit conditions (Blum 2009).

This is supported by the fact that in water-limited environments, the timing of flowering is perhaps the most important trait for breeders to select in order to achieve a good balance between the water used during canopy development and the water used during seed setting and grain filling (Passioura and Angus 2010; Fischer 1979). This is because the yield is correlated with the soil moisture available from the soil storage and is supplemented by the rainfall or irrigation during the yield formation period for all crops.

However, because of the yearly variation in the length of the rainfed growing period, the crop in which yield formation begins early may do better in one season whereas the crop with a later set of yield formation may do better in another season. Under water deficit or drought situations, many short-duration modern cultivars are less able to cope due to the lack of elasticity and, combined with the high-density close spacing approach, often fail completely to produce a yield. Local cultivars, on the other hand, often have a better ability to respond to drought with a reduction in yield rather than complete failure.

The ability to withstand, tolerate, and recover from drought depends on the extent to which the crop can adjust its solute potential to maintain turgor in the roots and in the shoots and leaves (Passioura and Angus 201; Blum 2009; Ali et al. 1999; Ludlow and Muchow 1988; Kassam et al. 1979). Thus, it should be possible to produce cultivars that have a full complement of drought-tolerant and drought-resistant genes introgressed through marker-assisted breeding as well as through gene transformation including trait-specific genes from novel sources. Such drought tolerance would also impart salinity tolerance, making possible the more effective use of saline water.

However, it must be emphasized that the best drought proofing cannot be achieved through genetic improvement alone. In the final analysis, adaptability to drought is a production system responsibility in which agronomic manipulation and the management of all the different components of the soil–plant–nutrient–water system have an influence on the final outcome in terms of WUE and WP. Often, the agronomic manipulation and the soil management to improve the root formation and the rooting depth, as in the case of CA or the system of rice intensification (SRI) in uncompacted and well-structured soils with deep reaching biopores, is the best foundation layer of resilience against drought that can be deployed.

#### 10.4.1.4 Pest (Weeds, Insects, and Pathogens) Management

Unhealthy and weak plants in degraded agroecosystems tend to succumb to infestation by pests of all kinds, thereby reducing both the WUE, or EUW, and WP. The reductions in WUE and WP can occur mainly through a reduction in the photosynthesis and the growth of the crop plants, including the root system, due to competition from weeds or an attack by insect pests or pathogens.

In the case of weeds, the decrease in WUE and WP occurs because water that would otherwise be available for crop growth is transpired by weeds. The loss of water through weeds can occur at any stage in the cropping cycle, but this has to be balanced with evaporation loss from the bare soil surfaces. Weeds also compete with crops for nutrients and light, thereby reducing their growth. In the case of semiparasitic weeds such as *Striga*, the host plant becomes stunted, thereby decreasing both WUE and WP. Where cropping relies on stored water in the soil in water-limited environments, WUE and WP can be increased by keeping the land weed free through the entire cropping season, as was shown by Anderson and Greb (1987) for proso millet grown in dryland agriculture in the Great Plains of the United States. Similarly, in the case of summer fallow periods to accumulate and conserve soil moisture for subsequent cropping, weed growth during the fallow period is reduced or avoided by using herbicides.

Herbicide technology eliminates the need for tillage in many cropping systems (Shear 1985). However, tillage is still common in many regions of the world, and where it is practiced, WUE and WP are lower as a result of the loss of soil moisture in land preparation and also due to the delay in sowing. Many weed seeds are relatively small and can only thrive because of tillage, which creates improved seedling establishment conditions. Where crop residues are used to develop a mulch soil cover, many weeds are disadvantaged. Thus, integrated weed management involving the use of NT and mulch cover offers an important opportunity for weed suppression (Liebman and Mohler 2001), thereby increasing WUE and WP.

In situations where there is no alternative use of soil water, growing spontaneous vegetation can have a positive impact on the overall WUE and WP because the biomass generated can be used to develop mulch cover as well as protect the soil from erosion. Such vegetation can also include plants normally regarded as weeds, provided their further propagation is avoided by adequate measures.

Insect pest and diseases usually reduce the crop capacity to protect itself against unproductive water loss. This can occur because of a loss in the leaf surface area from attack by leaf-eating insects and by pathogens that cause leaf spots, leaf streaks, and crinkling, thereby reducing photosynthesis. The damage caused to the root systems by soil diseases and nematodes leads to a reduced ability to fully explore and utilise soil water, thereby reducing WUE and WP. Such damage can be greater under conditions of cereal monocropping. Losses can be reduced by using nonhost crops in rotation with cereals, as is occurring in southern Australia, Canada, and Eurasia (Baig and Gamache 2009; Flower et al. 2008; Gan et al. 2008; Goddard et al. 2008; Blackshaw et al. 2008).

#### 10.4.1.5 Fertilization and Nutrient Management

Plant nutrients play an important role in determining the growth of roots and the yield (Rockstrom and Barron 2007) because the source of the substrate for root growth is photosynthesis, which depends on the unit leaf rate as well as on the leaf area, both of which are nutrient-dependent, as well as age-dependent. The leaf area directly affects the transpirational losses, and there is a linear relationship between the transpiration and the biomass that a crop produces, but the slope of the line depends on the nutrient availability. However, the portion of the biomass that is harvested as yield (HI) is a feature of the crop type or variety and of the moisture regime and the sensitivity of the crop growth stage to water deficit and nutrient stress (Doorenbos and Kassam 1979).

An adequate and balanced nutrient supply from a healthy soil is a prerequisite for good growth of the roots and the aboveground plant parts, for yields, and therefore for WUE and WP (Ali and Talukder 2008; Hatfield et al. 2001; Ryan 2000; Liu et al. 1998). For example, when the roots are not impaired by pathogens, the higher N status of the crop leads to a larger root system and to more soil water extraction (Deng et al. 2003; Angus and van Herwaarden 2001; Liu et al. 1998). However, as indicated earlier, under the variable rainfed conditions of the semiarid tropics and subtropics, both summer and winter rainfall, effective nutrient management for improved WUE and WP can be achieved through the practice of response farming in which risk can be minimized by delaying the decision to apply fertilizer, and how much, until later in the season when it becomes possible to predict what kind of moisture season it is most likely to be (Stewart 1991). In southern Australia, this tactic has also been shown to work and the advantage of delaying the decision to top dress is in the saving on the cost of fertilizer and avoiding yield loss by not applying fertilizer if the season is dry (Passioura and Angus 2010; Angus 2001; Angus and Fischer 1991). In practice, effective nutrient management must be seen in terms of the nutrient needs of the crops within the cropping systems in space and time so that the overall production system deployed is also conducive to efficient nutrient productivity alongside the aim of maintaining desirable levels of WUE and WP. Thus, nutrient management under the CA system for improved WUE and WP is a fundamentally different nutrient management strategy compared with that under a tillage-based system (Kassam and Friedrich 2009). Under the CA systems, the WP and the nutrient productivities are higher, and often less mineral fertilizer is needed because of greater biological nitrogen fixation and improved nutrient conservation within the cropping system (Baig and Gamache 2009; Friedrich et al. 2009; Goddard et al. 2008).

Vegetative growth has a direct relation to water use, as well as to the yield and WP for a given supply of soil water. In the case of cereals, this is because the vegetative biomass at the time of anthesis is related to the number of grains per unit area. Similarly for legume crops, biomass at the onset of flowering and subsequent biomass growth during further flowering determine the numbers of flowers, pods, and seeds produced per unit area. In the case of root and tuber crops, biomass at the time of tuber initiation and the subsequent growth of the crop determine the number of tubers per unit area, the number that actually bulk, and the extent of bulking. Assuming healthy crop roots, vegetative growth and the formation of reproductive- or yield-forming parts depend on the nutrient status of the soil and of the plants. Too little vegetative growth, and therefore suboptimal WUE and WP, can be caused by insufficient nutrients, late sowing, and suboptimal plant density. On the other hand, early sowing, excessive nitrogen, and high plant density cause excessive vegetative growth. In areas that suffer from end-of-season drought, excessive growth can lead to the exhaustion of the soil water, leaving insufficient soil water for transpiration and grain filling (Passioura and Angus 2010). There is also evidence that excessive nitrogen can lead to greater structural carbohydrate rather than stored carbohydrate that can be translocated to the grain together with nitrogen during grain filling, thus reducing WP. Further, excessive nitrogen can lead to foliar diseases and insect attack (Kitchen et al. 2008; Chaboussou 2004) and crop lodging, all of which can lower WUE and WP.

The above effects from an excessive nitrogen supply have been recorded when using mineral sources of nutrients under production systems involving tillage over many years so that the soil health is often in a suboptimal condition from compaction, poor infiltration, and low SOM. Results can also be in the opposite direction when organic sources of nutrients are used or when inorganic and organic sources are used in combination. For example, with maize, an increase in the WUE and WP was recorded when the ratio of the organic to the inorganic nitrogen fertilizer was 1:2 (Xiaobin et al. 2001). Larger root systems are produced when there is an organic source of nutrients and where the SOM content is higher and the soil microorganisms are more active and diverse (Uphoff et al. 2006). In this regard, the behavior of the rice grown under mostly aerobic soil conditions, as is the case under the SRI methods, is of particular interest. Under the SRI approach, some 20%–30% less fertilizer is required compared with irrigated flooded rice grown under the best management practice, and 40%–50% less water is required to produce a full crop. Because of the greater yields with SRI and the reduced water requirement, both WUE and WP are higher, and nutrient productivity is superior (see the SRI case description for more details).

Examples of soil nutrient deficiencies affecting WUE and WP also relate to the zinc deficiency in wheat in Turkey (Cakmak et al. 1996) and the sulfur deficiency in groundnuts in India (Patel et al. 2008). The role of calcium and magnesium in improving the pH, the soil structure, and the water-holding capacity and, consequently, WUE and WP is well known. Similarly, several researchers (e.g., Cakmak 2005) have recorded the role of the potassium nutritional status in alleviating the detrimental effects of abiotic stresses through osmotic adjustment.

Evidence shows that mineral fertilization requirements, particularly of N and P, decrease in soils that have been under the CA system for extended periods of time (Landers 2007), and the problem of low availability or immobilized P in soil is ameliorated, even when soil analyses do not show high quantities of soluble P (FAO 2008; Turner et al. 2006). Thus, combined water and nutrient productivity improved over time in CA systems, whereas with tillage-based production systems, nutrient and total productivity including WP remained at a suboptimal level.

#### 10.4.1.6 Agronomic Manipulation for Best Phenotypic Expression

Much of our scientific thinking about agronomic practices and crop production has been based on the assumptions that a crop can be best produced with soils that must be tilled year after year and with increasing tillage intensity in many cases; that soil microorganisms and the SOM are not essential to soil fertility or to the maintenance of soil health and ecosystem health; that plant root systems and their interactions with the soil microorganisms can be ignored in studies aimed at understanding the ecophysiological basis of nutrient- and water-use efficiencies and productivity; that soil mulch cover and crop rotation can be considered as optional in the maintenance of soil, crop, and ecosystem health and in the optimization of the use of resources such as water and nutrients; that there is only one standard way of agronomically manipulating the crop–soil–nutrient–water parameters; that the so-called undefined and unbridled quest for genetic improvement must continue to override improvements that are possible through alternative crop production practices.

For example, the CA and SRI approaches to crop production show us a different way forward. CA and SRI are both works in progress and their concepts and methods are being extended to more crops and more agroecologies, for small-scale and large-scale production. These systems are harnessing an agronomic performance that cannot be predicted by current models or the scientific knowledge generated through the reductionist scientific research approaches that have characterized much of the agricultural research during the last century and still continue to do so. It would appear that there has been a "closure of the mind" in the last three to four decades, particularly within the global public research system, with regard to the additional opportunities that exist in improving WUE and WP through agronomic manipulation of soil–plant–water–nutrient relationships as well as the manner in which the soil health and root systems are managed. Systems such as the CA, SRI, and CA–SRI have not been receiving the kind of attention they should from the scientific community. Given that such systems and agronomic manipulation can help small farmers to improve their overall and factor productivity and livelihood, this lack of attention is a serious gap in the current knowledge system.

While early planting with CA and SRI permits better WUE and WP because of improved soil moisture, upon which the nutrient productivity depends, optimal spacing appears to depend on the soil fertility conditions. Although, generally, a high seed rate and closer spacing have been the dominant approach with modern cultivars that are selected within such conditions, this may not always be optimal, as has been recently shown by the SRI approach for rice, as well as with other crops such as sugarcane, wheat, and finger millet (Uphoff and Kassam 2009). The high-density seed rate appears to have been favored over the past three to four decades, but the SRI approach shows that it is possible to improve the genetics × environment (G × E) interactions and achieve higher WUE and WP through the integration and manipulation of a crop establishment strategy with crop nutrition and weed management. In fact, CA and SRI have revealed a whole new set of opportunities to improve WUE and WP based on alternative approaches to crop and water management (as elaborated in the CA and SRI case details elsewhere).

#### 10.4.1.7 Crop Rotation and Intensification

Many advantages and benefits are associated with crop rotations, including the possibility of higher WUE and WP for the individual crops participating in the rotation and for the cropping system as a whole, when compared with monocropping. In environments of variable rainfall, crop rotations with crops of different maturity allow the reduction of climatic risk because in poor years, not all crops are affected equally and there are positive effects between crops in the rotation, involving cereal and legume crops, from the yield viewpoint, and therefore improved WUE and WP (Tanaka et al. 2005). Equally, rotations also reduce the risk of attack by insect pests and diseases (Chabossou 2004; Krupinsky et al. 2002), thus maintaining WP. Rotations involving high biomass legume crops also allow the in situ production of functional biomass in terms of crop residues and green manure crops and can help add organic matter to deeper layers in the soil as well as increase the soil biopores (Friedrich et al. 2009; Shaxson et al. 2008) Mixed sequences of crops, plus the presence of a permanent soil cover, tend to inhibit the buildup of specific weed species that would thrive under less varied or monocrop conditions and reduce WUE and WP.

The rotation of crops involves the rotation in sequence of several species of crops, including legumes as symbiotic (plant × rhizobia) sources of plant-fixed atmospheric N, and other usable green manure cover crops, for maintaining the soil cover at all times, as well as the provision of labile organic residues both at and below the surface. It is important that the nutrient balances in the soil are maintained from one rotation cycle to the next. C accumulation only seems to occur when there is a legume in the system that fixes more N than is removed in the crop products or is otherwise lost from the system (Boddey et al. 2006; Uphoff et al. 2006).

Crop intensification involves making fuller use of the time available within the annual cropping cycle by introducing additional crops within and between seasons, thereby making fuller use of the soil water while keeping the ground covered for longer periods. According to Gan et al. (2008), long-term studies in Kazakhstan have shown that reducing and gradually eliminating summer fallow are feasible (Suleimenov and Akshalov 2007), thus improving WUE and WP. Similarly, studies in the Canadian prairie have indicated that conventional summer fallow can be replaced using annual grain legumes or green manure crops (Gan et al. 2008), and similarly in North Dakota in the United States (Ransom et al. 2006). Such replacement in the rotational system has been shown to improve the overall farm productivity as well as profitability and improving WUE and WP by 30% (Gan and Goddard 2008; Peterson and Westfall 2004).

The greater the range of plants grown, in mixtures or in sequence, the more varied will be the biodiversity of associations of organisms above ground and inhabiting the rooting depth, and the greater the competition that can suppress those that may be detrimental to the root function and thus considered weeds or pests. A crop rotation will further help in interrupting the infection chain of diseases and might have other insect pest–repellent and insect pest–suppressing characteristics. For the alterations in cropping systems to be worthwhile to farmers, there need to be local uses and/or markets for additional outputs generated by improved crop sequences and mixtures.

## 10.4.2 IRRIGATION MANAGEMENT

Irrigation plays and will continue to play an important role in global food security, and the need and the opportunities for expansion of irrigated cropland still exist (Oweis and Hachum 2003; Seckler et al. 2003). However, and in agreement with Rockstrom and Barron (2007), to minimize further blue water withdrawals and increase WP, a reduction in green water (water that is stored in the root zone) losses is critical. In irrigated agriculture, the fundamental question still lingers: How to produce more with the same or even less amount of water? The answer to this question is still, undoubtedly, linked to the possibilities of minimizing unproductive water losses, namely, runoff (tail water), evaporation, and deep percolation (Rockstrom et al. 2002). Sustainable management practices and technically feasible and cost-effective solutions to maximize crop transpiration and soil water storage and minimize runoff and evaporation, as well as irrigation systems to carry out such efforts, are examined here. They have to consider the different processes that affect the soil water (Figure 10.1) and the parameters that influence the processes (Figure 10.2).

### 10.4.2.1 Irrigation Performance

Worldwide, irrigation schemes are often designed and managed to maximize irrigation efficiencies and minimize labor and capital requirements. For this multiobjective goal, one major challenge that confronts every designer and irrigator is that the soil that conveys the water over the field has properties that are highly variable both spatially and temporally, creating an engineering problem in which at least two of the primary variables, discharge and time of application, must be estimated not only at the field layout stage, but must also be judged by the irrigator prior to the start of every irrigation event (Trout et al. 1992; Keller and Bliesner 2001; Walker and Skogerboe 1987). Recent developments in surface irrigation technology, with its array of automating devices, have largely caught up with the irrigation efficiency advantages of the sprinkler and microirrigation systems (Duke et al. 1992; Heerman et al. 1992). Thus, while it is possible for the new generation of surface irrigation systems to be attractive alternatives to the sprinkler and drip systems, their associated design and management practices are much more difficult to define and implement (de Sousa et al. 1999; Clemmens et al. 1998; Clemmens and Dedrick 1982; Heerman et al. 1992).

Among the factors that are used to judge the performance of an irrigation system or its management, the most common are efficiency and uniformity (Clemmens and Molden 2007; Hamdy 2007; Santos 1996a, 1998; Heerman et al. 1992; FAO 1989). These parameters have been subdivided and defined in a multitude of ways and have been named in various manners (Hamdy 2007; Bos and Nugteren 1990; ASCE 1978; ICID 1978). However, there are other factors influencing irrigation efficiency, building a chain of efficiency steps (Hsiao et al. 2007), and irrigation efficiency at a field or farm level may not be the same as at water basin level (Jensen 2007). In agriculture, farmers,

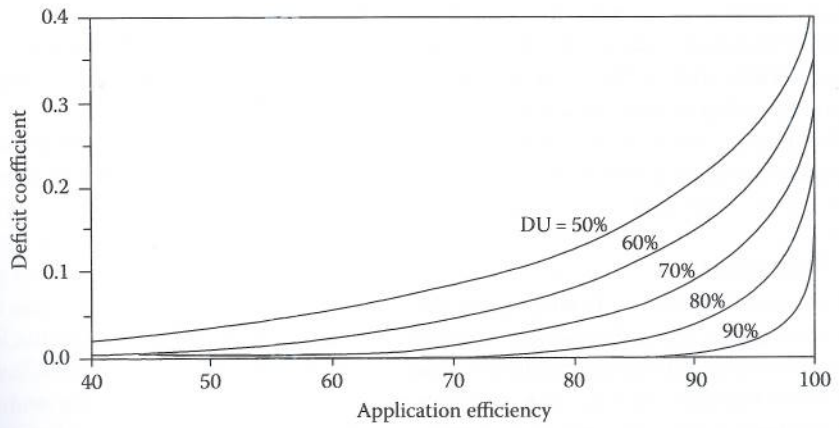

**FIGURE 10.8** The relationship between the deficit coefficient, the application efficiency, and the distribution uniformity (DU), assuming normal distribution of the infiltrated applied water. The deficit coefficient is the fraction of the root zone that has not undergone irrigation. (From Playan, E. and Mateos, L., *Agr. Water Manage.*, 80, 100, 2006. With permission.)

irrigation project managers, and river basin authorities may define WUE quite differently, consisting of various components and taking into account losses during storage, conveyance, and application to irrigation plots (Hamdy 2007; ICID 1978). More consensually, uniformity (distribution uniformity) is used to express the variation in the depths of application or supplied volumes (ICID 1978; Christiansen 1942). Conceptually, the adequacy of on-farm irrigation (field level) depends on how much water is stored within the crop root zone, the losses percolating below the root zone, the losses occurring as surface runoff or tail water, the uniformity of the applied water, and the remaining deficit or underirrigation within the soil profile following irrigation (Fereres and Soriano 2007; Hamdy 2007; Heerman et al. 1992; Bos and Nugteren 1990; Losada et al. 1990). Assuming that the statistical distribution of the infiltrated water follows a normal distribution (Santos 1996a,b, 1998; Losada et al. 1990; Till and Bos 1985), Figure 10.8 illustrates the relationships between uniformity, the water deficit, and the percolation (Playan and Mateos 2006). For a given target deficit coefficient, the lower the distribution uniformity, the lower is the application efficiency.

With proper and careful design and operation, high on-farm irrigation efficiency and uniformity can be achieved directly with systems such as sprinkler and microirrigation systems (Keller and Bliesner 2001; Solomon and Keller 1978; Hart and Heerman 1976) that do not depend on the soil surface for water distribution. The issue is more challenging for surface irrigation systems that depend on the soil to convey water and where the depth of water infiltrated (defining the distribution uniformity) is a function of the opportunity time, the length of time for which water is present on the soil surface to infiltrate (Heerman et al. 1992; FAO 1989). It is worthwhile remembering that the practice of surface irrigation is thousands of years old and, collectively, it still represents perhaps as much as 95% of the common irrigation activity of today (Oweis and Hachum 2003; FAO 1989; Walker and Skogerboe 1987).

With the two sources of surface irrigation system inefficiency in mind, deep percolation and surface runoff or tail water, a very large number of causes of poor on-farm irrigation performance have been outlined in the technical literature (Hamdy 2007; Heerman et al. 1992; Trout et al. 1992). They range from inadequate design and management at the farm level to inadequate operation of the upstream water supply facilities (Walker and Skogerboe 1987). Nonetheless, since the depth of the water infiltrated at several locations in the field is commonly taken as a function of the opportunity time for water to infiltrate, in terms of a root cause, it is a most often accepted fact that the soil physical conditions and characteristics, primarily the soil infiltration capacity, constrain the sustainable performance of irrigation and the economical production of irrigated crops (Tarboton and Wallender 1989). Management practices that can eliminate or at least mitigate these constraints are reviewed in Heerman et al. (1992), Trout et al. (1992), and FAO (1989), among others. Outlined management options include both cultural practices that alter the undesirable soil condition and irrigation practices that minimize or avoid the constraints. The underpinning conclusion is that soil must absorb adequate water during irrigation to meet the crop water requirements between irrigations, with water absorption depending on the soil infiltration characteristics, the irrigation system, and the system's management.

### 10.4.2.2 Infiltration

Infiltration changes a great deal from irrigation to irrigation (temporal variability), from soil to soil (excessive, inadequate, and inherent spatial variability) and is neither predictable nor effectively manageable. Thus, the infiltration rate is an unknown variable in irrigation practice (Tarboton and Wallender 1989; Walker and Skogerboe 1987). Soil infiltration varies both locally and with time, the former resulting from a nonuniform soil texture and structure, topography, soil cover rate, tillage, and wheel traffic, and the latter from soil structure changes caused by SOM accumulation or depletion, frost action, tillage, consolidation from wetting and drying, surface sealing due to drop impact and overland flow, soil animal and microorganism activity, and changes in the ionic soil composition (Trout et al. 1992; Tarboton and Wallender 1989; Undersander and Regier 1988). Soils that absorb water rapidly (excessive infiltration) or slowly (inadequate infiltration) or store only limited quantities in the soil profile (inadequate water-holding capacity) often increase the costs and/or decrease the efficiency of irrigation.

Soils that slowly absorb water constrain the irrigation process by requiring low application rates to avoid water wastage (redistribution and runoff) and long application times or short irrigation intervals to maintain adequate soil moisture in the root zone. Management strategies that increase infiltration require determining the location and the nature of the restricting layer and the process that created it (Trout et al. 1992). The agronomic remedial actions that are required to improve the existing conditions are (1) NT to promote the formation and maintenance of biopores created by the macrofauna activity and the former root channels, in combination with surface residue retention (Jordan et al. 2010; Tebrugge and During 1999; Miller et al. 1987); (2) reduced or controlled traffic to decrease the formation of dense tillage pans and compaction of the tillage layer (Fornstrom et al. 1985; Eisenhauer et al. 1982); (3) deep, vertical, noninversion subsoiler to break tillage hard pans; (4) increased organic matter content or a decrease in the proportion of sodium in the soil, to enhance soil aggregate stability (Ben-Hur and Lado 2008); (5) use of chemical soil stabilizers such as polyacrylamide (PAM) to maintain soil stability (Orts et al. 2000; Lentz and Sojka 1994); (6) reduction of clay dispersion by calcium addition (Trout et al. 1992); and (7) use of plants and residues for the protection of the soil surface aggregates from water drop impact (pressurized systems) and the shear force of the overland flow (Silva 2010; Cary 1986). As already outlined in previous sections, there are ways to approach agricultural production systems, whether rainfed or irrigated, to conditions that are close to those of natural ecosystems in terms of hydrophysical conditions, which per se show the most favorable, site-specific behavior in terms of water infiltration. However, in tillage-based production systems where soil infiltrability is below the necessary rate, the irrigation system and the system's management must be adapted to the low rate, to improve the existing conditions, with (1) use of long and frequent irrigations and systems (level-basin, surge flow, cablegation) that allow for the rapid advance of surface flows and uniform infiltration opportunity times (de Sousa et al. 1999; Clemmens 1998; Shahidian et al. 1998; Clough and Clemmens 1994; Kemper et al. 1987); (2) use of sprinkler spray heads on drop tubes (Thompson and James 1985); (3) use of spray booms or long throw nozzles to reduce sprinkler application rates (Solomon et al. 1985); (4) conversion of center pivots to lateral move or stationary systems that allow for the application of smaller application depths with an increased irrigation frequency (Trout et al. 1992; Solomon et al. 1985); (5) use of microbasin or reservoir (Garvin et al. 1986) to pond and hold water until it can infiltrate; and (6) conversion to or use of microirrigation (drip irrigation), which allows low application rates to match the low soil infiltrability (Keller and Bliesner 2001; Solomon and Keller 1978). Cablegation systems are automated surface irrigation gated-pipe systems (de Sousa et al. 1999; Shahidian et al. 1998; Kemper et al. 1987) that inherently provide for cutbacks in the furrow stream and the subsequent reduction in runoff, potentially increasing the irrigation efficiency in low infiltrating soils. Surge flow (surge irrigation) (de Sousa et al. 1999; Miller et al. 1987) is a process by which an irrigation is accomplished through a series of individual pulses of water onto the field such that the flow interruption is long enough to infiltrate all surface water.

Soils with excessive infiltration are usually coarse-textured soils, freshly tilled soils that develop large voids between aggregates following tillage, and shrinking/swelling clays. Reducing their high infiltration rate is difficult, with irrigation usually increasing the cost and/or decreasing the WUE (Trout et al. 1992). A mix of agronomic and irrigation management practices is needed to cope with the conditions of excessive infiltration: (1) compaction (Khalid and Smith 1978) and compact furrows with equipment and/or pacing wheels (Fornstrom et al. 1985; Musick et al. 1985); (2) NT or a reduction of the depth and disturbance of the tillage to improve the soil aggregation and to reduce the creation of interaggregates; (3) surge irrigation (de Sousa et al. 1999; Miller et al. 1987); (4) high surface irrigation applications, level basin systems (Clemmens 1998; Santos 1996b; Clough and Clemmens 1994), and a reduced field length to decrease the time required to spread the water across the field and thus improve the water distribution uniformity; and (5) conversion from surface to sprinkler or drip systems that do not depend on the soil surface for water distribution, therefore circumventing the problem.

All soils exhibit some degree of soil infiltration variability, locally (spatial) and with time (temporal). Spatial infiltration variability results from a nonuniform soil texture and structure (inherent variability), topography, tillage, and wheel traffic (Miller et al. 1987; Fornstrom et al. 1985; Trout and Kemper 1983), while temporal infiltration variation results from structural changes caused by distinct causes. Identifiable, large-scale spatial variability is best dealt with through (1) differential application of the residue and other organic matter that counteracts it and (2) subdivision of large fields into management subunits based on infiltration. Inherent soil variability is difficult to ameliorate. However, spatial variability resulting from tillage and wheel traffic can be ameliorated through (1) management of tillage and equipment traffic to reduce uneven soil compaction; (2) even traffic across all or alternate furrows; and (3) wheel compaction (better used with surge irrigation) to reduce the subsurface texture or structure of nonuniformity soils (Purkey and Wallender 1989). As far as delivering irrigation water is concerned, the fix is more challenging and complex because the means to deal with both the spatial and temporal variabilities in infiltration is to monitor the irrigation, to adjust the application rates, and to set times to obtain acceptable performances (Trout et al. 1992; Walker and Skogerboe 1987). Manual adjustments are critical, but costly. Feedback control systems that automatically adjust the irrigation application rates and times based on automatically sensed advance rates and tail water runoff have been effectively used (de Sousa et al. 1999; Purkey and Wallender 1989). In such cases, according to Purkey and Wallender (1989), surge irrigation decreased the effect of the infiltration variability by as much as 50%. Precision irrigation has also been advocated (Sadler et al. 2005). Sprinkler and drip irrigation systems that do not depend on the soil surface infiltration rate for water distribution are the next best option to deal with the infiltration variability. As long as their water application rates do not exceed the infiltration rates, water will be absorbed into the soil, counteracting the infiltration variability problems (Silva 2010; Keller and Bliesner 2001; Solomon et al. 1985; Solomon and Keller 1978).

Control systems, water supply management, and precision irrigation certainly present real opportunities to handle the uncertainty associated with variable soil infiltration and to apply water to croplands uniformly and efficiently (Heerman et al. 1992; FAO 1989). The literature suggests that in all cases where high levels of uniformity and efficiency were achieved, irrigators utilized one or more of the following practices: (1) precise and careful field preparation; (2) timely irrigation scheduling; (3) regulated inflow discharges; and (4) tail water runoff restrictions, reduction, or reuse. Opportunities for water conservation with such precision irrigation and cutting-edge soil management practices are discussed in Sadler et al. (2005).

### 10.4.2.3 Soil Water Storage

The water storage capacity varies primarily with the texture, the SOM (Rawls et al. 2003), the inherent restrictive layers, and the compacted soils layers formed by tillage and equipment traffic (Voorhees et al. 1986), limiting the maximum amount of water that can be efficiently applied and the allowable interval between irrigations. The worse situation is when irrigation management must adapt to spatial soil variations in infiltration alongside variations in the soil water storage capacity. Either or both of those characteristics being lower in one location than in the bulk of the field can cause runoff from that location, despite the irrigation system being optimally designed for the bulk of the field (Sadler et al. 2005). Runoff water collecting within the irrigated area or leaving the field damages crops, wastes water, and moves sediments, nutrients, and biocides.

The frequent, light irrigation applications required on soils with a low-water-holding capacity increase the labor costs (except for mechanized irrigation systems) and decrease the water distribution uniformity of the surface systems (Trout et al. 1992; Walker and Skogerboe 1987). Management practices, such as restricted traffic; lightweight tillage or no-tillage, harvesting, and transport equipment; and the avoidance of traffic in moist soil, have been successfully used to slow the creation of compacted layers (Musick et al. 1985; Kaddah 1976). Since short or frequent irrigation intervals require the systems to apply small amounts of irrigation water efficiently, conversion to automated, mechanized, or microirrigation systems is advocated when possible (Sadler et al. 2005; Buchleiter et al. 2000; Camp et al. 1998; Batchelor et al. 1996; Duke et al. 1992).

### 10.4.2.4 Soil Crusts

Soil crusts occur over a wide range of soils due to the action of rainfall and irrigation water and are more prevalent in soils with a low organic matter and a high silt content (Ben-Hur and Lado 2008; Lado et al. 2004; Bjorneberg et al. 2003; Ramos et al. 2003; Santos and Serralheiro 2000; Miller and Gifford 1974). Created when the water-drop impact and the overland flow break down the surface structure and rearrange particles into a denser, amorphous, and hard mass, the crusts impede seedling emergence and impact the exchange of water, air, and heat between the soil and the atmosphere, thereby substantially lowering the infiltration (Trout et al. 1992; Miller and Gifford 1974). Irrigation management practices comparable to ones used to deal with low infiltration soils (described above) are advocated (Ben-Hur and Lado 2008; Lado et al. 2004). Reduced and especially NT systems that leave enough crop residues and promote the accumulation of organic matter at the surface provide the effect of shielding the soil surface from those destructive forces and are the first option to be considered in preventing soil sealing and crusting (Lado et al. 2004; Rawls et al. 2003; Miller and Gifford 1974). Comparing different irrigation methods, sprinkler systems are the main culprit in causing surface crusts. Minimum sprinkler application—in amount, intensity, and kinetic energy breakdown—with reduced sprinkler height and droplet sizes can decrease the soil collapse and crust formation (Silva 2010; Bjorneberg et al. 2003). Soil conditioners, such as PAM, also tend to stabilize the soil aggregates from the destructive impact energy of the sprinkler irrigation systems' water droplets (Bjorneberg et al. 2003; Sojka and Bjorneberg 2002) and the surface irrigation shear forces of the overland flow (Sojka and Bjorneberg 2002; Santos and Serralheiro 2000).

### 10.4.2.5 Irrigation-Induced Soil Erosion

An overview of water erosion from irrigation by Koluvek et al. (1993) indicates that measured annual sediment yields from furrow-irrigated fields often exceed 20 t/ha with some fields exceeding 100 t/ha. Under the center pivot, sediment yields as high as 33 t/ha were measured, with annual sediment yields as high as 4.5 t/ha also reported from irrigation tracts. Typically, overland flow applies shear forces to the soil surface, which causes particle detachment and movement (Sojka and Bjorneberg 2002; Koluvek et al. 1993). As flow velocities increase, shear forces increase and eventually exceed the shear stress required to overcome the cohesive forces between the soil particles. Under surface irrigation, as the water infiltrates the soil, the sediments deposit at the furrow surface to form a thin seal or depositional layer (Orts et al. 2000; Trout and Neibling 1993). The process is potentially halted if the depositional seal formation is slowed down and high infiltration is maintained through the use of known erosion control practices coupled with minimum soil disturbance and the selection of the appropriate cropping sequences (Lado et al. 2004; Koluvek et al. 1993; Trout et al. 1992). Furrow erosion has been reduced using various approaches, including straw placed in furrows (Brown 1985) and sodded furrows (Cary 1986). With a large percentage of the total seasonal furrow erosion occurring during the first irrigation following tillage (Lentz et al. 1992), PAM with an 18% negative charge density injected in the irrigation furrow advance water has also been used to reduce furrow erosion (Orts et al. 2000; Lentz and Sojka 1994; Lentz et al. 1992). Santos and Serralheiro (2000) showed that PAM increased the cumulative infiltration by 15%–20% on furrow-irrigated Mediterranean soils. Permanent ridges for furrow irrigation systems and crop establishment under NT have been successfully applied (Cahoon et al. 1999) and could substantially reduce furrow erosion.

Silva (2010) has reviewed the factors affecting runoff and control practices under sprinkler irrigation that cause erosion only if the application rate exceeds the soil infiltration rate, resulting in water ponding and subsequent surface flow (Lyle and Bordovsky 1983). The soil and topographic variations, along with the water supply and economic constraints, often compromise system designs, and repeatedly, the application rates exceed soil infiltration rates, primarily under the outer spans of the center pivots irrigation system and with the use of low-pressure nozzles that have smaller wetted diameters (Silva 2010; Bjorneberg et al. 2003; Sojka and Bjorneberg 2002; Trout et al. 1992). With an improper average operating pressure as the most common cause for poor sprinkler system performance (Heerman et al. 1992), reducing the sprinkler application rate or increasing the soil infiltration capacity (described above) reduces or eliminates runoff. Tillage practices, such as basin or reservoir tillage, increase the surface storage to prevent overland flow (Garvin et al. 1986) and erosion. Sprinklers applying high molecular weight, water-soluble, anionic PAM were shown to improve the soil infiltration rate and reduce soil erosion (Santos et al. 2003; Aase et al. 1998). PAM applied to the soils through the irrigation water acted as a binding and settling agent to increase the soils aggregate stability and infiltration and reduce runoff and sediment losses (Santos et al. 2003; Bjorneberg and Aase 2000; Aase et al. 1998).

### 10.4.2.6 Deficit Irrigation

The inherent and management-induced nonuniformity of the irrigation systems implies that some water deficit and/or percolation must occur even with the best irrigation schedule. With volumes of irrigation less than the volume of water needed for ET (crop water requirement), under deficit irrigation, all of the applied water remains in the root zone and may be used in ET (Fereres and Soriano 2007). Evidently, the whole field will have some soil water deficit after irrigation and there will be areas with a level of deficit that may be detrimental for production (Fereres and Soriano 2007; Zwart and Bastiaanssen 2004), emphasizing the need for irrigation systems that can deliver high uniformity water applications (Figure 10.8). In the process, the WP (either taken as yield or net income per unit of water used in ET) of the applied irrigation water under deficit irrigation, that is, the application of water below the full crop water requirements or ET, is higher than under full irrigation (water satisfying the full crop water requirement) (Fereres and Soriano 2007).

Broadly, two types of deficit irrigation, sustained (SDI) and regulated (RDI), are assumed (Ramos and Santos 2009, 2010; Fereres and Soriano 2007; Santos et al. 2007; Shatanawi 2007). In SDI, the irrigation is reduced during the whole season while RDI starts with normal irrigation and then the irrigation is gradually reduced. In RDI, the deficit irrigation strategy is based on limiting the nonbeneficial water losses by reducing the amount of water for the crop during the noncritical phenological stages. The deficit irrigation is controlled during times when the adverse effects on productivity are minimized. As summarized in Aboukeira (2010), Geerts and Raes (2009), and Fereres and Soriano (2007), field results from both these practices in annual crops and fruit trees and vines show that deficit irrigation can reduce irrigation water use and raise crop WP in a number of crops. Globally, the potential benefits of deficit irrigation derive from three factors: reduced costs to production, greater irrigation WUE, and the opportunity costs of water (Aboukeira 2010).

Accomplishments in the irrigation of fruit trees and vines with an innovative technique of imposing deficit irrigation by alternating drip irrigation on either side of the fruit tree and vine row (partial root zone drying; PRD) are summarized in Fereres and Soriano (2007), dos Santos et al. (2003), and Goldhamer et al. (2002). In Perry et al. (2009), Ali and Talukder (2008), and Bouman (2007), the factors affecting WP in crop production and techniques to increase WP are analyzed.

#### 10.4.2.7 Evaporation

Reducing evaporation while increasing productive transpiration can enhance WP if there is adequate plant nutrition. Evaporation varies with agricultural practices (Burt et al. 2005) and ranges from 4% to 15%–25% in sprinkler irrigation systems (Burt et al. 2001) where wind is the major concern (Playan and Mateos 2006). The adverse effects of an incremental wind drift increase the evaporation losses and sharply reduce irrigation uniformity. The amount of evaporation depends on the climate, the soils, and the extent of the mulch cover and of the crop canopy that shades the soil, with evaporation claiming a very high share of ET with low plant densities. As for the rainfed systems, evaporation losses under irrigation can be drastically reduced by both the tillage system and stubble or mulch. In a furrow-irrigated cotton crop with 325 mm of rain plus irrigation water, Lascano et al. (1994) measured 100 mm of evaporation under NT with standing stubble against 160 mm under CT without residues. The importance of the surface mulch rates was reported by Hares and Novak (1992), who found 1-day evaporation losses of 1.9, 1.7, 0.6, and 0.3 mm with 0, 907, 9070, and 18140 kg/ha spread straw, respectively. Burt et al. (2005) report that drip and sprinkler irrigation systems do not necessarily result in less evaporation than good surface irrigation systems. Nonetheless, the decreased area of surface wetting obtained with microirrigation is a distinct advantage to minimize the evaporation from the soil surface (Pereira 2007; Batchelor et al. 1996). Burt et al. (2005) also highlight that frequent microspray irrigation and rapid cycling of the center pivots can result in a high percentage of soil/plant surface evaporation.

### 10.4.3 CASE STUDIES ON IMPROVED PRODUCTION SYSTEM MANAGEMENT

The following two case studies have been chosen to illustrate how changes in the production system concepts and the associated management practices can improve land productivity through better use of water and improvements in the soil quality.

#### 10.4.3.1 Soil Tillage Systems in the Central Great Plains

A field study was set up in 1989 by the Kansas State University near Tribune, a region with a semiarid continental climate (mean annual precipitation = 425 mm, mean annual air temperature = 11.2°C), on a deep and well-drained loess-derived silt loam, very characteristic of the west-central Great Plains. Three different tillage systems were established on a virgin, native grass prairie area with a 3-year rotation of wheat–sorghum–fallow (WSF) under rainfed conditions. The CT system was based on a sweep plow, also used for the necessary weed control during the fallow period (three to four operations). RT used a combination of tillage and herbicides to control weeds during fallow, whereas in the NT system, weed control was entirely based on herbicides both during fallow and between crops. In all three systems, in-crop weed control was done by herbicides as needed. Fertilization was identical for the three systems, as well as the maintenance of the crop residues in the field. The only difference between the tillage treatments was that the row spacing and the drill system used in the wheat crop was 30.5 cm (hoe drill) for CT and RT and 19.1 cm (single-disk opener drill) for NT (Stone and Schlegel 2010).

This study continues today and the effects of the tillage systems on the soil physical properties are described in several publications. Based on soil samples taken in 2000, Stone and Schlegel (2010) measured the bulk density, the total N and C, the water content at –1.5 MPa matric potential, and the aggregate stability, the latter through the determination of the concentration of the WSA and the MWD. The ponded, steady-state infiltration rate was also measured in 2000 using double-ring infiltrometers. The results of these measurements are summarized in Table 10.5, and the respective yield data can be found in the Report of Progress 997 of Kansas State University Southwest Research-Extension Center (2008), available online through the Kansas State University library. More recent measurements regarding this experimental site and other long-term tillage studies in the central Great Plains have been published by Blanco-Canqui et al. (2009a,b). Those studies focus on the aggregate properties with regard to soil erodibility and SOC, maximum bulk density ($BD_{max}$), and critical water content (CWC).

**TABLE 10.5**
**Some Soil Parameters after 10 Years under Different Tillage Systems**

| Parameter | Units | Tillage System | | | |
|---|---|---|---|---|---|
| | | NT | RT | CT | NP |
| Total carbon | g/kg | 19.3 | 18.1 | 17.5 | 20.1 |
| Water content at –1.5 Mpa | kg/kg | 0.131 | 0.124 | 0.122 | 0.145 |
| Mean weight diameter | Mm | 1.55 | 0.66 | 0.57 | 3.78 |
| Ponded steady-state infiltration | mm/h | 30.6 | 15.3 | 11.4 | 24.3 |

*Source:* Adapted from Stone, L.R. and Schlegel, A.J., *Agron. J.*, 102, 483, 2010.
*Note:* NT: no-till; RT: reduced tillage; CT: conventional tillage; NP: native prairie.

The data presented by Stone and Schlegel (2010) on some soil parameters after 10 years of differentiated tillage treatments indicate that of the three tillage treatments, NT maintains soil conditions closest to those determined under native prairie. Although the water content at –1.5 MPa matric potential is not an indicator for plant-available water, the authors interpret its good correlation to SOC as a strong reason for the water-holding capacity of the soil. Together with the much higher infiltration rate under NT, which surpassed even the infiltration capacity of the native soil, there is strong evidence that the decrease in tillage intensity improves plant-available soil water. The results of the parameters MWD and the concentration of WSA from samples taken in 2000 are a clear indicator for better aggregate stability under NT when compared with the two tilled treatments. These results were confirmed 19 years after the start of the study by Blanco-Canqui et al. (2009a,b), who found that 4.75–8 mm aggregates from the NT treatment required a significantly higher kinetic energy to be disintegrated than the aggregates from RT and CT. This behavior was corroborated by the water-drop penetration test and measurements of $BD_{max}$ and CWC. Although soil erosion by water is certainly not a major issue on the plain and the permeable soil of this study, other areas with even gentle slopes may lose part of the scarce precipitation through runoff.

The grain yields obtained in this study show a clear benefit of the conservation tillage systems over CT, which was more pronounced in grain sorghum. On average, over 17 years, CT produced 75% and 50% and RT 87% and 79% of NT yields, for wheat and sorghum, respectively. Both graphs of Figure 10.9 also indicate a trend for the differences increasing with time.

Although no in-field soil moisture data are available from this study, Stone and Schlegel (2010) conclude from their results that the better conditions of aggregation and water infiltrability under NT management are indicators for a better water intake and therefore enhanced precipitation use efficiency. In fact, the considerable differences in yield between the tillage systems, especially in the summer rotation crop, corroborate the interpretation of water availability being the main responsible factor for the differences in crop performance.

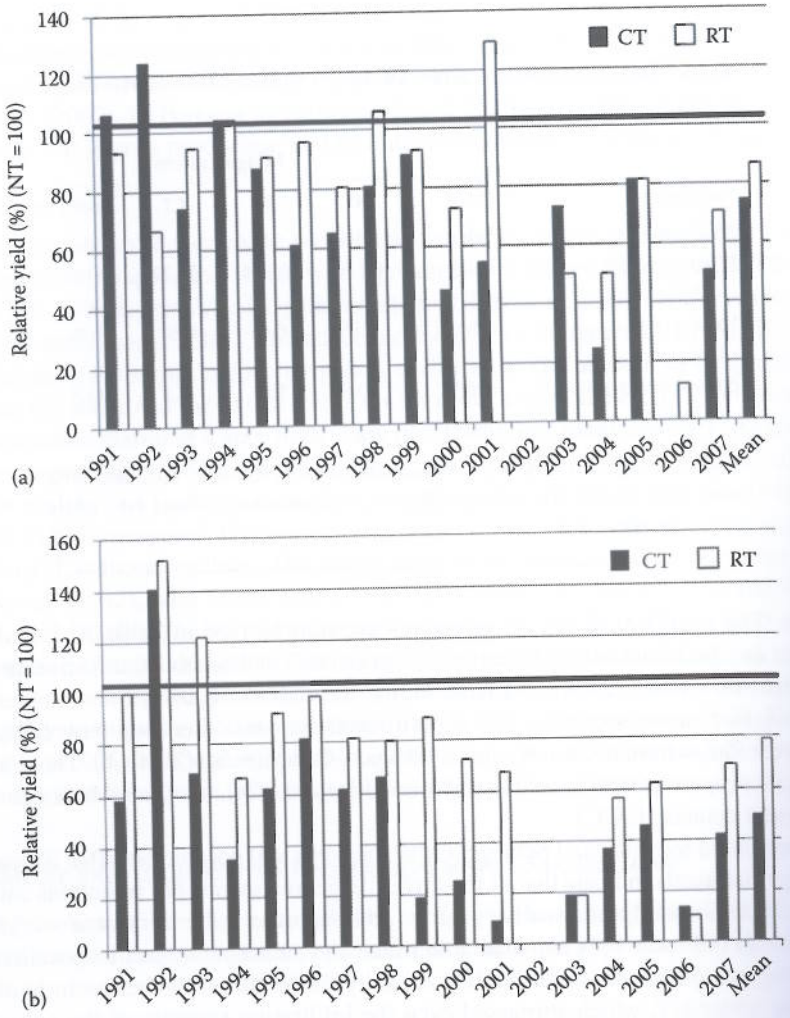

**FIGURE 10.9** Relative grain yields of (a) wheat and (b) sorghum of conventional (CT) and reduced tillage (RT) as compared with no-till (NT). (From Kansas State University Southwest Research-Extension Center, 2008.)

### 10.4.3.2 The System of Rice Intensification

The SRI—a rice production system based on alternative ideas about crop and water management practices—has taken root on an international scale, moving far beyond its origins in Madagascar. At the same time, the diversity of reports shows that SRI is "not yet finished," it is still evolving and changing. The productivity gains, including WP and a decrease in the water requirement, from SRI changes in the management of crops, soil, water, and nutrients have now been demonstrated in more than 40 countries by farmers and a diverse group of stakeholders who support resource-limited, small-scale rice farmers in raising their output and incomes by using locally available resources as productively as possible.

Over recent years, the merits of the SRI system as compared with the recommended anaerobic (flooded) rice production systems have become better understood, based on both scientific and empirical data. The SRI production concept has been defined on the basis of six agronomic practices: (1) the use of very young—about 10 days old—seedlings for transplanting; (2) single transplant/hill; (3) wide spacing of transplants, from 20 × 20 cm to 50 × 50 cm depending on the variety and the soil fertility; (4) mainly moist (not saturated and flooded) soil water regimes kept through intermittent irrigation; (5) regular weeding through a rotary hoe to also facilitate soil aeration; and (6) liberal use of organic fertilizers. These practices were first described in detail some 30 years ago by Henri de Laulanié, a Jesuit priest, who recognized that small rice farmers in Madagascar simply lacked the resources to invest in intensifying their rice cultivation practices through the recommended "modern" technological package based on costly (and unavailable) external inputs and inadequate or nonexistent extension support.

de Laulanié paid little attention to the issue of genetically improved and input responsive modern varieties (the backbone of "modern" rice production and indeed of industrialized agriculture in general). Yet, by manipulating the other crop management factors, including their interactions, he recorded a large decrease in the water requirement and spectacular yield increases, for the local varieties. This corresponded to large water savings as well as greatly increased WP. In essence, SRI crop management and water management at the level of practice represents an "integrated" agronomy. Through integrated management of its various crop–soil–soil biota–water–nutrient–space–time components, SRI seeks to capitalize on a number of basic agronomic principles aimed at optimizing the aboveground as well as the belowground plant growth and development and the performance of the crop as a whole.

Of particular interest here is the SRI recommendation of keeping the soil just moist but not continuously flooded, either by making minimum daily applications of water or by intermittent irrigation. SRI practices of single seedling per hill and wider spacing together with aerobic soil conditions are reported to increase the yields of irrigated rice by 25%–75% or even more with an even greater increase in WP and a reduction in the water requirement by 40%–50%, in seeds by 80%–90%, in the cost of production by 20%, and in the use of fertilizer by some 50%.

Thus, SRI offers an opportunity to reduce water demand while enhancing yields and WP. As has been shown in several studies, the most evident phenotypic difference with SRI is in the plant root growth. Direct measurements confirm that the SRI methods induce both greater and deeper root growth, which contributes to increased WUE and nutrient uptake throughout the crop cycle, compared with the shallower rooting and shorter duration of root functioning under continuous flooding. Rice plants grown with the SRI methods take up more macronutrients than the roots of conventionally managed plants.

Evidence is accumulating that making the changes in the rice-growing practices that constitute SRI can result in win-win outcomes—for farmers, consumers, and the environment—in terms of WP as well as water savings. These gains are possible across a wide range of agroecosystems and are not limited to smallholders. Although the greatest benefits come from using the full set of practices, and using them as recommended, there are demonstrable advantages from "partial SRI." Based on the results of large-scale factorial trials in Asia and Africa, one can predict that in most of the cases reported, there are opportunities to achieve still-greater benefits from SRI methods.

SRI methods, with appropriate adaptations, are effective in a wide variety of environments: tropical humid ecology (Panama), a semiarid region on the edge of the desert (Mali), midaltitude subhumid tropical environment (Madagascar), sandy–marshy regions (southern Iraq), various dry and humid environments in Asia (India, Pakistan, and Indonesia), and even mountainous areas with a short growing season (northern Afghanistan). In each of these environments, farmers have found it possible through their modifications of standard rice-growing practices, according to the SRI principles, to create microenvironments that are favorable to a more beneficial expression of rice genetic potential. A crop management and water management strategy such as SRI is *not an alternative* to getting and using genotypes best suited to a given production situation; rather, it is a way to make the most of any given variety's production capability.

The success of SRI is not dependent on using more modern rice cultivars, although most of the highest SRI yields have come from combining its practices with high-yielding varieties or hybrids. Plant breeding has been, and will continue to be, successful in improving yield and other crop potentials. It is true, however, that SRI methods can also raise the yields of most indigenous varieties, and where these command a higher market price because of consumer preferences, farmers may find these "unimproved" varieties more profitable. This can help with the conservation of rice biodiversity.

Another important consideration is that SRI phenotypes are widely reported by farmers and observers to be less susceptible to pest and disease damage. In 2005–2006, a systematic evaluation was carried out in eight provinces in Vietnam, comparing SRI plots with neighboring farmer-practice plots. This found the prevalence of major rice diseases and pests (sheath blight, leaf blight, small leaf-folder, and brown planthopper) to be 55% less on SRI plants in the spring season and 70% less in summer (National IPM Program, 2007). Farmers frequently say that with SRI management, their rice plants are resistant enough to crop damage that agrochemical protection is unnecessary or it gives them no net economic benefit. The SRI approach is an example of a paradigm shift, to more biologically driven, agroecological strategies for crop production, in contrast to chemically dependent ones.

With any agricultural strategy, we should be concerned about the genetic potentials, as these are the starting points for all life. However, the SRI experience is showing that better optimizing management of the environment for growth can achieve a fuller expression of these potentials while using overall water use and maximizing crop WP.

## 10.5 CONCLUSION

At the end of the first decade of the twenty-first century, there is more awareness than ever before regarding the future need and the importance of producing more food, feed, fiber, and biofuels that must be attained through a 70% increase in total global output based on increased productivity per unit of land and production inputs rather than by extending agricultural production to so far untouched terrestrial ecosystems. The production inputs used to push forward the "Green Revolution" in the 1960s and 1970s, mainly based on high yielding "modern" varieties, more and better use of fertilizers, plant protection products, and tillage, contributed decisively to production increases over the past few decades to keep pace with population growth. Today, there are many voices highlighting the fact that the potential productivity gains through increases in the HI and in the use of water, agrochemicals, and tillage have been met and that a new kind of Green Revolution is needed to match the increasing demand for agricultural commodities while conserving and enhancing natural as well as altered ecosystems and environmental quality. Additionally, such a Green Revolution must address the challenges of increasing food, energy and input costs, pervasive poverty, water scarcity, land degradation, loss of biodiversity, and climate change.

In this context, two aspects are of fundamental importance for agricultural intensification: soil quality and the EUW. Within the ecosystem, both soil resources and water resources are inextricably linked, and so is their management for agricultural and nonagricultural uses. However, the expansion of irrigated land and the withdrawal of blue water for irrigation purposes are reaching their normal exploitable limits, thus making further improvements in WUE and WP a necessity in both irrigated and rainfed agriculture. This entails increasing the productive use of rainfall that infiltrates the soil and is accessible to plants, for use in transpiration in support of biomass growth and harvestable yields. The latter also applies to irrigated lands, because a larger green water share in the soil water balance effectively reduces the amount of supplementary irrigation.

The key message of this chapter, based on substantial empirical and scientific evidence, is that it is perfectly possible to design and put into practice sustainable production systems, both rainfed and irrigated, that are simultaneously productive, profitable, resource conserving, and environmentally protective. In such production systems, the management of the soil water balance in favor of sustainable intensification and therefore the optimization of rainfall infiltration, soil water storage, WUE and WP, as well as all the ecosystem services required by society, can be achieved, provided the three principles of CA are applied simultaneously: minimum soil disturbance, permanent organic soil cover, and diversified cropping system. Similarly, SRI agronomy and water management show that there is a large scope for improving WUE and WP in conventional irrigated or flooded rice systems.

However, CA and SRI (or CA–SRI) systems are "works in progress" and their development has been led largely by farmers. These systems deserve much greater attention from the scientific research community and policy makers. Improved modern varieties and irrigation systems can be important in enhancing WUE and WP, but in themselves, they can only do so much. CA and SRI provide excellent examples of how to obtain "more output for less input" from most adapted cultivars, traditional or modern. They show that when production systems pay attention to ecosystem services, it is possible to achieve sustainable intensification. While CA and SRI are not organic, they can be; they are probiotic and promote biodiversity in all parts of the production systems. They can maintain high overall farm productivity as well as individual factor productivities by promoting soil life and biodiversity, large root systems, organic matter as a substrate for soil micro-organisms and soil organic cover, and species diversification in the cropping systems. These attributes strongly suggest that the principles of the CA and CA–SRI systems need to be better understood and spread over ever-larger areas to meet the future global food security and ecosystem service needs. They embody the notion of sustainable soil water management.

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# 11 Sustainable Management of Brackish Water Agriculture

*Paramjit Singh Minhas*

## CONTENTS

## 11.1 INTRODUCTION

Land irrigation is playing a major role in enhancing food and livelihood security the world over, especially three-fourths of the area that is present in developing countries. About two-fifths of the world's total food and fiber output is contributed by irrigated agriculture, although its area is only 17%. The FAO (2003) estimates that ~70% of the water withdrawn from rivers, lakes, and aquifers (~$820 \times 10^7 m^3$/day) is used for irrigation. In fact, the productivity of irrigated areas in arid and semiarid regions largely depends upon the ability to enlarge this resource base by better rainwater management and/or development of groundwater. Globally, the aquifer withdrawal has increased manifold during the second half of the last century. For example, in the United States the share of groundwater used for irrigation has increased from 23% in 1950 to 42% in 2000. In the Indian subcontinent, groundwater use soared from 10–20 $km^3$ in 1950 to 240–260 $km^3$ during 2000. Nevertheless, a typical scenario in the groundwater-irrigated regions has emerged: the areas