## Meso-level eco-efficiency indicators to assess technologies and their uptake in water use sectors

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# Innovative Technologies for Eco-Efficiency Improvement in Agricultural Water Use

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# Abstract

This document delivers the results of Task 2.3 focusing on the identification of technologies and practices for eco-efficiency improvement. It is linked to the Technology Inventory of Task 1.2, and will involve the selection of technologies that will be assessed in T2.4.

The concept of eco-efficiency, output/input relationships and eco-efficiency framework and its indicators are reviewed in the introductory part of the document. Then, the basic concepts of water productivity and efficiency are presented focusing on irrigated agriculture and beneficial and non-beneficial water use (of particular interest for meso-scale analysis).

Several technologies and management practices for eco-efficiency improvement are taken into consideration for both case study areas, taking local specificities into account. These technologies and practices include: i) advanced technologies for water supply management (remote and automated control of irrigation, shifting to efficient irrigation methods – drip and subsurface drip, deficit irrigation strategies), ii) energy saving technologies (variable speed pumps, network sectoring, dynamic pressure regulators), iii) eco-friendly agronomic practices (cropping pattern changes, super high density plantations for olive farming, conservation agriculture and organic farming techniques).

Examples of application of each technology with their pros and cons in terms of eco-efficiency improvement and applicability under different environmental conditions are reported. A synthesis of identified technologies, their characterization and potential impact are given in the Annex of this document.

# Table of Contents

# List of Figures

# List of Tables

# 1. Introduction

## 1.1. The concept of efficiency in agriculture

Ever since humans intervened in natural ecosystems to gather food, there has been interest in raising the efficiency of agro-ecosystems. Yield per unit land area is the simplest and most widely used eco-efficiency measure for field crops. However, there are inevitably **multiple efficiency measures** at play at the same time, such as water use efficiency (yield per unit of water used, e.g., rainfall, stored soil moisture, and/or irrigation), nutrient use efficiency (yield per unit nutrient uptake or nutrient supplied), radiation use efficiency (biomass produced per unit radiation intercepted), labour efficiency (production per unit labor invested), return on capital (profit as a fraction of capital invested), and so on.

Even within these simple ratios, there are multiple ways that efficiency can be measured. Eco-efficiency is invariably influenced by **multiple factors interacting** on growth and development processes in **non-linear and non-additive** ways. In a classic paper, de Wit (1992) argues that the totality of resources are utilized most efficiently when their supplies are all close to yield-optimizing levels, the reality of a response curve for any single factor is that the highest increments in output are achieved for the first increments in inputs and efficiency declines thereafter. The phenomenon of decreasing efficiencies with increasing inputs is well illustrated for yield response to N fertilization.

Eco-efficiency can be examined at **different spatial scales**. At the **canopy** or **crop level**, harvested yield can be interpreted in terms of efficiency of water transpired, water lost via evapotranspiration, or water supplied as rain or irrigation (Sinclair et al., 1984). At the **farm level**, eco-efficiency might be represented in terms as diverse as the food or economic output per unit labor, the bio-diversity benefits provided by retention of natural habitat per unit food production, or the aggregate food/economic output per unit water or fertilizer applied (or energy used). **Regional level** analyses might target differences in the relationships between inputs and outputs associated with a diverse range of impacts on the economy and the natural resource base.

Farming system eco-efficiency can **vary with time**. A farming system that is mining soil nutrient reserves or depreciating the productive capacity of soils through physical or chemical degradation may appear highly efficient at the outset but progressively deteriorates as degradation intensifies. Classic examples of such thresholds include rising water tables or irrigation leading to salinization in dryland or irrigated systems, often long after shifts in water balance first occurred (McFarlane and George, 1992).

## 1.2. The output/input relationships

Effective application of the eco-efficiency concept requires an understanding of the **production functions** that relate agricultural outputs to the level of resource and other inputs (Dillon, 1977). Figure 1 illustrates three production functions that relate production to inputs at any spatial or temporal scale. The lowest production function depicts the current efficiencies observed on farms in a particular agro-ecological or farming system setting and may represent the performance of the best managed farms across a range of input usage. While **efficiency** is the ratio of the output achieved to the input applied, the slope of the function represents the **marginal efficiency** gain from moving along the production function.

The second higher function represents the achievable efficiencies through the deployment of the best known technologies for that setting. This function is a styled example of such a **frontier based on currently known technologies** and practices adapted to local circumstances. The gap between the observable farm efficiencies and those obtainable with known technologies is caused in the core by economic, social, and institutional factors. Through successful agricultural research even greater efficiencies are continually sought for a given level of input (the third highest curve in Figure 1). Generally such production or efficiency functions exhibit the diminishing returns curve displayed in Figure 1.

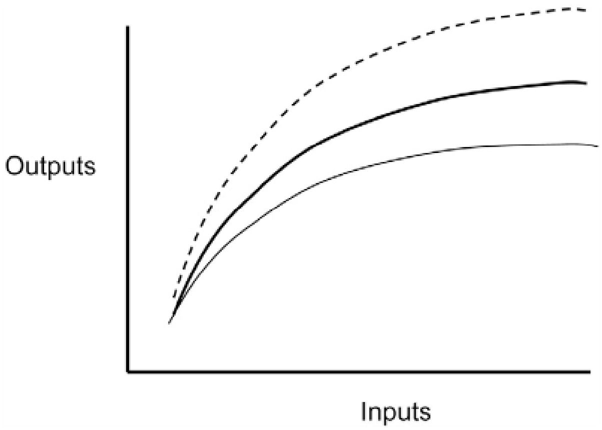


**Figure 1** Example of production functions that relate agricultural outputs to the level of inputs for observed farm performance (bottom), current best technologies (middle) and foreseen new technologies (top) (adapted from Keating et al., 2010).

In most agricultural output–input relationships, however, there is a **probability distribution of responses** driven by sources of variability, primarily climate but also due to the inherent diversity in biological systems and different management across farms and years. The higher the climate variability the more pronounced will be the risk dimension of any eco-efficiency enhancing strategy.

Based on both the input–output space in Figure 1, Keating et al. (2010) suggested three specific pathways to address productivity improvement:

- **moving along the efficiency frontier**, but with associated increase in inputs and riskiness;
- **addressing system inefficiencies** through best practice for a certain level of input and risk and,
- **breakthrough new technologies or practices** to redefine a new efficiency frontier.

The term “**yield gap**” has often been used to describe the difference between actual yields recorded on farmer fields and the yields that are possible with known technologies and practices (identified via farm demonstration plots or a combination of on-farm experiments and simulation modeling). Yield gaps are pertinent to this discussion on eco-efficiency because they are indicative of the eco-inefficiency that persists in different food production systems of the world.

## 1.3. Efficiency from the economic perspective

Even though the economic efficiency is generally expressed in net profit per unit of irrigation water applied, the efficient level of irrigation application is the profit maximizing level of irrigation taking into account all costs, prices, and crop yield response to irrigation. Economists assign monetary values to all the inputs used in crop production and the yield and the efficient use of irrigation water occurs when **marginal revenue** (price of the crop produce in a perfectly competitive market) is equal to the price of water. Most of the irrigation scientists look at economic efficiency as **allocative efficiency** where returns from the use of water can be improved by reallocating the water from lower to higher valued use (Keller et al., 1996; Seckler, 1996). Reallocating water to higher valued uses increases efficiency. This is also true within agriculture when higher valued crops compete with lower valued crops.

From the economical point of view, the most efficient use of resources occurs when the **marginal cost of the resource used is equal to the marginal benefit** derived from applying that resource (Beattie et al., 2009). So, economists add the concept of value to quantities, and aim to maximize the profit from irrigated agriculture by optimizing water use, taking into account all the **costs** (pumping, irrigation application, application rates of other inputs, etc.) and the **yield and price of the produce**. The optimal and most efficient application of irrigation water occurs when the marginal revenue of water is equal to the price of water (Ward and Michelsen, 2002; Young, 2004).

To understand how the **agronomic water use efficiency** measured as a quantity of crop product per unit quantity of water is **related to the economic efficiency**, consider the classical production function provided in Figure 2(Nair et al., 2013). This figure shows the total physical product (TPP, which is the quantity of output produced), the average physical product (APP, which is the output per unit of water used), and the marginal physical product (MPP, which is the output produced when an additional unit of water is applied). The dotted line depicts a ray that begins at the origin and is tangent to the TPP curve, with the maximum slope $Y/X$ (maximum). According to the general definition of water use efficiency used by agronomists and irrigation engineers (quantity of output produced/quantity of water used), this is the point at which efficiency is maximum. The tangent point of this line is economically efficient (profit maximizing) only when $w/p = Y/X$, where $w$ is the cost of water, $p$ is the price of output, $Y$ is the quantity of output produced, and $X$ is the quantity of input used. When $w/p = Y/X$, $wX = pY$, however, meaning that the input cost is equal to total revenue and hence the profit will be zero.

This indicates that the technically efficient (yield per unit of water used) level of irrigation application is economically efficient (profit maximizing) only when the maximum profit realized is zero. The vertical red line shows the yield-maximizing level. This can be economically efficient only when the **water cost** is zero. Even when users do not pay for water, there are **costs associated with water application** (pumping costs, irrigation equipment operation and maintenance, irrigation labor costs, etc.) and hence this cannot be the efficient level of water usage. The **economically efficient water use** is between these two points (in Stage II) and it depends on the price of output and the cost of inputs. At the most efficient level of irrigation water usage, the marginal value product of water will be equal to the price of water.

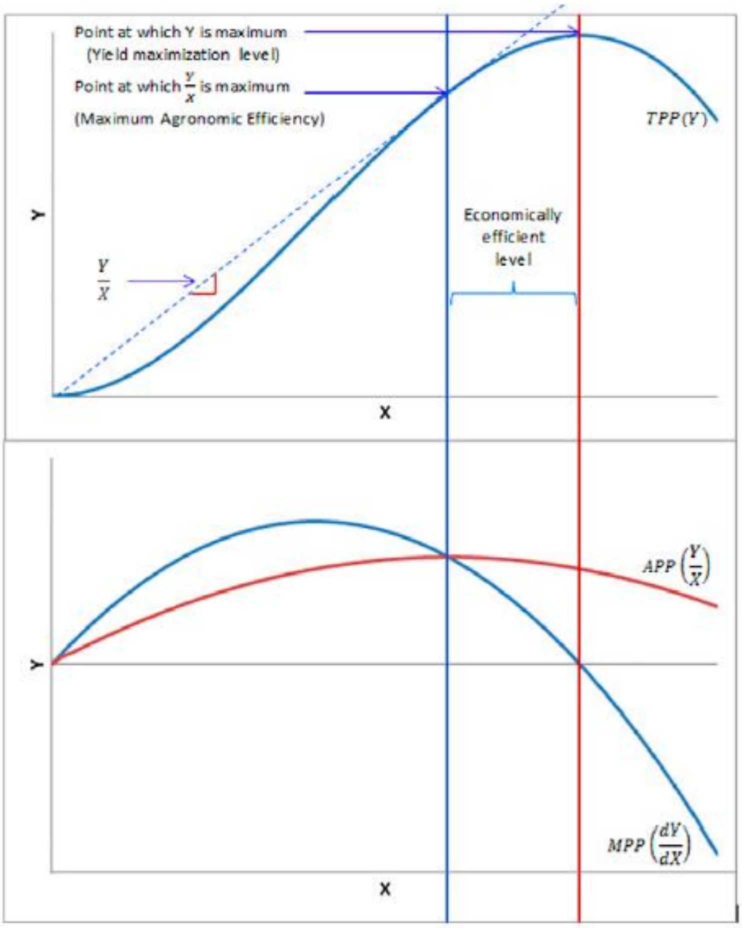


**Figure 2** A graphical illustration of the comparison among agronomic efficiency, economic efficiency and yield maximization level of input usage, TTP – Total Physical Product, APP – Average Physical Product, MPP – Marginal Physical Product (from Nair et al., 2013).

All of the analyses of economic efficiency discussed above assume that the private cost is the same as the **social cost**. In reality, when a number of users extract water from a common source, there is a common pool externality, which arises because the **water extraction** by one person may impart a cost on another person who extracts water from the same source and this can lead to inefficient use of resources (e.g. Koundouri, 2004). Another kind of externality arises from the **leaching of agricultural chemicals** ($NO_3$ or pesticide leaching), which pollute the streams and groundwater and imposes a cost on the users of the polluted water. When externalities are present, economists consider the total cost to society in place of the cost of application of water, and the economically efficient irrigation level is where the marginal social cost of water is equal to the marginal benefit (Anderson et al., 1985; Braden et al., 1989; Färe et al., 2006; Ribaudo et al., 1999; Shortle and Horan, 2001).

## 1.4. Eco-efficiency framework and indicators

If efficiency is simply the level of output per unit of input, "**eco-efficiency**" targets this simple notion toward the **production of food and fibre products relative to the ecological resources used as inputs**, mainly land, water, nutrients, energy, or biological diversity. Such focus should not be considered in isolation of the critical human and economic dimensions of **labor and capital** nor ignoring **outputs such as environmental loads** on wider ecosystems—nutrient, salt, acid, or sediment losses to terrestrial, aquatic, or marine ecosystems, greenhouse gas emissions to the atmosphere—or **other ecosystem services** that might be positively or negatively influenced by agricultural practice (Keating et al., 2010).

Any measure of eco-efficiency involves some **measures of outputs (desired or undesired)** related to some **measure of inputs** or alternative independent variable against which outputs are assessed. Figure 3 presents a set of output-input relationships, normally representing crop and environmental responses to increasing nitrogen supply. The shape of these response functions, their intercept, and scale will depend on the measure being used and the responses observed under the spatial and temporal drivers of variability (e.g. climate) (Keating et al., 2010).

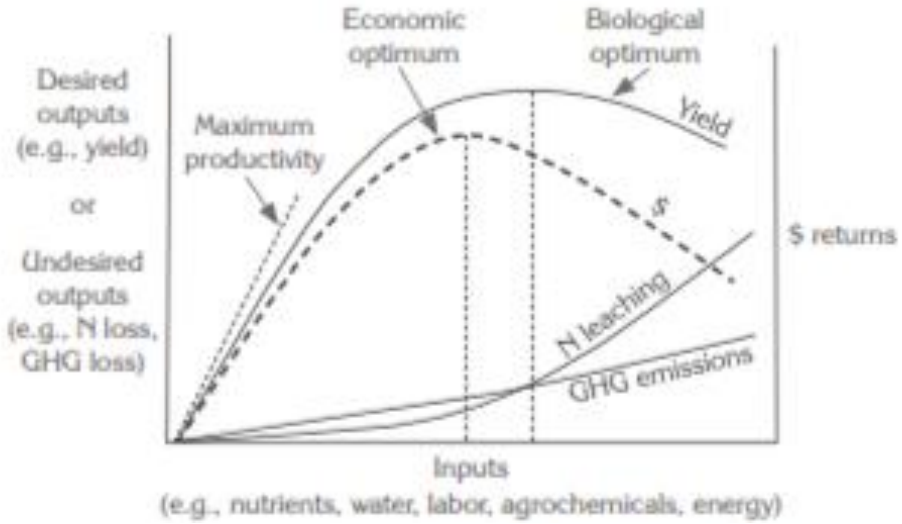


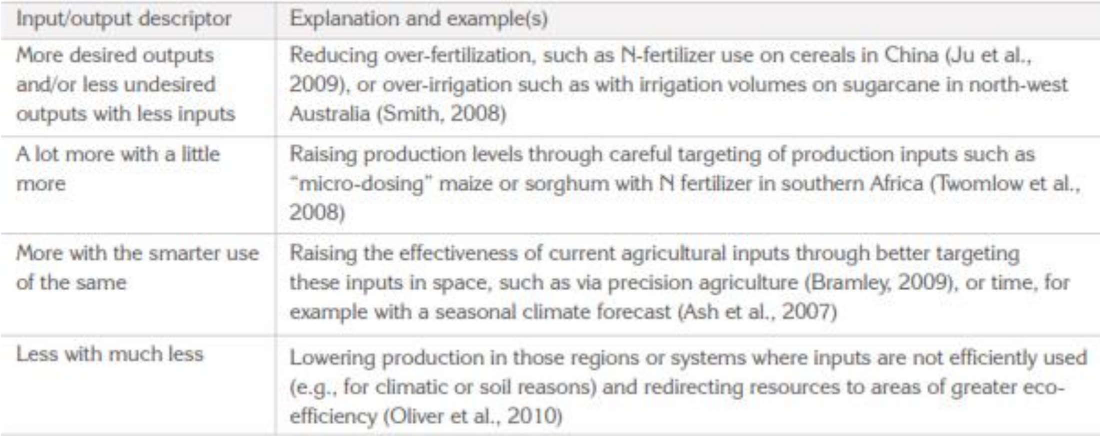
**Figure 3** Example of output-input relationship relating desired and undesired agricultural outputs to the level of resource supply including water, nutrients, energy, agrochemicals, labor, etc.

**Desired output** measures might typically include some measure of harvested product, profit or return on investment, or of the security of a food system; measures could also extend to quality aspects or ecosystem services. **Input** measures typically involve a unit of land, nutrients, water, energy, labour or capital investments. In agriculture, alongside the desired outputs from production, some **undesired outputs** are possible such as biodiversity loss, GHG emissions, nutrient or soil loss, and other forms of land degradation, and these undesired outputs are often a function of relevant input levels.

Production functions relate agricultural outputs to the level of resource and other inputs and, at one level, are a measure of eco-efficiency. Keating et al. (2013)

suggest that, while eco-efficiency carries the notion to produce "more with less", this doesn't mean only higher outputs with lower inputs, but at least four different scenarios can be envisaged for raising eco-efficiency (Table 1).

**Table 1** Example of eco-efficiency scenarios expressed in input/output terms (from Keating et al., 2013).



| Input/output descriptor | Explanation and example(s) |
|---|---|
| More desired outputs and/or less undesired outputs with less inputs | Reducing over-fertilization, such as N-fertilizer use on cereals in China (Ju et al., 2009), or over-irrigation such as with irrigation volumes on sugarcane in north-west Australia (Smith, 2008) |
| A lot more with a little more | Raising production levels through careful targeting of production inputs such as "micro-dosing" maize or sorghum with N fertilizer in southern Africa (Twomlow et al., 2008) |
| More with the smarter use of the same | Raising the effectiveness of current agricultural inputs through better targeting these inputs in space, such as via precision agriculture (Bramley, 2009), or time, for example with a seasonal climate forecast (Ash et al., 2007) |
| Less with much less | Lowering production in those regions or systems where inputs are not efficiently used (e.g., for climatic or soil reasons) and redirecting resources to areas of greater eco-efficiency (Oliver et al., 2010) |

The range of outputs from agriculture, both desired and undesired, can be assessed in **trade-off relationships** (Figure 4), often where production outputs are counterbalanced against the state of a system in environmental or social terms (Kelly et al 1996). When represented graphically, an **outer efficiency frontier** can be drawn to represent the outermost desirable system outputs for the range of known (undesired) system states. Any point under the efficiency frontier represents room to move, with resultant wins and/or losses for both production and environmental outputs.

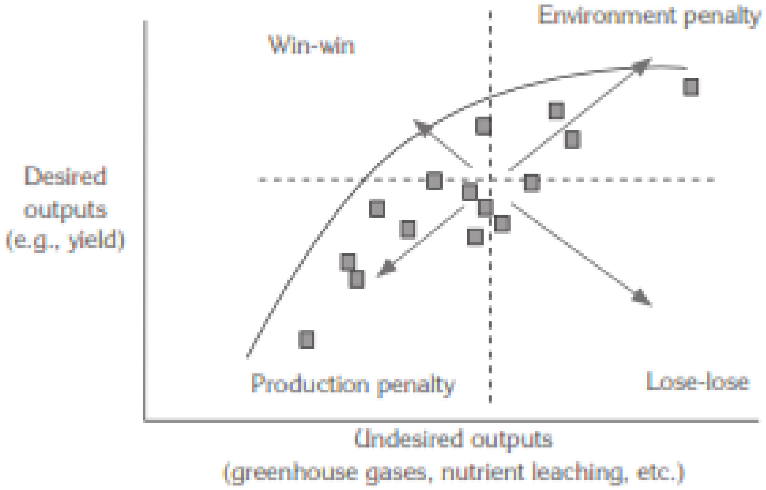


**Figure 4** Example of trade-off relationship between desired output and undesired output (points) resulting in ana efficiency frontier of outermost points (line).

**Eco-efficiency index (EEI)** can be defined as the **ratio of economic to environmental/ecological efficiency or impacts of a production system or process** (e.g., Park et al 2010; Van Meensel et al 2010; Brussaard et al 2010; Huppes and Ishikawa 2005; Gómez-Limón et al. 2012). The EEI approach integrates measures of economic performance and the associated environmental or ecological performance of agricultural production systems into a single dimensionless (aggregate) index (Figure 5). The EEI approach has been widely used around the world to understand business decision issues, such as optimizing resource use efficiency while minimizing pollution production (Schmidheiny 1992; Jollands et al 2004).

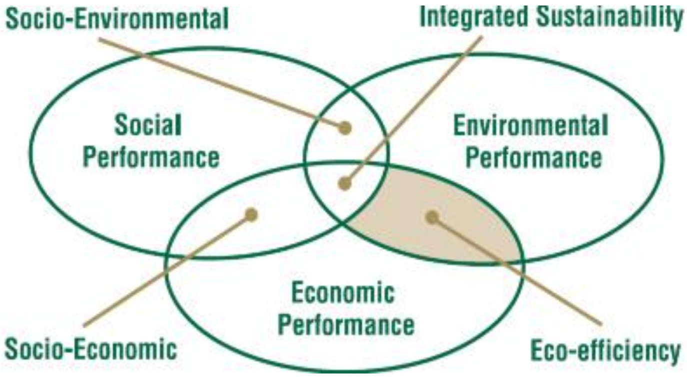


**Figure 5** Sustainable development dimensions and inter-relationships among social, environmental and economic performances (Source: *International Council on Metals and the Environment, 2001)*.

Mathematically, EEI is generally expressed as a ratio of a measure of “economic value creation” to “environmental impact” (Schaltegger et al 2003):

$$EEI = \frac{Added\ economic\ value}{Ecological\ or\ environmental\ impact}$$

**Eco-efficiency of agricultural systems** can be enhanced by choice of crops and farming practices (such as rotation sequence) which reduce negative environmental impacts while at the same time maintaining or increasing farm returns (Del Grosso et al., 2000). Thus, agricultural production systems with **higher EEIs** are considered more economically and environmentally sustainable. The EEI framework has been used to assess trade-offs between agricultural production and various environmental impacts (Brussaard et al 2010; Park et al 2010).

Recent applications of the EEI method in agriculture include comparison of managerial and program eco-efficiency of a sample of olive farmers (Gómez-Limón et al. 2012), while Reith and Guidry (2003) also applied eco-efficiency analysis to a 600-acre experimental farm in south-central Louisiana with the objective to determine and recommend crop management strategies with potential for continuous improvement farm environmental quality and risks.

For example, Kim and Dale (2008) evaluated the effects of economically and environmentally optimal nitrogen fertilization rate on nitrate leaching and returns from corn production, by applying the following **empirical model to estimate EEI**:

$$EEI = \frac{\left\{\frac{[(Y_N - Y_0)p - (w\,X_N) + A_c]}{(Y_0\,p)}\right\}_{ik}}{\left\{exp\,\frac{(V_N - V_0)}{V_0}\right\}_{ik}}$$

where $Y_N$ is the average crop yield (t $ha^{-1}$) generated by the application of a certain rate of nitrogen (N) fertilizer, $Y_0$ is the average crop yield (t $ha^{-1}$) without any N application, $p$ is output price (€ $t^{-1}$), $w$ represents the unit price (€ $t^{-1}$) of N fertilizer, $X_N$ is the level of fertilizer applied, $A_C$ represents the variable cost (€ $ha^{-1}$) associated with the fertilizer application, $V_N$ is nitrate-N leached (kg N $ha^{-1}$) from fertilizer applied at various rates, while $V_0$ is nitrate-N leached (kg N $ha^{-1}$) without fertilizer application, and finally the indexes $i,k$ refer to the effect of additional management practices (e.g. tillage and rotation).

# 2. Water Productivity and Efficiency in irrigated agriculture

## 2.1. Water use, consumptive use, water losses and performance

The performance of water supply systems and water use activities are often expressed with terms relative to **efficiency**. The term efficiency is often used in the case of irrigation systems and it is commonly applied to each irrigation sub-system: storage, conveyance, off and on-farm distribution, and on-farm application sub-systems. It can be defined as input to output ratio, between the water depth beneficially used by the sub-system under consideration and the total water depth applied to that sub-system. A schematic of processes involved in irrigation water use is given in Figure 6.

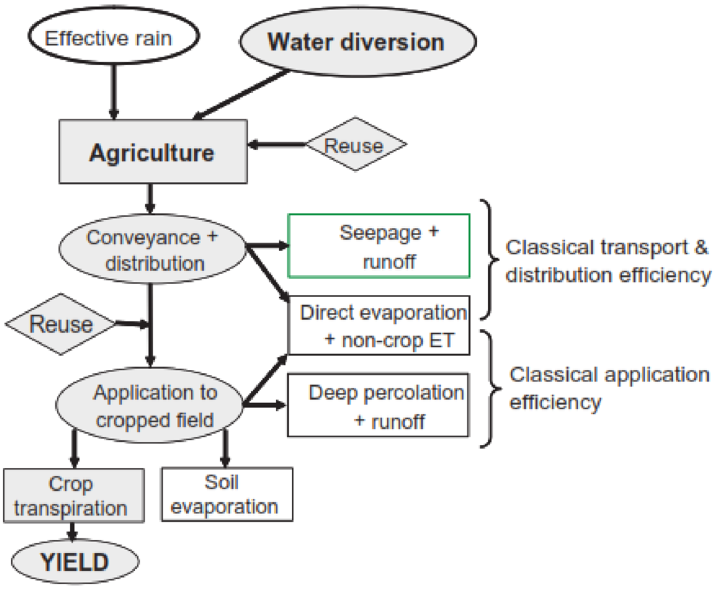


**Figure 6** Processes influencing irrigation efficiency off- and on-farm: grey boxes are the processes leading to the crop yield, white boxes to water wastes and losses (Pereira et al., 2012).

**Table 2** Beneficial and non-beneficial water use and its relation to consumptive and non-consumptive uses in irrigation (Pereira et al., 2012).

| | *Consumptive* | *Non consumptive but reusable* | *Non consumptive and non-reusable* |
|---|---|---|---|
| ***Beneficial uses*** | ET from irrigated crop<br>Evaporation for climate control<br>Water incorporated into the product | Leaching water added to reusable water | Leaching added to saline water |
| ***Non beneficial uses*** | Excess soil evaporation<br>ET from weeds<br>Sprinkler evaporation<br>Canal and reservoir evaporation | Deep percolation added to good quality water<br>Reusable runoff<br>Reusable canal seepage and spills | Deep percolation added to saline groundwater<br>Drainage water added to saline water bodies |

Additionally, new concepts to clearly distinguish between **consumptive and non-consumptive uses**, and **beneficial and non-beneficial uses** are being developed

(Table 2). Similarly the differences between and **non-reusable** fractions of the non-consumed water diverted into an irrigation system or subsystem are being clarified. When water is diverted for any use only a fraction is consumptive use, the non-consumed fraction is returned after its quality preserved or degraded. Quality is preserved when the primary use does not degrade its quality to a level that does not allow reuse, or when water is treated after that primary use, or when water is not added to poor quality, saline water bodies.

Both consumed and non consumed fractions concern beneficial (fully oriented to achieve the desirable yield or product or service) and non-beneficial (when the use is un-appropriate or un-necessary) water uses. Reusable water fractions are not lost because they return to the water cycle and may be reused later, and they are '**wastes**' since they are unnecessarily mobilized. The non-beneficially water consumed or returned to poor quality water bodies is effectively a water loss. Figure 7, **beneficial and non-beneficial water uses** (respectively BWU and NBWU) are schematically summarized, the latter being those that result from excess irrigation, poor management of the supply system, or from misuse of the water.

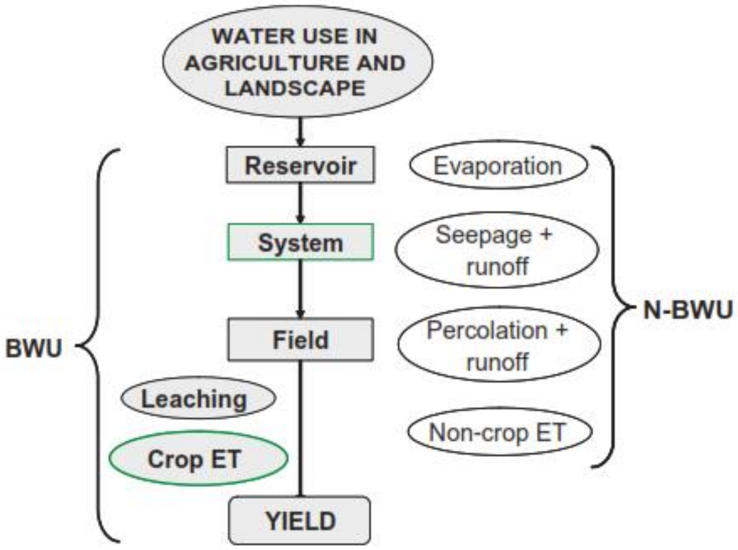


Figure 7 Beneficial (BWU) and non-beneficial (NBWU) water use in crop irrigation (Pereira et al., 2012).

Assuming the concepts above, it is possible to introduce the meaning of "**efficient water use**" (Figure 8): first it is necessary to identify the water pathways in the specific water use, then to distinguish what is consumptive and non consumptive water use, what is beneficial and non-beneficial, and which fractions are losses or wastes.

Then a water use is more efficient when **beneficial water uses are maximized**, water **productivity is increased**, and **water losses and wastes are minimized**. However, it does not mean that less water is consumed when making water use more efficient because maximizing beneficial water uses and water and land productivities through the use of improved technologies may give the opportunity for higher crop evapotranspiration with reduced water wastes and losses. The term "efficient water use" may therefore be thought of as a synonymous with "sustainable" or "rational" water use.

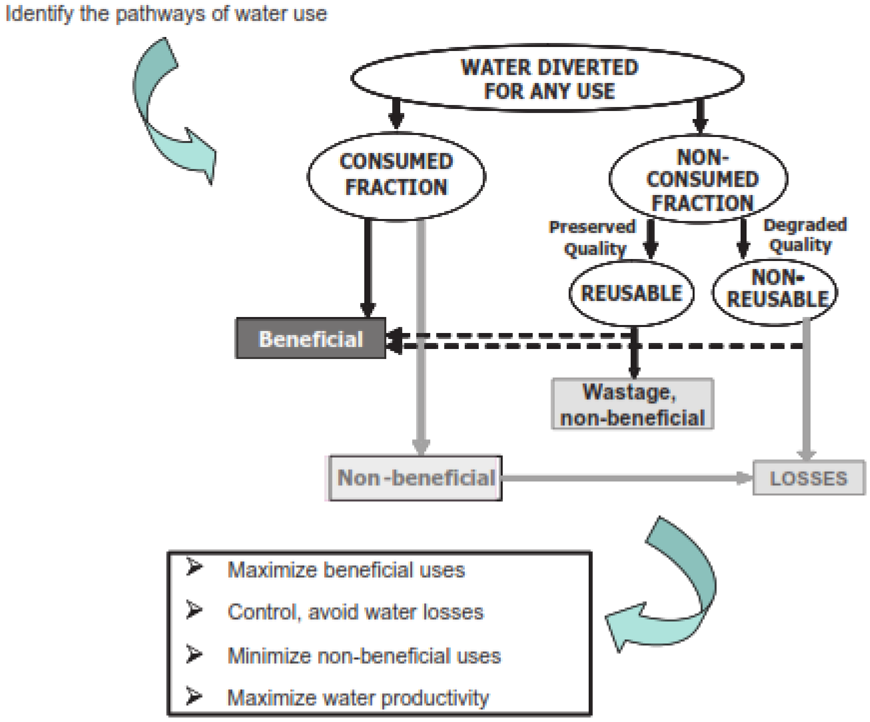


**Figure 8** Water use, consumptive and non-consumptive use, beneficial and non beneficial uses, water wastes and losses (Pereira et al., 2012)

## 2.2. The improvement of crop water productivity (at farm scale)

Nowadays, the goal to increase water use efficiency (WUE) and water productivity (WP) is an important issue in irrigation (Molden et al. 2003, 2010; Clemmens and Molden 2007). The meaning of terms WUE and WP is different at various scales (Steduto et al., 2007; Molden et al., 2010; Pereira et al., 2012) (Figure 9).

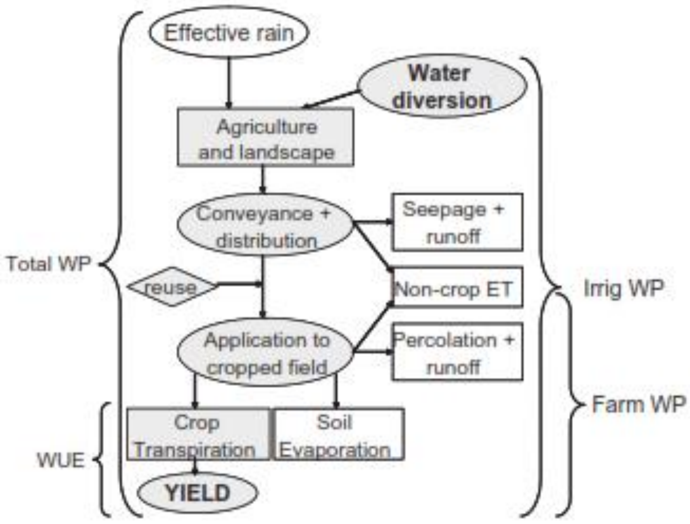


**Figure 9** Water productivity in agriculture at various scale: (a) plant (water use efficiency, WUE), (b) irrigated crop at farm scale (farm WP), (c) irrigated crop at system level (Irrig WP), and the crop including rainfall and irrigation water (Total WP) (Pereira et al., 2012).

According to Pereira et al. (2012) it is possible to define the term **water use efficiency (WUE)** as referred to the measure of the water performance of plants and crops, irrigated or non-irrigated, to produce assimilates, biomass and/or harvestable yield. Production can be defined as the WUE times the amount of water used (Passioura, 1977):

$$Y = WUE_T * T = \frac{Y}{T}\, T = HI\, \frac{B}{T}\, T$$

where $Y$ is the production, $WUE_T$ is the crop production per unit of water transpired (transpirational yield WUE), $T$ is the total amount of water transpired, $HI$ is the harvest index and $B$ the total above-ground biomass; the ratio $B/T$ can be referred to the transpiration (biomass) WUE. Similarly, following Tanner and Sinclair (1983), Debaeke and Aboudrare (2004) suggested the following conceptual framework:

$$\boldsymbol{Y = HI * B = HI\, \frac{B}{T}\, T = HI\, \frac{B}{T}\, \frac{(ET - E)}{VPD}}$$

where $E$ is the soil evaporation component and $VPD$ is the vapour pressure deficit. Following these approaches, it can be observed that an increase in the total yield can be obtained with:

- an **increase** in the **biomass transpiration efficiency (*B/T*)**;
- an **increase** in the **harvest index (*HI*)**;
- an **increase** in the **total water use (*ET*)**;
- an **increase** in the **total amount of water transpired (*T*)**;
- a **decrease** in the **soil evaporation component (*E*)**;
- by placing the crop under climatic conditions of **low vapour pressure deficit (*VPD*)**.

An additional useful description of crop production in terms of water use can be defined as follows (Bouman, 2007):

$$Y = WUE_T\ T = {}^{Y}\!/_{T}\ [C_S\, (Inflow - Outflow) - \Delta W]$$

where $C_S$ is the storage size term, *Inflow* represents the sum of all water inflow components, *Outflow* is the sum of all water outflow components (other than transpiration) and $\Delta W$ is the change in the stored water. The objectives to increase total crop production and to minimize the use of scarce/expensive irrigation water can be realized by the following principles (Bouman, 2007):

- **increase** the **storage size** in time or space,
- **increase** the proportion of non irrigation **water inflows**,
- **decrease** the non-transpirational **water outflows**.

The above-mentioned four principles to increase production and minimize irrigation water can be implemented by **improvement of the germplasm** and/or **in crop/field management**.

The same analysis of crop production and water saving can be addressed at different spatial scales, for example plant, field, farm to regional or basin level. In a systems approach, the boundary conditions define the components of inflow and outflow, the nature and size of the storage pool, and determine which of the flow rates are internally or externally determined. At the **field-farm scale**, the previous formula can be written as (Figure 10):

$$\boldsymbol{Y = HI\,\frac{B}{T}\,\{C_S\,[(I + P + CR + S_{in} + R_{on}) - (E + T_{weed} + S_{out} + DP + R_{off})]\}}$$

The system boundaries are the top of the crop and the bottom of the root zone in the vertical plane and the field boundaries in the horizontal plane. The storage unit is the rooted soil volume plus any storage on the surface of the soil. The water inflows are irrigation ($I$), rainfall ($P$), capillary rise ($CR$), lateral subsurface inflow ($S_{in}$) and runon ($R_{on}$). The water outflows are evaporation ($E$), transpiration by the crop ($T_{crop}$), transpiration by the weeds ($T_{weed}$), lateral subsurface outflow ($S_{out}$), deep percolation (D$P$) and runoff ($R_{off}$). Finally, $B_{crop}$ and $T_{crop}$ are respectively the biomass and transpiration of the whole crop.

The term **water productivity (WP)** can be adopted to express the quantity of product (or service) produced by a given amount of water used, i.e. consumptive and non-consumptive uses, both in irrigated and non-irrigated water uses (Figure 7). With specific reference to the irrigated crops, **WP** may be generally defined as the ratio between the actual crop yield achieved (Ya) and the water use, expressed in kg $m^{-3}$. The denominator may be referred to the total water use (TWU), including rainfall, or just the irrigation water use (IWU), resulting in the following indicators:

$$WP = {}^{Ya}\!/_{TWU} \qquad\qquad WP_{irrig} = {}^{Ya}\!/_{IWU}$$

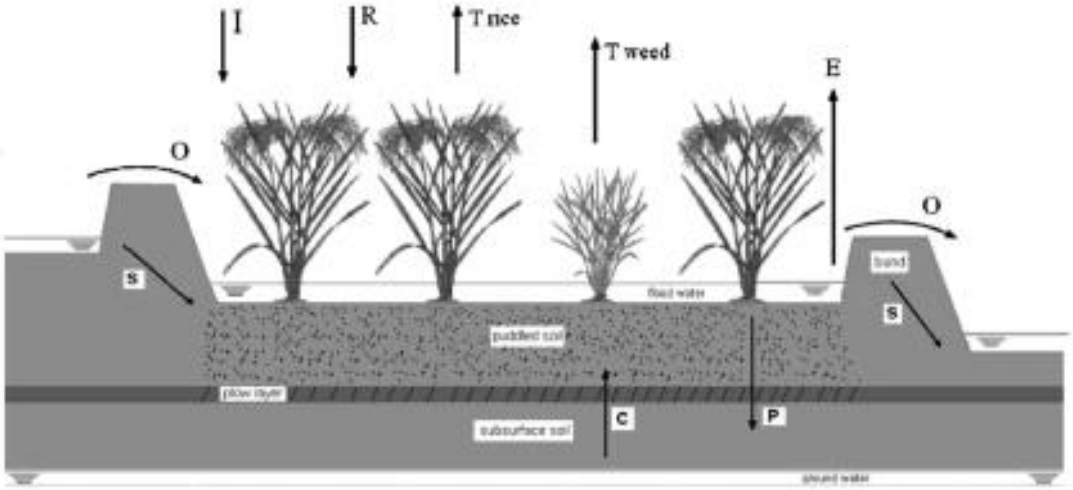


**Figure 10** Water flows and system boundaries at the field level (example of a flodded rice field) (Bouman, 2007)

The same yield depends not only on the amount of irrigation water used but also on the amount of rainfall water that the crop could use, depending on the rainfall distribution during the season. Moreover, improvements of crop yields are often related more with agronomic practices and the adaptation of the crop variety to the given environment.

At **farm scale**, discussing **how to improve WP** requires the consideration of the following factors:

- the contribution of the rainfall to satisfy crop water requirements;

- the management and technologies of irrigation;
- the agronomic practices;
- the adaptability of the crop/variety to the environment;
- the WUE of the crop/variety under consideration.

The WP equation could be also written as:

$$WP = \frac{Ya}{P + CR + \Delta SW + I}$$

where *P* is the seasonal amount of rainfall, *CR* the capillary rise, *ΔSW* is the variation in the soil water storage in the root zone, and *I* the seasonal amount of irrigation input. For example, when **appropriate soil water conservation techniques** are adopted, the proportion of the total P that is available for the crop is increased. Besides, if irrigation practices are oriented for **water conservation**, crop roots may be better developed and the amount of water from *CR* and *ΔSW* may become higher.

Another useful alternative formulation of *WP* is:

$$\boldsymbol{WP} = \frac{\boldsymbol{Ya}}{\boldsymbol{BWU} + \boldsymbol{NBWU}} = \frac{\boldsymbol{Ya}}{(\boldsymbol{ETa} + \boldsymbol{LF}) + \boldsymbol{NBWU}}$$

where *ETa* is the actual seasonal evapotranspiration, *LF* is the leaching fraction, and *NBWU* is the sum of the non beneficial water uses, i.e. the water in excess to the beneficial *ETa* and *LF* water needs, resulting in percolation through the bottom of the root zone, runoff out of the irrigated fields, losses by evaporation and wind drift in sprinkling. According to this formulation, the *WP* may be increased by minimizing the *NBWU* components and through higher yields, by increasing the *ETa* to its maximum level (*ETc*). So, maximum value of *WP* in irrigation requires that **yields are maximized**, ***ET* and *LF* are optimized** and ***NBWU* is minimized**. A high WP may be also obtained when a crop is water stressed, but then the yield is reduced, as in the case of **deficit irrigation**.

## 2.3. Irrigation efficiency

Irrigation efficiency is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and to promote better or improved use of water resources, particularly those used in agriculture management (Bos, 1979). Irrigation efficiency could be defined in terms of **irrigation system performance** and/or **uniformity of the water application**. Each of these irrigation efficiency measures is interrelated and will vary with scale and time.

The **spatial scale** can vary from a single irrigation application device to an irrigation set, to broader land scales (field, farm, an irrigation canal lateral, a whole irrigation district, a basin or watershed, a river system, or an aquifer). The **time-scale** can vary from a single application (or irrigation set), a part of the crop season, the irrigation season, to a crop season, or a year or a period of years (a drought or a “wet” cycle) (Howell, 2003).

The irrigation water can be diverted from a storage reservoir and transported to the field or farm through a system of canals or pipelines; it can be pumped from a reservoir on the farm and transported through a system of farm canals or pipelines; or it might be pumped from a single well or a series of wells through farm canals or pipelines. Irrigation districts often include small to moderate size reservoirs to regulate flow and to provide short-term storage to manage the diverted water with the on-farm demand. Some on-farm systems include reservoirs for storage or regulation of flows from multiple wells.

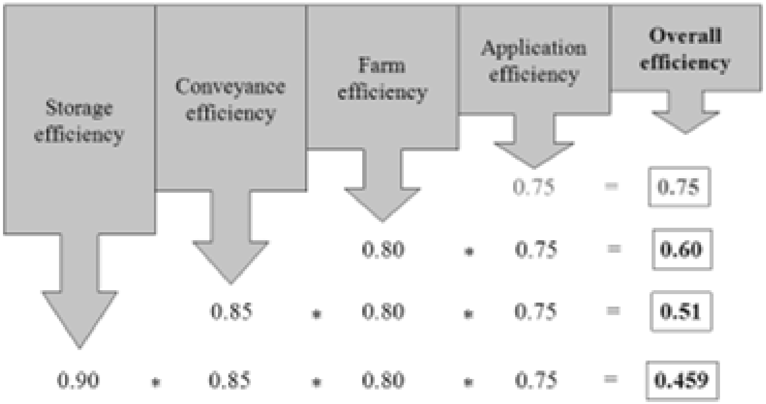


**Figure 11** Efficiency chain of water from reservoir to plant: a multiplicative approach (modified from Hsiao et al., 2007)

In relation to the **irrigation system performance**, several authors have introduced efficiency indicators (e.g. Hermann et al., 1990; Wolters, 1992; Bos et al., 1994; Howell, 2003; Hsiao et al., 2007). The **conveyance efficiency** is typically defined as the ratio between the water that reaches a farm or field and that diverted from the irrigation water source, as:

$$Ec = 100\frac{Vf}{Vt}$$

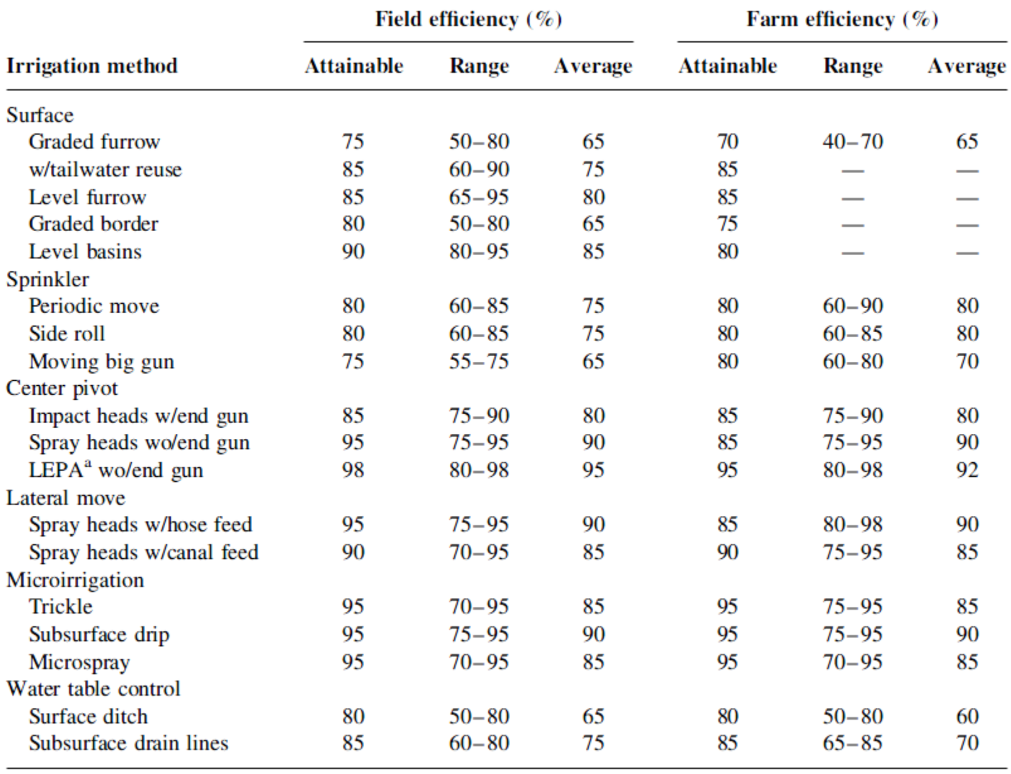
where *Ec* is the conveyance efficiency (%), Vf is the volume of water that reaches the farm or field ($m^3$), and Vt is the volume of water diverted ($m^3$) from the source. Conveyance losses include any canal spills (operational or accidental) and reservoir seepage and evaporation that might result from management as well as losses resulting from the physical configuration or condition of the irrigation system. Typically, conveyance losses are much lower for closed conduits or pipelines compared with unlined or lined canals. Even the conveyance efficiency of lined canals may decline over time due to material deterioration or poor maintenance.

The **application efficiency** relates to the actual storage of water in the root zone to meet the crop water needs in relation to the water applied to the field. It might be defined for individual irrigation or parts of irrigations (irrigation sets). Application efficiency includes any application losses to evaporation or seepage from surface water channels or furrows, any leaks from sprinkler or drip pipelines, percolation beneath the root zone, drift from sprinklers, evaporation of droplets in the air, or runoff from the field. Application efficiency is defined as:

$$\boldsymbol{Ea = 100\frac{Vs}{Vf}}$$

where *Ea* is the application efficiency (%), *Vs* is the irrigation needed by the crop ($m^3$), and *Vf* is the water delivered to the field or farm ($m^3$). Some irrigations may be applied for reasons other than meeting the crop water requirement (germination, frost control, crop cooling, chemigation, fertigation, or weed germination). The crop need is often based on the “**beneficial water uses**.” (Burt et al., 1997). Table 3 provides a range of typical farm and field irrigation application efficiencies (Howell, 1988; Meriam and Keller 1978; Keller and Bliesner, 2000) and potential or attainable efficiencies for different irrigation methods that assumes irrigations are applied to meet the crop need.

**Table 3** Examples of field and farm irrigation application efficiencies (from Howell, 2003).



| | Field efficiency (%) | | | Farm efficiency (%) | | |
|---|---|---|---|---|---|---|
| **Irrigation method** | **Attainable** | **Range** | **Average** | **Attainable** | **Range** | **Average** |
| Surface | | | | | | |
| Graded furrow | 75 | 50–80 | 65 | 70 | 40–70 | 65 |
| w/tailwater reuse | 85 | 60–90 | 75 | 85 | — | — |
| Level furrow | 85 | 65–95 | 80 | 85 | — | — |
| Graded border | 80 | 50–80 | 65 | 75 | — | — |
| Level basins | 90 | 80–95 | 85 | 80 | — | — |
| Sprinkler | | | | | | |
| Periodic move | 80 | 60–85 | 75 | 80 | 60–90 | 80 |
| Side roll | 80 | 60–85 | 75 | 80 | 60–85 | 80 |
| Moving big gun | 75 | 55–75 | 65 | 80 | 60–80 | 70 |
| Center pivot | | | | | | |
| Impact heads w/end gun | 85 | 75–90 | 80 | 85 | 75–90 | 80 |
| Spray heads wo/end gun | 95 | 75–95 | 90 | 85 | 75–95 | 90 |
| LEPA[a] wo/end gun | 98 | 80–98 | 95 | 95 | 80–98 | 92 |
| Lateral move | | | | | | |
| Spray heads w/hose feed | 95 | 75–95 | 90 | 85 | 80–98 | 90 |
| Spray heads w/canal feed | 90 | 70–95 | 85 | 90 | 75–95 | 85 |
| Microirrigation | | | | | | |
| Trickle | 95 | 70–95 | 85 | 95 | 75–95 | 85 |
| Subsurface drip | 95 | 75–95 | 90 | 95 | 75–95 | 90 |
| Microspray | 95 | 70–95 | 85 | 95 | 70–95 | 85 |
| Water table control | | | | | | |
| Surface ditch | 80 | 50–80 | 65 | 80 | 50–80 | 60 |
| Subsurface drain lines | 85 | 60–80 | 75 | 85 | 65–85 | 70 |

Since the crop root zone may not need to be refilled with each irrigation, the **storage efficiency** has been defined (Heermann et al., 1990). The storage efficiency is given as:

$$Es = 100\frac{Vs}{Vrz}$$

where *Es* is the storage efficiency (%) and *Vrz* is the root zone storage capacity ($m^3$). The root zone depth and the water-holding capacity of the root zone determine *Vrz*. The storage efficiency has little utility for sprinkler or micro-irrigation because these irrigation methods seldom refill the root zone, while it is more often applied to surface irrigation methods.

The **seasonal irrigation efficiency** is defined as:

$$Ei = 100\frac{Vb}{Vf}$$

where *Ei* is the seasonal irrigation efficiency (%) and *Vb* is the water volume beneficially used by the crop ($m^3$). *Vb* is somewhat subjective, but it basically includes the required crop evapotranspiration (*ETc*) plus any required leaching water (*Vl*) for salinity management of the crop root zone.

In terms of **uniformity of water application**, the fraction of water used efficiently and beneficially is important for improved irrigation practice. The uniformity of the applied water significantly affects irrigation efficiency. The uniformity is a statistical property of the applied water's distribution, which depends on many factors that are related to

- method of irrigation
- soil topography
- soil hydraulic or infiltration characteristics
- hydraulic characteristics (pressure, flow rate, etc.).

Irrigation application distributions are usually based on depths of water (volume per unit area); however, for micro-irrigation systems they are usually based on emitter flow volumes because the entire land area is not typically wetted. Examples of widely used irrigation **uniformity coefficients** are: i) the 'Christiansen's uniformity coefficient' (Christiansen, 1942), commonly used for the evaluation of sprinkler systems; ii) the 'Distribution uniformity coefficient' (Warrick, 1983), normally used for surface irrigation systems; iii) and the 'Emission uniformity coefficient' (Keller and Karmeli, 1975) applied for micro-irrigation systems.

# 3. Technologies and practices to improve water eco-efficiency in agriculture

## 3.1. Agronomic and engineering strategies to improve water productivity

Generally, the strategies to improve water productivity can be referred to both agronomic and engineering technologies and practices, as suggested by Wallace and Batchelor (1997) and aiming to: i) increasing the harvest index (*HI*) through crop breeding or management; ii) reducing the transpiration ratio (*T/B*) by improved species selection, variety selection, or crop breeding; iii) maximizing the dry matter yield through enhanced fertility, disease and pest control, and optimum planting (precision agriculture research to enhance yields relative to needed inputs at the correct time and location in the field); iv) increasing the transpiration (*T*) component relative to the other water balance components (almost all current water conservation technologies to enhance rainfall capture and to improve irrigation technologies to avoid or minimize application losses). The latter strategy can be obtained by: a) reducing evaporation (*E*) by increasing residues, shallow mulch tillage, alternate furrow irrigation, or narrow row planting; b) reducing deep percolation (*D*) by avoiding overfilling the root zone and minimizing leaching to the absolute minimum for salinity control; c) increasing effective rainfall (*P*) and reducing surface runoff ($R_{off}$) by using furrow diking, dammer diking, crop residues, or avoiding soil compaction and hardpan problems; d) increasing soil water depletion from the profile by gradually imposing soil water deficits, deeper soil wetting, or using deeper rooted varieties.

## 3.2. Technologies and practices under evaluation

For the specific purposes of this study, and on the basis of large stakeholders consultations, a selection of advanced water and energy technologies and farm management practices for eco-efficiency improvement have been done to be evaluated and suggested for practical application in two case study areas (Table 4). Hereafter, this report includes a synthesis of the identified technologies, together with a brief review regarding their potential impact in terms of eco-efficiency improvement.

**A. Advanced technologies for water supply management**

- a. Remote and automated control of irrigation water supply;
    - i. Sensors for monitoring weather variables and soil moisture content
    - ii. Variable Rate Irrigation (VRI)
- b. Efficient irrigation methods
    - i. Sprinkler irrigation
    - ii. Micro-irrigation (drip and subsurface)
- c. Deficit irrigation strategy
    - i. Supplemental irrigation (SI)
    - ii. Regulated Deficit irrigation (RDI)

    d. Use of treated wastewater

B. **Energy saving technologies**
    a. Variable speed pumps for irrigation
    b. Network sectoring and dynamic pressure regulation

C. **Eco-friendly agronomic practices**
    a. Cropping pattern changes
        i. Crop and variety selection
        ii. Early sowing and crop rationing
        iii. Super high density plantations (for olive farming)
    b. Conservation agriculture and soil management techniques
        i. Conservation tillage and surface residue management
        ii. Use of biodegradable mulches
    c. Organic farming and agro-ecological practices
    d. Sustainable land management practices

**Table 4** Brief description of the ECOWATER agricultural case studies

| | Sinistra Ofanto | Monte Novo |
|---|---|---|
| **Surface area [ha]** | 34000 | 7500 |
| **Age of system** | Old, completed in 80's | New, under development |
| **Crops** | Low water demanding (olives, wheat, vineyards, orchards) | High water demanding (maize, intensive olives, pastures) |
| **NIR indicative [m3/ha]** | Olives 1500, wheat 1000, vineyards 3500, orchards 4500 | Maize 6000, olives 1500-3000, pastures 10000 |
| **Water availability** | Limited since its construction | Actually (almost) not limited |
| **Technologies** | • **Variable speed pumps,**<br>• **Shifting from sprinkler to drip and from drip to subsurface,**<br>• **Water tariffs changes,**<br>• **Change from full to RDI**<br>• **Changes from rainfed to irrigation** | • **Variable speed pumps,**<br>• **Shifting from sprinkler to drip and from drip to subsurface,**<br>• **Water tariffs changes,**<br>• **Change from full to RDI,**<br>• **Changes from intensive to super intensive olive production** |
| **Water Supply Chain** | • Storage + Gravity<br>• Pumping<br>• Lifting + Gravity | • Gravity<br>• Pumping |
| **Actors** | • Regional River Basin Authority (Consortium Bonifica della Capitanata)<br>• Farmers Associations | • EDIA<br>• AB Monte Novo<br>• Farmers |
| **Environmental Indicators (denominators of EE)** | • Energy use (kWh)<br>• Surface Water use ($m^3$)<br>• Groundwater use ($m^3$)<br>• Fertilizers (N, P) use (kg)<br>• $CO_2$ emissions (tons)<br>• N, P loads (kg) | • Energy use (kWh)<br>• Surface Water use ($m^3$)<br>• Groundwater use ($m^3$)<br>• Fertilizers (N, P) use (kg)<br>• $CO_2$ emissions (tons)<br>• N, P loads (kg) |

# 4. Advanced technologies for water supply management

The **importance of water supply management strategies in irrigation** is well identified in literature and practice, including (Pereira et al., 2002): i) increased storage capacities (including those to favor supplemental irrigation); ii) improved irrigation conveyance and distribution systems that provide increased flexibility of deliveries and reduce system water wastages; iii) enhanced operation and maintenance; and iv) development of new sources of water supplies, including treated wastewater, saline groundwater and drainage water (the use of which requires improved irrigation practices and management, mainly to avoid impacts on health and environment).

Supply management may be considered under the **perspective of system operation**, mainly related to delivery scheduling (Hatcho, 1998), including the exploration of hydro-meteorological networks, databases and information systems that support the improved management of reservoirs and irrigation systems, and may also be used as information to support farmers' irrigation decision.

Complementary to these networks are the agro-meteorological information systems, which include a variety of tools for farmers and managers to access information, comprising models, information systems such as GIS, and **decision support systems** (Pereira et al., 2002). Simulation models, information systems and DSS can be relevant to support farmers' selection of water-use options, including crop patterns and irrigation systems, and to implement appropriate irrigation scheduling (Rossi et al., 2002).

Solving the problem of optimizing water productivity may involve using **automated, real-time technologies**. Zapata et al. (2013) suggested a list of four types of possible solutions applied to different irrigation contexts (for additional references and details see Zapata et al., 2013):

- The first solution has been developed for sprinkler irrigation machines (center pivots and rangers). **Precision irrigation water application** is based on controlling the variability in irrigation pressure, soil properties, and topography. This approach is often based on the use of standard, off-the-shelf components, and control algorithms applied at the emitter level.
- The second type of solutions has been specifically designed for urban landscapes using drip irrigation systems, with the goal of increasing irrigation efficiency. **Control devices and algorithms** have been developed based on weather information and/or soil moisture sensors. These devices can address the spatial variability of soil water availability by exploiting a network of soil moisture sensors.
- The third type of solutions has been developed for drip irrigated fruit orchards. Solutions have addressed the development of automatic irrigation controllers based on **continuous monitoring of plant or soil water status**. Scientific effort is still needed to develop practical, hands-on procedures improving current water application in irrigated orchards. On the other hand, simple,

reliable, and low-cost sensors and controllers need to be developed in order for farmers to adopt these approaches for practical irrigation scheduling.

- The fourth type of solutions is based on **simulation tools**. Coupled solid-set irrigation system and crop models have been developed to support irrigation decision making. Target variables may involve irrigation performance indexes (optimizing irrigation), crop indexes (yield), or a combination of both (water productivity). This type of solutions addresses the management problems of solid-set irrigated plots, which can be summarized in maximizing irrigation uniformity and efficiency, minimizing sprinkler evaporation losses and energy costs, and maximizing crop productivity.

## 4.1. Remote and automated control of irrigation water supply

The application of new technologies to the **control and automation of irrigation** is becoming a very relevant issue in the last decade. This is due to a number of factors: i) generalization of real-time digital information on weather data and crop water requirements; ii) increased access to this information from remote sites through wireless connections; iii) improved reliability and effectiveness of sensors used for measurements in the soil-plant system; iv) communication possibilities offered by telemetry/remote control systems, being installed both in collective pressurized systems and in individual farms; v) the cost-effectiveness of these technologies in developed countries when compared to labor costs (McCarthy *et al.*, 2011; Romero *et al.*, 2012; Zapata *et al*., 2012).

**Control engineering approaches** may be applied to irrigation management to make better use of available irrigation water. These methods of irrigation decision-making are also being developed to deal with spatial and temporal variability in field properties, data availability and hardware constraints. One example of control system is 'advanced process control', particularly suited to the management of site-specific irrigation (McCarthy et al., 2011). A control engineering approach is one solution being developed to automate irrigation management. Figure 12 illustrates a generic irrigation control system that uses the full range of plant, weather and soil data for irrigation management, where:

- the '**decision support system**' embodies the control strategy;
- '**actuation**' is the action of adjusting the irrigation volume and/or timing;
- '**application**' is the resulting physical amount and timing of water and fertilizer applied to the crop.

This process can be applied to both constant and spatially varied irrigation management at a range of time scales. Similarly, the actuation of the irrigation volume application may be either manual or automated.

In general, automatic control has been seldom used in irrigation. The commercial solutions available on the market require the irrigation dose to be provided by the user. Only then, they are able to switch on/off the irrigation pump and to open or close the valves to apply the irrigation doses to every sector of the orchard. A popular irrigation technique to calculate the irrigation dose is based on a feed-forward strategy, which consists on applying irrigation to refill the water used by the plants the previous day, using crop potential evapotranspiration (ETc) or changes in the soil water content. This method is in fact an 'open-loop' controller and, therefore, it presents some limitations that can be overcome by the use of feedback, mathematical models and additional information provided by plant measurements.

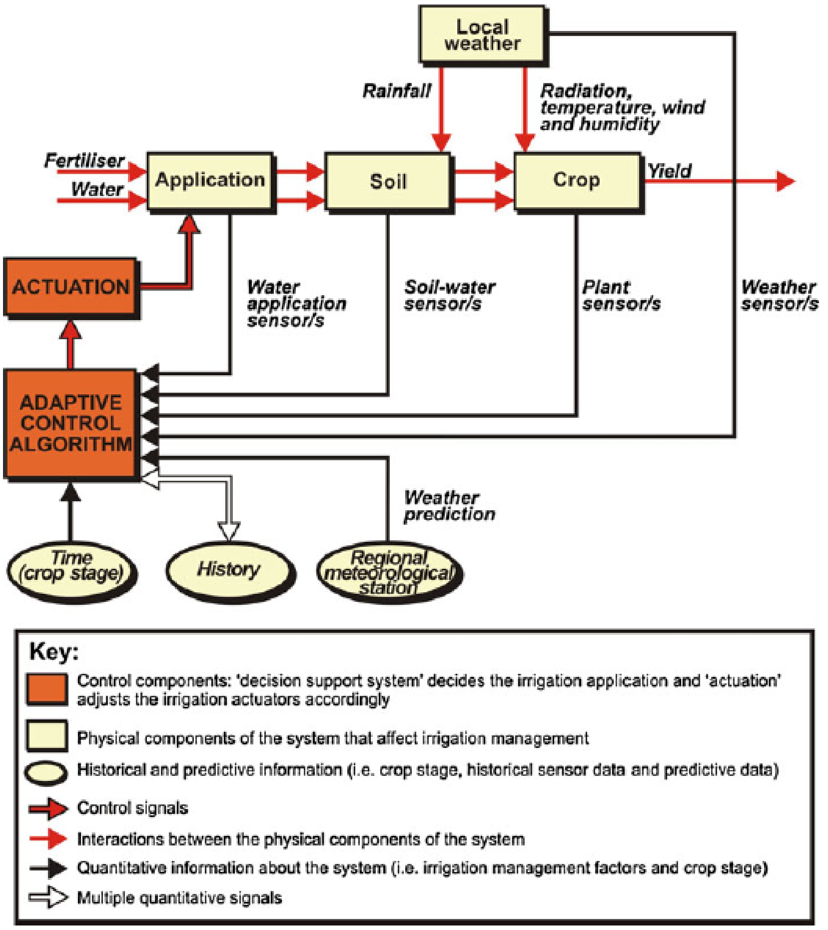


**Figure 12** Generic control scenario for irrigation application (McCarthy et al., 2011)

A more rational approach for optimizing irrigation is the use of **automatic irrigation controllers**. Automatic control has been applied in almost all engineering fields with great success (Bennett, 1996), although the impact in agriculture, and in particular in precision irrigation, is still limited. The key idea behind automatic control is the **use of feedback**. Feedback is a mechanism, process or signal that is looped back to control a system within itself. In the field of automatic irrigation, **measurements of soil, plant and atmosphere variables** related to the plant water status can provide the information of the consequences of previous actions to calculate the next irrigation dose.

Irrigation control can be approached by **adjusting the irrigation application** either:

- directly from the soil and/or crop response measurements ('**sensor-based control**');
- from responses simulated using a soil and crop production model ('**model-based control**').

These strategies are suitable for both **constant and/or site-specific irrigation**, where the measurements taken represent the whole field or a smaller area of the field, respectively. Sensor-based irrigation control systems may be implemented as a simple feedback control system (e.g. iterative learning control, Ahn et al. 2007) which adjusts the applied irrigation volume according to the difference between the desired and measured response. An alternate implementation is to evaluate the response of multiple irrigation volumes and apply the irrigation volume with the best response (e.g. iterative hill climbing control, McCarthy et al. 2010a).

An adequate planning of any control strategy should distinguish between the choice of the control system, the choice of the targets (variables to be controlled), and the choice of the variables measured or estimated in the control system to achieve that the targets meet the objectives. The irrigation control systems would be implemented in the field using the required sensors which may consist of one or a combination of the following: an **automatic weather station, soil moisture sensors and plant sensors** (eventually mounted on the irrigation machine). These sensors may transmit wireless data to a controller on the irrigation machine, or require manual upload and data transfer. In general, any measurement or estimation in the soil–plant–atmosphere system could be used as a target or as an intermediate variable in the control strategy. Main irrigation scheduling approaches are based on one or a combination of the following (Jones, 2004):

- Soil water measurements (soil water content or soil water potential);
- Soil water balance calculations (using estimations of evapotranspiration and rainfall) ;
- Plant-based measurements (tissue water status, stomatal conductance, sap flow sensors, dendrometry, etc.).

Over the past several years, there has been a considerable amount of research on different sensors and sensor systems to monitor and quantify within-field variability in plant water stress, soil water levels, plant nutrition status, percent cover, disease, and several other parameters (Sadler et al. 2002; Peters and Evett 2004, 2008; Andrade-Sanchez et al. 2007; Kim et al. 2008, 2009; O'Shaughnessy and Evett 2008, 2010a, b; Kim and Evans 2009; and others).

Control strategies can be either '**open-loop**' if they do not use sensor feedback to adjust the control, or '**closed-loop**' if the response of the system is monitored and used to adjust the control. Closed-loop irrigation control strategies in the literature have been developed using either in field soil sensors that aim to regulate the soil moisture content (Luthra et al. 1997; Smajstrla and Locascio 2000; Dukes and Scholberg 2005); plant sensors to irrigate when the plant has reached a stress point (Evett et al. 2002; Peters and Evett 2008); or calibrated crop production models to either achieve a desired soil moisture deficit (Capraro et al. 2008), or maximise yield, profit or water productivity (i.e. water use efficiency, Brown et al. 2010).

In general, a more complete solution to the irrigation control problem should come from using a combination of all the previous ideas: feed-forward, feedback and mathematical models, considering relevant variables in every part of the soil–plant–atmosphere system (Figure 13).

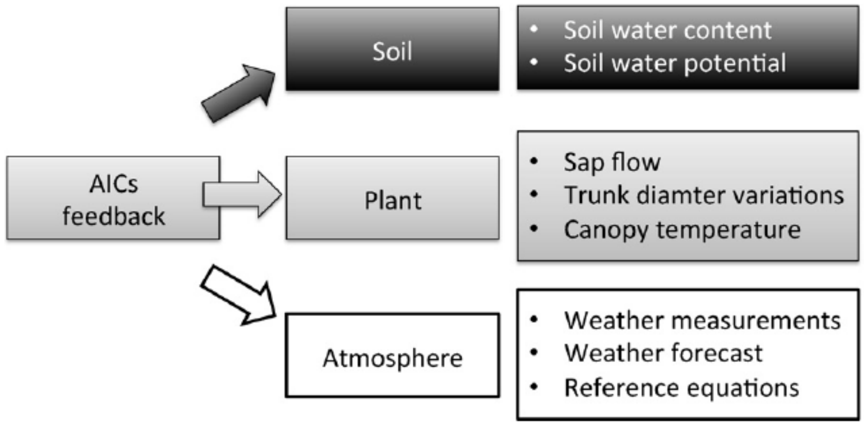


**Figure 13** Variables that can be used for automatic irrigation control (from Romero et al., 2012).

Although the first papers reporting ingenious automatic irrigation devices, such as the one based on the air-lift principle hydraulic equilibrium (Chapman and Liebig, 1938) or on solenoid valves activated by custom sensors detecting soil water content deficits (Bouyoucos, 1952), date back to the middle of previous century, there has been an increasing interest of the scientific community in this problem over the last years.

There are several **commercial automatic controllers** (*Acclima*, *Watermark*, *Rainbird*, *WaterWatcher*) that regulate soil water content (SWC) based on sensor measurements, and hence operating as closed-loop controllers. These controllers apply irrigation when sensors detect that the measurements are below a certain predefined threshold until another predefined threshold is overcome (**on–off control**). This reference is in general established as a constant value (i.e. 80% of field capacity, or a relative ratio of the readily available water). These commercial systems have been compared by Cardenas-Lailhacar et al. (2008, 2010) concluding that, when adequate threshold are defined, all these systems have the **potential to save water** when compared to a traditional time-based irrigation treatment. The authors also showed that, even under dry weather conditions, the incorporation of rain sensors as a feed-forward can save substantial amounts of irrigation water.

Hence, soil sensors that are easy to install would potentially be appropriate for sensor-based strategies, e.g. the soil moisture sensor array reported by Vellidis et al. (2008), but such low-cost sensor arrays have yet to be proven adequate for sensor-based control. Model- and sensor-based control strategies typically have different data requirements. For example, Smith et al. (2009) provides an introduction to the potential use of control systems to manage spatial and temporal variations in crop water requirements to improve the precision of irrigation applications.

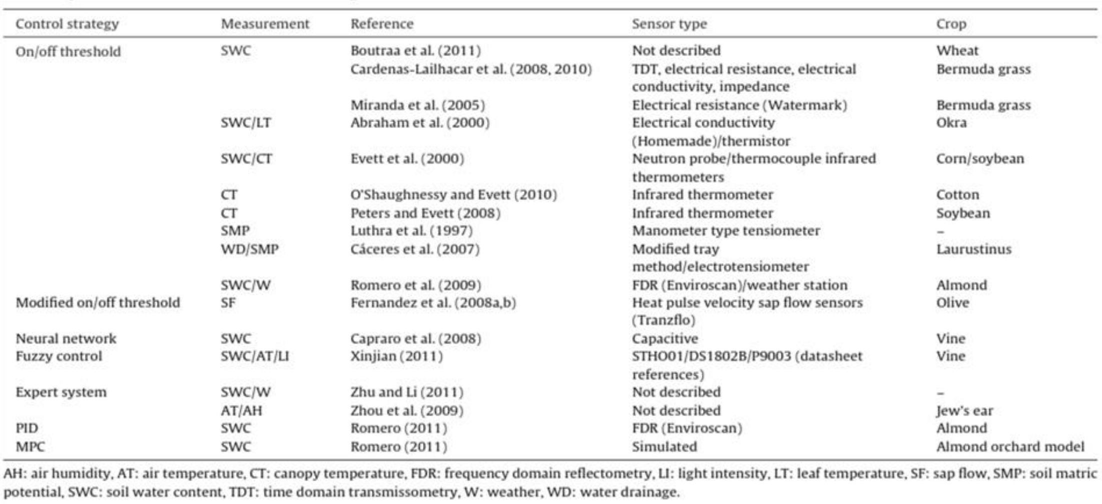
Most of the papers reporting automatic irrigation controllers in the last decade (Table 5) focus on regulating **soil water content (SWC) or tension (SWT)** with on/off strategies based on feedback (Luthra et al., 1997; Miranda et al., 2005; Cáceres et al., 2007; Boutraa et al., 2011). These devices are relatively inexpensive and easy to use, but ground water measurements imply certain limitations: they require a large number of sensors and do not take into account the plant status and response.

In O'Shaughnessy and Evett (2010) and Peters and Evett (2008), irrigation controllers aimed at regulating canopy temperature instead of SWC were proposed. Both **SWC and canopy temperatures** feedback strategies were compared in Abraham et al. (2000) and Evett et al. (2000).

Xinjian (2011) and Zhu and Li (2011) have recently reported irrigation controllers which use a combination of **SWC and weather data** to control drip irrigation. Xinjian's fuzzy logic controller measured air temperature, light intensity and SWC and was tested in vineyard's drip irrigation. The Zhu and Li's controller used air temperature, humidity, evaporation, rain and SWC measurements. They applied state space analysis methods to implement the irrigation control based on a knowledge base and an expert system rule base.

Protocols for automatic irrigation controllers have been reported based on **trunk diameter variation** (Goldhamer and Fereres, 2004; Garcia-Orellana et al., 2007) or **sap flow measurements** (Fernandez et al., 2001, 2008a). Both methods are considered having a great potential for irrigation control (Fereres et al., 2003; Jones, 2004).

**Table 5.** Examples of researches on automatic irrigation control (from Romero et al., 2012).



| Control strategy | Measurement | Reference | Sensor type | Crop |
|---|---|---|---|---|
| On/off threshold | SWC | Boutraa et al. (2011) | Not described | Wheat |
| | | Cardenas-Lailhacar et al. (2008, 2010) | TDT, electrical resistance, electrical conductivity, impedance | Bermuda grass |
| | | Miranda et al. (2005) | Electrical resistance (Watermark) | Bermuda grass |
| | SWC/LT | Abraham et al. (2000) | Electrical conductivity (Homemade)/thermistor | Okra |
| | SWC/CT | Evett et al. (2000) | Neutron probe/thermocouple infrared thermometers | Corn/soybean |
| | CT | O'Shaughnessy and Evett (2010) | Infrared thermometer | Cotton |
| | CT | Peters and Evett (2008) | Infrared thermometer | Soybean |
| | SMP | Luthra et al. (1997) | Manometer type tensiometer | – |
| | WD/SMP | Cáceres et al. (2007) | Modified tray method/electrotensiometer | Laurustinus |
| | SWC/W | Romero et al. (2009) | FDR (Enviroscan)/weather station | Almond |
| Modified on/off threshold | SF | Fernandez et al. (2008a,b) | Heat pulse velocity sap flow sensors (Tranzflo) | Olive |
| Neural network | SWC | Capraro et al. (2008) | Capacitive | Vine |
| Fuzzy control | SWC/AT/LI | Xinjian (2011) | STHO01/DS1802B/P9003 (datasheet references) | Vine |
| Expert system | SWC/W | Zhu and Li (2011) | Not described | – |
| | AT/AH | Zhou et al. (2009) | Not described | Jew's ear |
| PID | SWC | Romero (2011) | FDR (Enviroscan) | Almond |
| MPC | SWC | Romero (2011) | Simulated | Almond orchard model |

AH: air humidity, AT: air temperature, CT: canopy temperature, FDR: frequency domain reflectometry, LI: light intensity, LT: leaf temperature, SF: sap flow, SMP: soil matric potential, SWC: soil water content, TDT: time domain transmissometry, W: weather, WD: water drainage.

The **advances in wireless technology** have encouraged the application of wireless sensors and/or actuators in irrigation control or monitoring experiments. Depending on distance or power requirements consideration, a wide range of communication protocols can be applied like WHF (Zhu and Li, 2011), Zigbee (Zhou et al., 2009; Xinjian, 2011) and others. In particular Zigbee protocol is becoming a popular standard for agricultural environments since it is low power consumer and therefore the communication with standalone sensors can be powered with small solar panels or even only batteries.

Recently, there has been an increasing interest on developing **mathematical models** representing both the dynamics of water in the soil–plant–atmosphere (SPA) system and crop performance. Using these models is now possible to test automatic irrigation controllers in computer simulations prior to their use in field experiments. Among the most popular models are WAVE (Vanclooster et al., 1994), SWAP (van Dam, 2000; van Dam et al., 2008), MACRO (Larsbo and Jarvis, 2003), CROPGRO

(Boote et al., 1998), WOFOST (van Diepen et al., 1989) and DSSAT (Hoogenboom et al., 2004).

**Model based controllers** such as model predictive control (MPC) can use this knowledge to optimize irrigation, also including estimation of future changes or disturbances on the systems (e.g., weather forecast). These controllers, although successfully and extensively used in other areas of science and industry, have been seldom applied in agriculture. However, we might find promising examples, especially in the management of greenhouses environmental control (Rodriguez et al., 2008; Pinon et al., 2005; El Ghoumari et al., 2005). Park et al. (2009) applied a receding horizon control scheme in a center pivot system. It demonstrated to be a viable strategy for achieving water reuse and agricultural objectives while minimizing negative impacts on environmental quality.

### 4.1.1. Sensors for monitoring weather variables and soil/plant water status

As previously mentioned, **climatic and soil-plant sensors** can be integrated within a monitoring system in order to support farmers for irrigation management and scheduling, through the provision of crops' and environmental data. Irrigation efficiency depends not only on the type of irrigation used, but also on the **irrigation scheduling method** to determine the amount of water to be applied to a crop and the timing for application. Irrigation scheduling has a remarkable effect on water use efficiency and is crucial in intensive agriculture, since under-irrigation generally results in reduced crop yield and quality.

On the other hand, over-irrigation increases the nutrient requirements of the crop and its vulnerability to diseases, the energy costs for water pumping, water loss and environmental pollution due to the leaching of nutrients applied to the crop with conventional fertilization or fertigation (the technique of supplying fertilizers dissolved in the irrigation water). For example, Thompson *et al.* (2007) reported that the inadequate management of drip irrigation, which in many operations is still based on grower's experience, is one of the reasons for nitrate leaching in greenhouse tomato production in Almeria, Spain (at present, the largest greenhouse area in the world). The goal of an **efficient irrigation scheduling** is to **supply the crop with enough water** while **minimizing water waste due to deep percolation and runoff**.

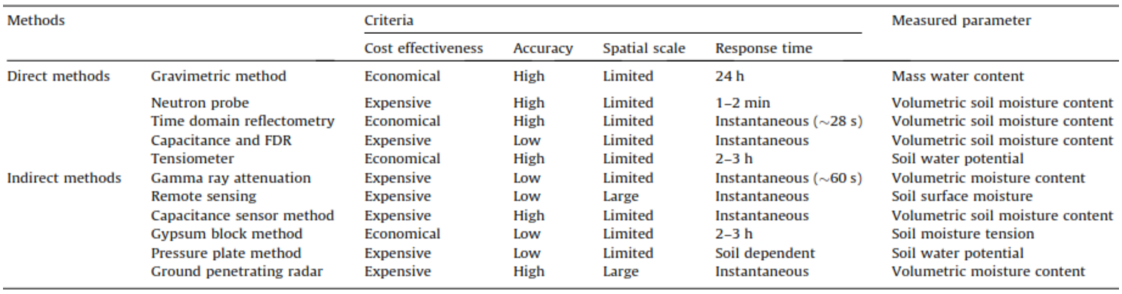
Different **approaches to irrigation scheduling** have been developed, each having both advantages and disadvantages (Jones, 2004). Innovative methods based on the direct monitoring of plant water relations have been also proposed for irrigation scheduling. Although some companies have designed irrigation control devices exploiting micro-measurements of stem diameter, leaf thickness or stem sap flow, plant-based irrigation management is still in the research or development state and is scarcely employed in commercial operations (Pardossi et al., 2009).

The most widespread irrigation scheduling method is based on the **determination of soil-water balance**, which implies the estimation of crop evapotranspiration (ETc). Generally, ETc is calculated combining the measurements of potential (or reference) evapotranspiration (ETo) through meteorological stations with crop coefficients (Allen et al., 1998). The latter need regular updating by the farmer for each crop type and growing stage which is adequate method for on-farm irrigation management. One rather new approach is to obtain crop coefficients with satellite based radiation images and a network of weather stations. Recently, D'Urso et al. (2009) developed such a system within the framework of two European projects: Demeter (www.demeter-EC.net) and Pleiades (www.pleiades.es). Access to the satellite data has become much easier and faster due to recent development with web-based access and due to improvements of sensor spatial resolution and accuracy. However, the application of satellite technology is limited to the irrigation districts and larger areas of at least several thousands of hectares.

Another approach to irrigation scheduling entails the direct or indirect **determination of soil moisture**, for which several methods are available (Table 6). The usual approach has been to monitor soil water at one or more depths until a threshold that indicates the need for irrigation is reached. Lately, continuous records of soil water status can be obtained and decisions are made based on the water extraction trends rather than on setting an absolute threshold point. Traditional soil-based sensors include the tensiometer, which measures soil water tension, and the gypsum block, which measures electrical resistance. Both of these devices and others developed more recently, such as the granular matrix sensors, use porous media where water enters and is in energy equilibrium with the surrounding soil.

So far, applications of root zone sensors (RZS) for irrigation management have been less common than those of the water balance method, but **novel types of RZS**, which are based on the **measurement of soil dielectric properties** (such as time domain reflectometry TDR, and frequency domain reflectometry FDR), have opened new possibilities for irrigation scheduling and nowadays the irrigation industry worldwide has recognized that RZS are valuable tools for modern smart water application technology in intensive agriculture (Pardossi et al., 2009). With the use of RZS the goal is to monitor soil moisture status and to replenish the water in growing medium to the desired level. In principle, this method by-passes the need to calculate ETc and works for any crop, as long as the set-points for the irrigation controller are correctly chosen. Instruments to determine either the soil water content or the soil water tension were developed long ago, although in the last decade techniques have become more sophisticated with the improvements in electronics. The examples of field sensors for soil moisture monitoring are given in Figure 14.

**Table 6** Comparison of different methods used for estimation of soil moisture (from Dabriyal et al., 2012)



| Methods | | Criteria | | | | Measured parameter |
|---|---|---|---|---|---|---|
| | | Cost effectiveness | Accuracy | Spatial scale | Response time | |
| Direct methods | Gravimetric method | Economical | High | Limited | 24 h | Mass water content |
| | Neutron probe | Expensive | High | Limited | 1–2 min | Volumetric soil moisture content |
| | Time domain reflectometry | Economical | High | Limited | Instantaneous (∼28 s) | Volumetric soil moisture content |
| | Capacitance and FDR | Expensive | Low | Limited | Instantaneous | Volumetric soil moisture content |
| | Tensiometer | Economical | High | Limited | 2–3 h | Soil water potential |
| Indirect methods | Gamma ray attenuation | Expensive | Low | Limited | Instantaneous (∼60 s) | Volumetric moisture content |
| | Remote sensing | Expensive | Low | Large | Instantaneous | Soil surface moisture |
| | Capacitance sensor method | Expensive | High | Limited | Instantaneous | Volumetric soil moisture content |
| | Gypsum block method | Economical | Low | Limited | 2–3 h | Soil moisture tension |
| | Pressure plate method | Expensive | Low | Limited | Soil dependent | Soil water potential |
| | Ground penetrating radar | Expensive | High | Large | Instantaneous | Volumetric moisture content |

**Figure 14** Some examples of field sensors for moisture monitoring. From left to right: Decagon ECH2O series sensors (placed at different depths); DeltaT PR2 probe; Sentek Diviner probe

Irrigation scheduling is affected by **accuracy of soil water sensing**. Most soils drain to field capacity quickly enough that irrigation management is, for practical purposes, constrained to working with water contents between field capacity (FC) and permanent wilting point (PWP) values, i.e. the range of plant available water (PAW). Since allowing the soil to dry to PWP causes irreversible plant damage, irrigation scheduling typically works with a management allowed depletion (MAD) range, which is taken fraction of PAW. For a MAD fraction of 0.6, this range varies from 0.02 to 0.13 $m^3 m^{-3}$ depending on the soil type (Evett et al., 2012), which can be smaller than the water content errors associated with many soil water sensors. Also important is to note that the water content range between MAD and PWP can be even smaller, so that relatively small errors in sensed water content can cause that irrigation can be delayed to the extent that the PWP is unintentionally reached (Figure 15). This problem becomes particularly important when attempting regulated deficit irrigation in order to increase WP since the MAD fractions associated with regulated deficit irrigation may exceed 0.6.

The advantage to know the **volumetric water content of soils** is that it allows the manager to determine quantitatively the amount of water in the soil. In order to accurately determine volumetric soil water content, all the previously-mentioned sensors must be calibrated for a particular soil. Although a recent study comparing the neutron probe against many other devices revealed that there is no suitable replacement technology for the neutron probe for measuring volumetric soil water content (Evett et al., 2012), the main advantage of the new sensors is that they provide continuous soil water records that can be useful for adjusting the irrigation schedule and they lend themselves to automated irrigation control (Fereres et al., 2012).

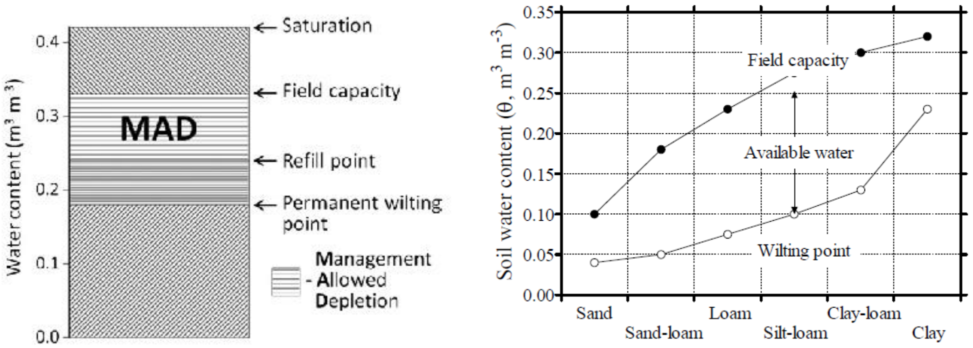


**Figure 15** *Left*: Diagram of the water contents associated with irrigation scheduling according to the concept of management allowable depletion (Evett et al., 2012). *Right*: Water content at field capacity and wilting point, and corresponding available water in different types of soils (Pardossi et al., 2009).

The two critical issues with this method are **where to place the sensors** in the field and how many observation locations (sensors) are needed to adequately characterize a field. It is instructive to conduct a soil survey in terms of soil depth and texture to find a location that is representative of a given field. The decision concerning placement will depend on whether the grower wants to irrigate the field according to the areas where the plants exhibit water deficits first (shallower and/or lighter-textured soils), to an average location, or based on any other management criteria. A simple couple of sensors placed in the same location at two different depths provide **useful information on the direction of soil water movement**.

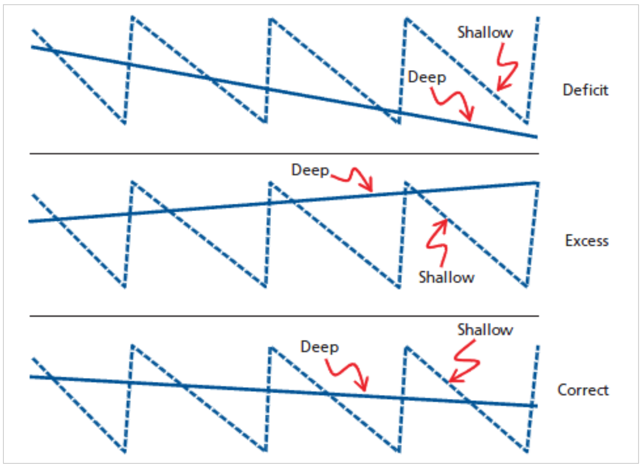


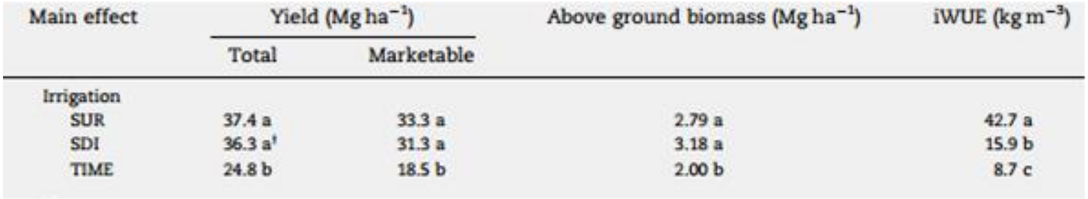
**Figure 16** Examples of soil water fluctuations at different depths under deficit, excess and correct irrigation management (Fereres et al., 2012).

A schematic example has been suggested by Fereres et al. (2012) (Figure 16), where a sensor is placed at the shallow depth (20-30 cm) while another one deeper (50-60 cm). Normally, the soil water fluctuations in the shallow depth (dotted line) show the typical responses to irrigation applications followed by fast extraction. In the top case, insufficient water application (deficit irrigation) is measured, based on the decline of soil water in the lower depth. On the other side, the center graph shows an increase with time in soil water deep in the profile, which indicates excessive applications. The third graph at the bottom represents a pattern indicative of adequate irrigation applications.

Important irrigation **water savings** with the use of soil moisture sensors have been published, both under field conditions (e.g. Cardenas-Lailhacar et al., 2008, 2010; McCready et al., 2009; Zotarelli et al., 2008, 2009; Smith, 2000) and under greenhouses (Pardossi et al., 2009).

Zotarelli et al. (2009) found that soil-moisture sensor (SMS) based irrigation systems in tomato significantly reduced the amount of applied irrigation, resulting in 15–51% less irrigation water applied for surface drip irrigation compared to the current 'fixed' time irrigation treatments, and 7–29% of reductions for subsurface drip irrigation. Corresponding tomato yields were increased of 11–26% for SMS-based treatments, thus resulting in an overall **increase of the irrigation water use efficiency** (tab). Similarly, Zotarelli et al. (2008) found that the use of SMS-based irrigation management for zucchini squash allowed more efficient use of irrigation water and a **reduction in irrigation water use** by 33–80% compared to a typical grower irrigation practices. A SMS-based subsurface drip irrigation system combined with surface applied fertigation, resulted also in a **reduction of nitrate leaching**, an increase in the nitrogen uptake efficiency, and similar or higher yields compared to other treatments.

**Table 7** Tomato yield, above-ground biomass and irrigation water use efficiency as affected by irrigation method and use of soil sensors (SUR = drip irrigation controlled by SMS; SDI = subsurface irrigation controlled by SMS; TIME = time-fixed irrigation) (Zotarelli et al., 2009).



| Main effect | Yield ($Mg\ ha^{-1}$) | | Above ground biomass ($Mg\ ha^{-1}$) | iWUE ($kg\ m^{-3}$) |
|---|---|---|---|---|
| | Total | Marketable | | |
| Irrigation | | | | |
| SUR | 37.4 a | 33.3 a | 2.79 a | 42.7 a |
| SDI | 36.3 a[1] | 31.3 a | 3.18 a | 15.9 b |
| TIME | 24.8 b | 18.5 b | 2.00 b | 8.7 c |

Thus, the appropriate use of soil moisture sensors may contribute to a consistent reduction of water use and nutrient leaching when the soil volumetric water content is maintained within the field capacity threshold, thus sustaining profitable yield and **increasing net returns** due to the lower amount of irrigation water and fertilizers to be applied.

Given the potential to optimize the water use efficiency, SMS-based irrigation reduce associated costs and **minimize the energy input requirement**, while enhancing the crop yield. For example, Marks et al. (2010) reported a range of 15-50% reduction in energy use with the utilization of the AgriMet technology. Investigation of precision irrigation technologies in the entire state of California concluded in 2 billion kWh energy savings and 1.2 million metric tons reductions in $CO_2$ emissions per year (Marks et al., 2010)

### 4.1.2. Variable rate irrigation (VRI)

**Precision agriculture (PA)** technologies are designed to be able to spatially optimize the use of various inputs for improving or enhancing economic crop production, by considering the site-specific on-farm and on-field variability. This variability can be caused by soil type, crop type, crop condition (stress, etc.) and meteorological conditions (e.g. rainfall). These factors are discussed further in Smith et al. (2009).

There are numerous PA technologies, including site-specific aspects of planting, fertilizer application, pest management, and irrigation designed to manage spatial and temporal variability within agricultural fields. Management tools include various types of **sensing systems, field sampling, geographic information systems (GIS), wireless communications, on-the-go yield monitoring, and decision support systems** (Evans et al., 2013). Recent innovations in low-voltage sensor and wireless radio frequency (RF) data communications combined with advances in internet technologies offer tremendous opportunities for the development and application of real-time management systems for agriculture.

These technologies have enabled implementation of advanced state-of-the-art water conservation measures with self-propelled sprinkler systems such as **site-specific variable rate irrigation (SS-VRI)** for economically viable, broad-scale crop production with full or limited water supplies. Evans et al. (2013) defines advanced SS-VRI technologies for center pivot and linear move sprinkler systems, by providing an historical overview of the available commercial evolution, considering that center pivots comprise about 99 % of the self-propelled sprinkler market. It is also estimated that actually about 95 % of all the SS-VRI sprinkler irrigation systems in the world are in the USA with Australia, New Zealand, and South Africa accounting for most of the remaining installations.

The VRI is a modern agricultural management concept, consisting of **hardware and software**, allowing the **continuous irrigation rate adjustment on individual management zones within the field** (Perry et al., 2012), and it has been proven to be very effective in fields with several soil types and non-uniform topography. It consists of electronically-hydraulically-pneumatically activated valves, controller(s) for the activation and regulation of sprinklers, a motor controller regulating the flow rate, a GPS and a user interface through which field mapping and system set up can be carried out. This system reduces climate risks through excluding non-cropped (or marginal) areas from water application, reducing the flow rate in both low-lying areas and soils with higher water-holding capacity (Perry et al., 2012).

**Center pivot and linear move sprinkler systems** are normally designed and generally operated so as to replace the average water used by the crop over the past few days as uniformly as possible across the field. However, stochastic spatial and temporal variability of a number of other interrelated factors (e.g., variations in soil properties, topography, runoff, tillage, fertilization) across a field can still affect crop growth during the growing season and from one season to the next. These factors can influence management decisions over time, which may also introduce additional infield variability to crop production.

Research into variable-rate irrigation technology for centre pivot and lateral move irrigation machines has spanned 20 years and produced a number of **commercial systems** (e.g. *Farmscan, Valmont, Zimmatic*). Manufacturers are just starting to offer site-specific controls for linear move sprinkler systems. Kranz et al. (2012) has summarized characteristics of some of the various commercial **site-specific control**

**systems and panels**. Center pivot manufacturers are also offering site-specific variable rate irrigation systems that can differentially apply water site specifically to irregularly shaped areas or management zones (‘**zone control**’). Specialized equipment such as **control, panels, many valves, supplemental wiring, and a GPS** is required to control the irrigation in each management zone.

Most zone control SS-VRI systems vary water application depths by various forms of pulse modulation (on–off cycling of spray-type sprinkler heads) for a given machine speed. Valves are located on every sprinkler head or groups of heads. Water is then applied to each zone by controlling water output amounts from each group of heads along the length of the machine depending on their location in the field. **Zone control has a larger potential for achieving efficient management of water and energy**.

Almost all of the SS-VRI research done to date has been directed toward **development and improvement of hardware and basic zone control software**, and several innovative technologies have been developed to variably apply irrigation water to meet anticipated whole field management needs in precision irrigation, primarily with self-propelled center pivot and linear move irrigation systems. These efforts have been reviewed by Buchleiter et al. (2000), Evans et al. (2000, 2012), Sadler et al. (2000), McCarthy et al. (2010), and others.

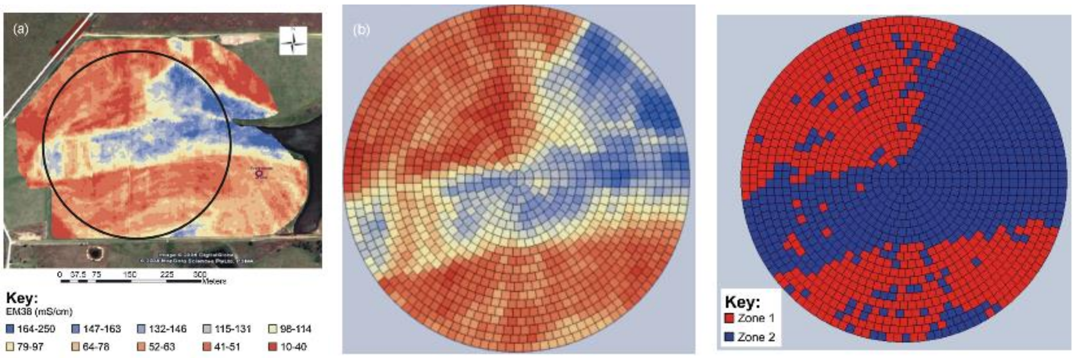


**Figure 17** An example of electrical conductivity map (left), corresponding values assigned to each cell of the area subjected to centre-pivot irrigation (centre) and zones for self-optimizing irrigation strategies (as managed by the VARIwise software, McCarthy et al., 2010).

Adoption of SS-VRI by producers has been slow and remains at low levels. Evans et al. (2013) reported that there are about 175,000 center pivot and linear move sprinkler systems in the USA (USDA, NASS 2009), but only less than 200 of these machines have SS-VRI capabilities other than speed control, end gun, and corner system controls, while the ones equipped with zone-controlled crop water management are probably less than 50. However, a **significant improvement of zone control SS-VRI technology is projected in the future** in relation to: (1) their cost-effectiveness due to higher water and energy costs; (2) regulatory limits on water application amounts; (3) economic incentives in compliance with environmental and other regulations; and (4) demonstrated increased economic returns.

The significant potential water savings by **VRI technologies** suggest that they **will become more affordable as irrigation costs increase**, as discussed by Sadler et al. (2005). In addition to cost benefits associated with water charges and reduced pumping costs, VRI allows better strategic use of allocated freshwater. This becomes important where allocated freshwater is limited, because the water saved can be diverted elsewhere. In this case VRI delays other strategies such as deficit irrigation, which aim to sustain irrigation systems in a region by conserving water but are accompanied by reduced yields. The use of zone control SS-VRI for general crop production is mostly directed towards adjusting for soil textural differences and treating symptoms such as localized **over-irrigation, under-irrigation, runoff**, ponding, limited or declining well capacities, fluctuating water supplies, maintenance issues, nutrient management, and related concerns under maximum evapotranspiration (ET) scenarios.

Figure 18 conceptually depicts the relative potential of various elements of center pivot technologies and existing research gaps (Evans et al., 2013). This figure shows the general trends for **increased water productivity** (more yield per drop) with increasing technology adoption and higher management levels with the associated nonlinear rises in marginal costs (change in cost per unit increase in water productivity) and water productivity. The major differences between the different regions in the figure are mostly related to the level of the control and associated decision support systems. It should be noted that many technologies such as **distributed sensor systems** and managed **deficit irrigation** can be applied across all control and management levels with varying degrees of effectiveness, but the supporting research is often missing.

Maintaining or **increasing crop productivity** while **reducing the amount of applied water** implies that producers will often be managing irrigations under severe to moderate soil water–deficit conditions (i.e., managed drought) in either time or space during at least part of the growing season. This is often referred to as **managed deficit irrigation**, which can have many forms and generally serves to increase crop water productivity. It is possible that SS-VRI could play a role in managed deficit irrigation of field crops when there is significant **variability in soils and topography**. Another case where SS-VRI might be an important management alternative would be when site-specific **planting of different varieties or variable planting densities** varies across a field to match specific predetermined conditions that would introduce additional artificial variability.

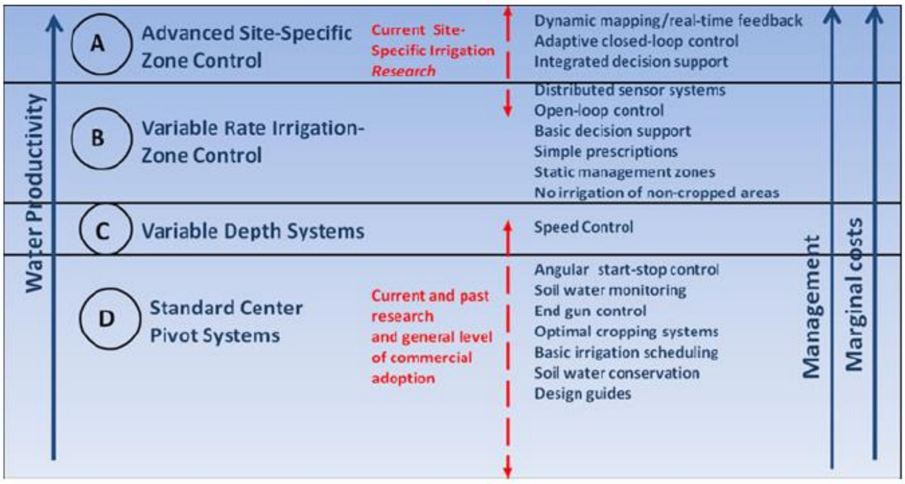


**Figure 18 Conceptual representation of the state of the art and relative capacity of various elements and supporting technologies of self-propelled sprinkler irrigation technologies to increase water productivity (Evans et al., 2013).**

Common **variations in soil properties and soil water availability over large fields** are appropriate for site-specific irrigation management. The spatial variability of soils and other characteristics in agricultural fields has been addressed in the precision agriculture literature (Irmak et al. 2002; Ahmad et al. 1999). Apparent **soil electrical conductivity (ECa)** mapping has been widely used as one way to characterize soil variability of agricultural fields (e.g. Farahani and Buchleiter 2004; Drummond et al. 2000). The mapping of ECa is a valuable method for high resolution quantitative assessment and mapping of soil variation, and it has been linked to the soil water holding properties AWC and FC, enabling the spatial variation of soil available water to be delineated (Figure 19).

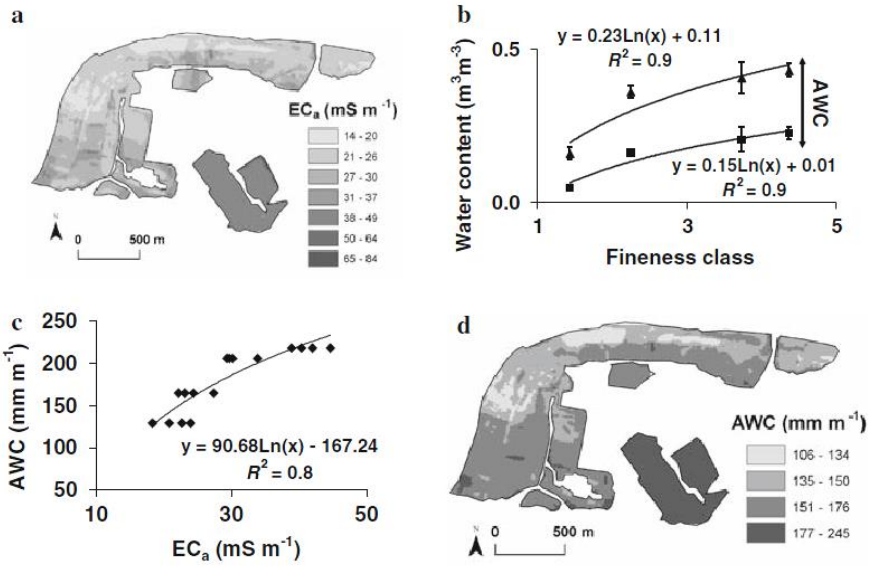


**Figure 19** a) ECa maps, b) water content-soil texture curves, c) AWC-ECa regression curve, d) derived AWC map (Hedley and Yule, 2009).

**In-field wireless sensing systems** have also been studied by many researchers to support VRI (e.g. Shock et al. 1999; King et al. 2000; Marinda et al. 2003). For example, Kim et al. (2009) have tested a wireless irrigation control system for real-time VRI control together with a distributed wireless sensor network (WSN) for in-field sensing of soil water conditions; they also used mapping of soil EC to provide a measure of the spatial variation of an experimental field so that a minimum number of in-field sensor systems could be placed with maximum impact for characterizing the scope of field information.

Hedley and Yule (2009) developed **soil water status maps** by using the relationship between available water-holding capacity (AWC) and soil apparent electrical conductivity (ECa), and adding a daily time-step water balance model to produce a file that could be uploaded daily to a computer-controlled variable rate irrigator. They found significant **potential water savings of 21.8–26.3%** when irrigation water is adjusted for variable soil AWCs and site-specific factors, such as poor drainage, to maintain soil water content above the critical deficit where plant growth starts to be limited.

Hedley et al. (2009) have evaluated VRI for three different combinations of crops (pasture, maize and potato) and soils using some performance indicators (irrigation water use per season; drainage and runoff; nitrogen leaching; energy usage per season; irrigation water use efficiency), and they found that VRI **saved 9 − 19 % irrigation water**, with accompanying **energy saving**; loss of water by **drainage was also reduced by 20 − 29%** using VRI, which **reduced the risk of nitrogen leaching**. Virtual water content of these three primary products further illustrates benefits of VRI and shows that virtual water content of potato production used least water per unit of dry matter production. The direct value of water savings using VRI was estimated to be 35−149 NZ$/ha under the three contrasting primary productions, a significant saving to the producer. In addition VRI reduced the pollution risk and extraction demand on freshwaters, two of the suite of freshwater ecosystem services, valued at about NZ$30 000/ha.

Similarly, computer simulation studies comparing conventional and ‘optimized’ advanced site-specific zone control by center pivot irrigation have reported **water savings of up to 26 %** (Evans and King, 2012). According to Perry et al. (2012), potential average reductions due to VRI in water use compared to uniform irrigation processes is about 8-20%.

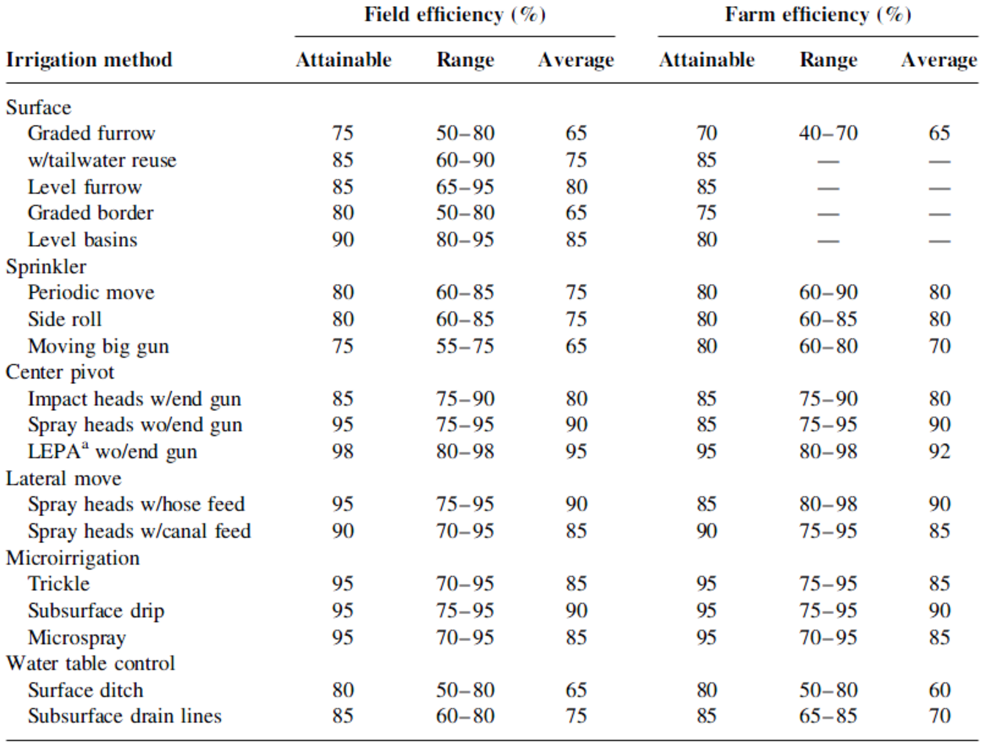
## 4.2. Efficient irrigation methods

In the frame of modernized irrigation systems, technical on-farm irrigation management implies **selecting the appropriate irrigation method and strategy** according to the water availability, to the characteristics of the climate, soil and crop, to the economic and social circumstances, and to the constraints of the distribution system. It also requires the actual application of the scheduled water, its distribution over the field, and the storage in the root zone of as much of the applied water as possible.

The many types of irrigation systems usually fall into one of three categories. **Surface irrigation systems** are those that depend on gravity to spread the water across the surface of the land. These systems also are referred to as gravity or flood irrigation systems. The shape of the soil surface and how the water is directed across the surface determine the types of surface systems (i.e., furrow, border, or basin). **Sprinkler systems** attempt to mimic rainfall by spraying the water evenly across the soil surface. The water is pressurized with a pump, distributed to areas of the fields through pipes or hoses, and sprayed across the soil surface with rotating nozzles or sprayers. Types of sprinkler systems depend on the layout of the distribution pipelines and the way they are moved (i.e., solid set, hand move, center pivot, or rain gun). **Micro-irrigation systems**, also called drip or trickle systems, use small tubing to deliver water to individual plants or groups of plants. These systems use regularly spaced emitters on or in the tubing to drip or spray water onto or into the soil. Micro-irrigation systems are categorized by the type of emitters (i.e., drip or micro-spray).

The **water application efficiency** of the various irrigation methods varies with conditions and system type, and it is difficult to estimate (Table 8). Surface irrigation is often relatively inefficient because of lack of water control and the dependence on inherently variable soils. The potential efficiency of micro-irrigation is very high but requires good system design, maintenance, and operation. Sprinkler irrigation also can be efficient, especially when used under low-wind conditions.

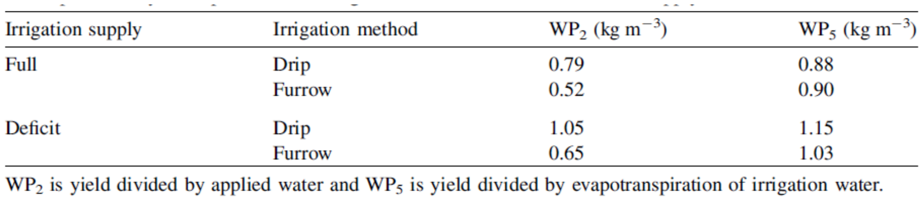
**Table 8** Examples of field and farm irrigation application efficiencies (from Howell, 2003).



| Irrigation method | Field efficiency (%) Attainable | Range | Average | Farm efficiency (%) Attainable | Range | Average |
|---|---|---|---|---|---|---|
| Surface | | | | | | |
| Graded furrow | 75 | 50–80 | 65 | 70 | 40–70 | 65 |
| w/tailwater reuse | 85 | 60–90 | 75 | 85 | — | — |
| Level furrow | 85 | 65–95 | 80 | 85 | — | — |
| Graded border | 80 | 50–80 | 65 | 75 | — | — |
| Level basins | 90 | 80–95 | 85 | 80 | — | — |
| Sprinkler | | | | | | |
| Periodic move | 80 | 60–85 | 75 | 80 | 60–90 | 80 |
| Side roll | 80 | 60–85 | 75 | 80 | 60–85 | 80 |
| Moving big gun | 75 | 55–75 | 65 | 80 | 60–80 | 70 |
| Center pivot | | | | | | |
| Impact heads w/end gun | 85 | 75–90 | 80 | 85 | 75–90 | 80 |
| Spray heads wo/end gun | 95 | 75–95 | 90 | 85 | 75–95 | 90 |
| LEPA[a] wo/end gun | 98 | 80–98 | 95 | 95 | 80–98 | 92 |
| Lateral move | | | | | | |
| Spray heads w/hose feed | 95 | 75–95 | 90 | 85 | 80–98 | 90 |
| Spray heads w/canal feed | 90 | 70–95 | 85 | 90 | 75–95 | 85 |
| Microirrigation | | | | | | |
| Trickle | 95 | 70–95 | 85 | 95 | 75–95 | 85 |
| Subsurface drip | 95 | 75–95 | 90 | 95 | 75–95 | 90 |
| Microspray | 95 | 70–95 | 85 | 95 | 70–95 | 85 |
| Water table control | | | | | | |
| Surface ditch | 80 | 50–80 | 65 | 80 | 50–80 | 60 |
| Subsurface drain lines | 85 | 60–80 | 75 | 85 | 65–85 | 70 |

Clemmens and Dedrick (1994) reported that all irrigation methods can attain approximately the same levels of efficiency. In spite of this fact, **differences among irrigation systems appear in many areas as a consequence of design, management and maintenance**. For example, in north-eastern Spain traditional surface irrigation systems often show on-farm efficiencies close to 50% (Playan et al., 2000), while properly designed and managed pressurized systems can attain 90% efficiency (Dechmi et al., 2003a, b). As a consequence, changing the irrigation system (from surface to sprinkler) in field crops such as maize results in the following effects: (1) a sharp **reduction in irrigation water demand** (roughly, from 12,000 to 7000 $m^3$ $ha^{-1}$); (2) a relevant **increase in crop yield** (typically from 10,000 to 12,000 kg $ha^{-1}$), resulting from improved irrigation uniformity, the control of the irrigation depth, and a flexible irrigation scheduling; and (3) an **increase in crop evapotranspiration** and **water productivity** (typically from 5000 to 6000 $m^3$ $ha^{-1}$).

**Table 9** Water productivity of drip and furrow irrigated corn at two levels of water supply (Playan and Mateos, 2004).

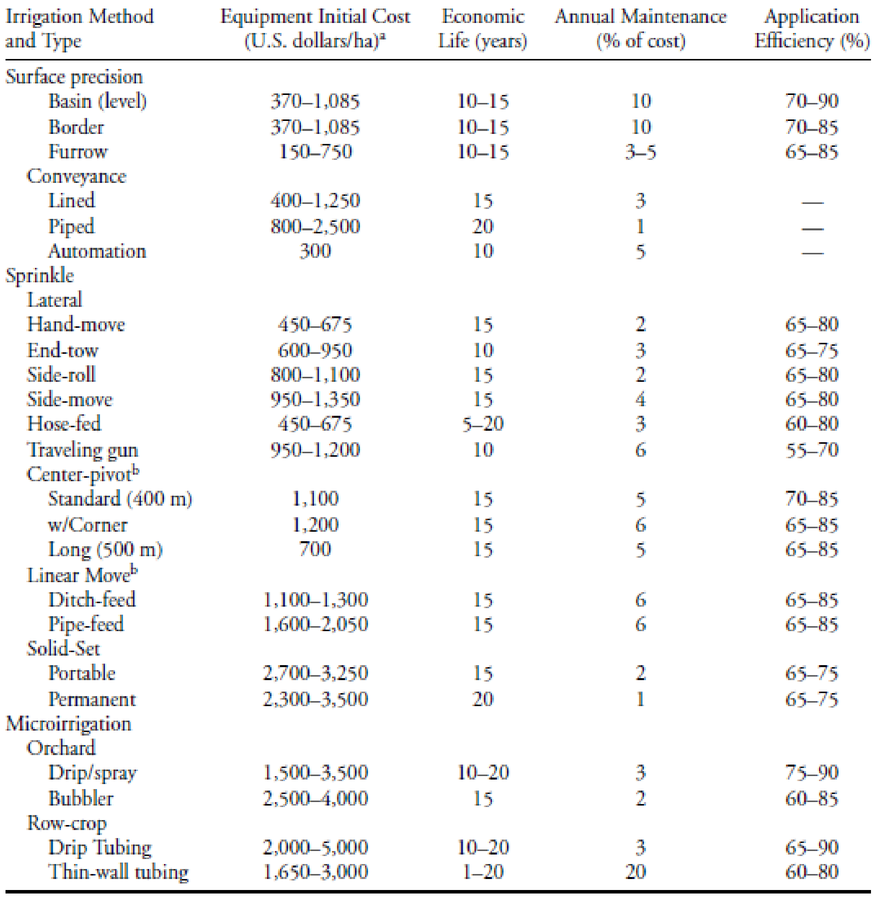


| Irrigation supply | Irrigation method | $WP_2$ (kg $m^{-3}$) | $WP_5$ (kg $m^{-3}$) |
|---|---|---|---|
| Full | Drip | 0.79 | 0.88 |
| | Furrow | 0.52 | 0.90 |
| Deficit | Drip | 1.05 | 1.15 |
| | Furrow | 0.65 | 1.03 |

$WP_2$ is yield divided by applied water and $WP_5$ is yield divided by evapotranspiration of irrigation water.

Table 10 contains indicative values for **initial investment costs, economic equipment life, and maintenance costs** of different irrigation methods and types, which can be useful to support system selection and evaluation (Pereira and Trout, 1999; Keller, 1992). The table also includes the expected range for the seasonal application efficiencies of the systems. This information is helpful for estimating the gross irrigation water requirements.

**Table 10** Examples of costs and efficiencies of different types of modern on-farm irrigation systems (from Pereira and Trout, 1999).



| Irrigation Method and Type | Equipment Initial Cost (U.S. dollars/ha)[a] | Economic Life (years) | Annual Maintenance (% of cost) | Application Efficiency (%) |
|---|---|---|---|---|
| Surface precision | | | | |
| Basin (level) | 370–1,085 | 10–15 | 10 | 70–90 |
| Border | 370–1,085 | 10–15 | 10 | 70–85 |
| Furrow | 150–750 | 10–15 | 3–5 | 65–85 |
| Conveyance | | | | |
| Lined | 400–1,250 | 15 | 3 | — |
| Piped | 800–2,500 | 20 | 1 | — |
| Automation | 300 | 10 | 5 | — |
| Sprinkle | | | | |
| Lateral | | | | |
| Hand-move | 450–675 | 15 | 2 | 65–80 |
| End-tow | 600–950 | 10 | 3 | 65–75 |
| Side-roll | 800–1,100 | 15 | 2 | 65–80 |
| Side-move | 950–1,350 | 15 | 4 | 65–80 |
| Hose-fed | 450–675 | 5–20 | 3 | 60–80 |
| Traveling gun | 950–1,200 | 10 | 6 | 55–70 |
| Center-pivot[b] | | | | |
| Standard (400 m) | 1,100 | 15 | 5 | 70–85 |
| w/Corner | 1,200 | 15 | 6 | 65–85 |
| Long (500 m) | 700 | 15 | 5 | 65–85 |
| Linear Move[b] | | | | |
| Ditch-feed | 1,100–1,300 | 15 | 6 | 65–85 |
| Pipe-feed | 1,600–2,050 | 15 | 6 | 65–85 |
| Solid-Set | | | | |
| Portable | 2,700–3,250 | 15 | 2 | 65–75 |
| Permanent | 2,300–3,500 | 20 | 1 | 65–75 |
| Microirrigation | | | | |
| Orchard | | | | |
| Drip/spray | 1,500–3,500 | 10–20 | 3 | 75–90 |
| Bubbler | 2,500–4,000 | 15 | 2 | 60–85 |
| Row-crop | | | | |
| Drip Tubing | 2,000–5,000 | 10–20 | 3 | 65–90 |
| Thin-wall tubing | 1,650–3,000 | 1–20 | 20 | 60–80 |

One way of improving water use efficiency is to replace gravity-fed irrigation systems such as border check and furrow, with more efficient pressurized systems (Zehnder et al., 2003; Lal, 2004; Playan and Mateos, 2006), because these conversions can offer a significant reduction in water application at the field scale. It seems reasonable to assume that one option for modernization will be **to convert to pressurized irrigation systems in order to generate significant water savings**.

On the other side, **irrigation is a primary consumer of energy on farms** (Naylor, 1996), so any changes to the irrigation method used can be expected to change on-farm energy consumption. Direct energy inputs are primarily the fuel sources used to operate farm machinery and pumps, while indirect energy inputs refer to energy that is used to produce equipment and other goods and services that are used on-farm (Pimentel, 1992). Between **23% and 48% of direct energy used for crop production is used for on-farm pumping** (Hodges et al., 1994; Lal, 2004). If a gravity-fed irrigation method is used in conjunction with a surface water source, the energy required to transport and apply water to the field is negligible (Stout, 1990). However, where pressurized groundwater extraction is used, there is always energy required for pumping and delivery to the field.

The energy required for pumping depends on crop water requirement, total dynamic head, flow rate and system efficiency (Lal, 2004). Crops with a higher water requirement result in a larger amount of water being pumped and increase energy consumption: this means that summer crops will typically consume more energy than winter crops. Where **groundwater** is used for irrigation, **converting to pressurized micro-irrigation systems can decrease energy consumption** if the conversion also means that operating pressures (and therefore total dynamic head) and pumping volumes are reduced (Hodges et al., 1994; Srivastava et al., 2003). Given that fossil fuel reserves are declining, it is important that any long term production plans for a commodity or industry depending on irrigated agriculture recognizes that current technology will be challenged by declining resources and increasing fuel prices (Jackson et al., 2010).

For example, Jackson et al. (2010) studied the water and energy budgets for crop production from land preparation to harvest were quantified on several farms. Converting from flood to pressurized systems resulted in a **reduction in water application** of between 10% and 66%. However, in the surface water supplied region, it also resulted in **energy consumption** being **increased** by up to 163%. In the groundwater dependent region, energy consumption was reduced by 12% to 44%. There is **potential to reduce energy consumption due to increased water use efficiency**, resulting in less water being pumped due to efficiency gains. Therefore, to optimize energy and water use, it is recommended that pressurized irrigation systems are used in areas requiring pressurized extraction of groundwater, while efficient gravity based irrigation methods, coupled with good management practices, are promoted in surface-water supplied areas.

**Irrigation is a very carbon-intensive practice**. Sloggett (1992) estimated that 23% of the on-farm energy use for crop production in the US was for on-farm pumping. The **energy required to pump water** depends on numerous factors including total dynamic head (based on water lift, pipe friction, system pressure), the water flow rate and the pumping system efficiency (Whiffen, 1991). The energy use depends on the water table depth or the lift height. Batty and Keller (1980) estimated pumping energy needed for different lift heights, and reported that energy required for surface irrigation (MJ/ha m) was 3184 for 0 m lift, 56,250 for 50 m lift and 109,317 for 100 m lift. The energy required was high for hand moved, side roll and center-pivot sprinkle system. In comparison, energy required was low for the trickle system, and was estimated (MJ/ha m) at 20,637 for 0 m lift, 50,118 for 50 m lift and 79,599 for 100 m lift (Batty and Keller, 1980).

Dvoskin et al. (1976) assessed fuel consumption for lifting irrigation water in several regions of the western US. The **C emission** ranged from 7.2 to 425.1 kg CE/ha for 250 mm of irrigation and from 53.0 to 850.2 kg CE/ha for 500 mm of irrigation. Schlesinger (1999) estimated C emission from irrigation at 220–830 kg CE/ha/year. West and Marland (2002) estimated emission by irrigation at 125–285 kg CE/ha/year. In comparison, irrigation of winter wheat in Punjab, India, by tube well was estimated to emit 3–25 kg CE/ha (Singh et al., 1999). Similar to fertilizer and pesticide use, enhancing water use efficiency (WUE) is important to decreasing emissions. Strategies to improve WUE include eliminating flood and furrow irrigation in favor of sprinkler irrigation, for most upland crops (although rice requires flooding), using drip and sub-irrigation, adopting conservation tillage with residue mulch to reduce evaporation losses, and using supplemental irrigation only at critical stages of crop growth.

### 4.2.1. Sprinkler irrigation

There are many types of sprinkler systems, but all have the following basic components: i) the **pump** draws water from the source, such as a reservoir, borehole, canal, or stream, and delivers it to the irrigation system at the required pressure; it is driven by an internal combustion engine or electric motor, but if the water supply is pressurized, the pump may not be needed; ii) the mainline is a pipe that delivers water from the pump to the laterals; iii) the lateral pipeline delivers water from the mainline to the sprinklers; it can be portable or permanent and may be made of materials similar to those of the mainline, but is usually smaller; in continuous-move systems, the lateral moves while irrigating; iv) **sprinklers** spray the water across the soil surface with the objective of uniform coverage.

**Figure 20** Examples of sprinkler irrigation systems (from top-left to bottom-right): rotary set-sprinklers; moving laterals; moving guns; center pivot.

Sprinklers irrigation systems can be divided broadly into **set and continuous-move systems**. In set systems, the sprinklers remain at a fixed position while irrigating; in continuous-move systems, the sprinklers operate while the lateral is moving in either a circular or a straight path. The principal continuous-move systems are center-pivot and linear-move laterals, and traveling rain-gun sprinklers.

Sprinklers are available in **a wide range of characteristics and capacities** and are **suitable for most crops and adaptable to most irrigable soils**. Care is required to select the proper sprinklers for the existing conditions. Sprinklers can be adapted to most climatic conditions, but high wind conditions decrease distribution uniformity and increase evaporation losses, especially when combined with high temperatures and low air humidity. Although sprinkling is adaptable to most topographic conditions, large elevation differences result in non-uniform application unless pressure regulation devices are used (Keller and Bliesner, 1990; Giller 1996).

**Table 11** List of the main advantages and limitations of sprinkler irrigation systems (from Pereira and Trout, 1999)

| Advantages | Limitations |
|---|---|
| Properly designed and operated sprinkler irrigation systems can give **high seasonal irrigation efficiencies and save water**.<br>**Soils with variable textures and profiles** can be efficiently irrigated.<br>Sprinkler irrigation performance is not dependent on soil infiltration as long as **application rate does not exceed infiltration rate**<br>**Mechanized sprinkler systems require very little labor** and are relatively simple to manage. Periodic-move sprinkler systems require only unskilled labor; irrigation management decisions are made by the manager. Fixed sprinkler systems require very little field labor during the irrigation season and may be fully automated.<br>Land leveling is not required; shallow soils that cannot be graded for surface irrigation without detrimental results can be irrigated.<br>Fixed sprinkler systems can be **used to control weather extremes** by increasing air humidity, cooling the crop, and reducing freeze damage.<br>Sprinklers can be managed for **supplement irrigation**.<br>Sprinklers can **leach salts from saline soils** more effectively than surface or micro-irrigation methods.<br>Cultural practices such as **conservation tillage and residue management** can be used easily under sprinkler irrigation. | **Initial costs are higher** than for surface irrigation systems unless extensive land grading costs are required.<br>**Energy costs for pressurizing water are a significant expense**, depending on the pressure requirements of sprinklers used and power costs.<br>Soil infiltration rate of less than 3–5 mm $h^{-1}$ will constrain system selection and operating procedures and may result in runoff; center pivots require initial infiltration rates above 20 mm $h^{-1}$.<br>**Windy and dry conditions cause water loss** by **evaporation** and wind drift.<br>Irregular field shapes are more expensive and less convenient, especially for mechanized sprinkler systems.<br>Water containing trash or sand must be cleaned to avoid clogging and nozzle wear.<br>Sprinkler irrigation **water containing salts** may cause problems because salts drying on the leaves affect some crops. High concentrations of bicarbonates in irrigation water may affect the quality of fruits. Sodium or chloride concentration in the irrigation water exceeding 70 or 105 parts per million (ppm), respectively, may injure some fruit crops.<br>The **high humidity and wet foliage** created by sprinkling is conducive to some fungal and mold **diseases**. |

Sprinklers generally cannot produce an even water distribution over the whole of the wetted radius. Often the application is highest close to the sprinkler and decreases toward the edge, resulting in a radial pattern of distribution shaped like a triangle. **To**

**make the distribution more uniform** over the field, several sprinklers must operate close enough together that their distribution patterns overlap. The sprinkler pattern determines the desired spacing between sprinklers. Uniformity usually is improved by putting sprinklers close together, but this increases water application rates and cost of the system.

**Table 12** Examples of the main technical characteristics of different sprinkler types (from Pereira and Trout, 1999).

| Sprinkler type | Pressure | Wetted diameter | Drop size | water distribution | Application rate | Suitable for |
|---|---|---|---|---|---|---|
| **Low-pressure impact or spray sprinklers** | 35–140 kPa | Small wetted diameter (6–15 m) | Large water drops | Fair water distribution | Relatively high (>10 mm $h^{-1}$) | Small areas or continuous-move systems |
| **Rotary sprinklers with low to moderate pressure** | 105–210 kPa | Medium wetted diameter (18–24 m) | Water drops are fairly well broken up | Good when the pressure is near 200 kPa | Can be selected over a wide range (>3 mm $h^{-1}$) | Suitable for most crops, including vegetables and under-tree irrigation and are also suitable for continuous-move systems |
| **Low- to medium-pressure spinners or sprayers** | 70–245 kPa | Moderate diameters (12–27 m) | Moderate size drops | Fairly good water distribution | Large range of application rates is obtainable (>5 mm $h^{-1}$) | Ideal for orchards in windy areas (under-tree irrigation) |
| **Medium pressure rotary sprinklers** | 210–410 kPa | Medium to large circle (23–37 m) | Well-broken water drops | Excellent water distribution | Very wide range (>2.5 mm $h^{-1}$) | All type of soils, including those with low intake, and all crops |
| **High-pressure rotary sprinklers** | 340–690 kPa | Large diameters (34–90 m) | Well broken | Good (when wind speed does not exceed 6 km $h^{-1}$) | Application rates are relatively high (>10 mm $h^{-1}$) | Suitable for field crops, soils with non limiting infiltration rate and regions without excessive wind |
| **Very high pressure gun sprinklers** | 550–830 kPa | Large diameters (60–120 m) | Very well broken water drops | Good under calm conditions (distorted easily by wind) | High application rates (>15 mm $h^{-1}$) | Field crops in soils with good infiltration characteristics |

Fixed set sprinklers usually are placed in a square or rectangular grid, although triangular grids improve pattern overlap and distribution uniformity. In continuous move systems, only spacing along the lateral affect distribution (assuming the movement is adequately continuous). Continuous move systems usually produce better uniformity than set systems.

In choosing a sprinkler, the aim is to find the combination of sprinkler spacing, operating pressure, and nozzle size that provides the desired application rate with the best distribution uniformity. The uniformity obtainable with a set sprinkler system depends largely on the water distribution pattern and spacing of the sprinklers. The uniformity is strongly affected by wind and operating pressure.

In general, these classifications should be combined and considered under the perspective of **adaptability of the sprinkler to the field conditions**. In Table 12, a list of sprinkler types is presented, together with their main characteristics and suitability for field application (Keller and Bliesner, 1990; Pereira and Trout, 1999).

### 4.2.2. Micro-irrigation (drip and subsurface irrigation)

**Micro-irrigation**, also called **trickle or drip irrigation**, applies water to individual plants or small groups of plants. Application rates are usually low to avoid water ponding and minimize the size of distribution tubing. The principle micro-irrigation systems in common use today can be classified in two general categories (Pereira and Trout, 1999): i) **drip irrigation**, by which water is applied slowly through small emitter openings from plastic tubing; drip tubing and emitters may be laid on the soil surface, buried, or suspended from trellises; ii) **micro-spray irrigation**, also known as micro-sprinkling, by which water is sprayed over the soil surface.

Drip irrigation systems (surface or sub-surface) utilize a number of point sources for the slow and precise application of water/nutrients directly to the root zones in a controlled flow/pattern that satisfies the peak crop water requirements. Drip tubes are normally laid out in, or parallel to, crop rows. The tubing often is laid on the soil surface. In crops with trellising, such as vineyards, the tubing may be suspended from the trellising to keep it out of the way of tillage operations. In horticultural crops, thin-wall tubing (drip tape) may be placed a few centimeters below the soil surface and/or under plastic mulch to help hold it in place.

Drip tubing also can be placed up to 60 cm below the soil surface. **Subsurface drip irrigation (SDI)**, when placed below tillage depths, allows the tubing to be left in place for several seasons. It also **minimizes wetting of the soil surface** and thus **weed germination** and **surface evaporation**. Subsurface drip usually requires specialized tillage operations and equipment, and also requires special equipment or management to prevent roots from growing into and plugging the emitters.

Sprinkle irrigation is the method by which pressurized water is ejected through the nozzle of the sprinkler-device and it is sprayed on the land in the form of artificial rain. Small sprinkler heads can operate at low pressures/flow conditions and are suitable when a small radius of throw is required (mini-sprinklers operate at flow rates between 150-300 l/h). **Micro-spray emitters** spray water over 2 to 6 m diameter circles or partial circles. Micro-spray was developed to wet a larger percentage of the rooting area of tree crops than was practical with drip irrigation. Micro-spray heads are small versions of low-pressure sprinkler heads, they are commonly used for widely spaced tree crops, where one or two sprayers are used on each tree.

Micro-irrigation systems require a pump to pressurize the water; one or more filters to clean the water, and valves to regulate pressure. Micro-irrigation water is applied under low pressure, usually in the range of 50 to 200 kPa.

**Figure 21** Examples of surface (left) and subsurface (right) drip irrigation systems.

Based upon analyses provided by Pair *et al.* (1983), Keller and Bliesner (1990), and Papadopoulos (1996), Pereira and Trout (1999) identified main advantages and disadvantages of micro-irrigation systems as reported in Table 13.

**Drip irrigation**, especially in horticultural systems, offers a **high potential to limit water inputs**, to **improve water use efficiency**, and to better match the crop water demand in time and space. The major constraints are the high investment and management costs. A combination of drip irrigation and cover crops is also possible by adding cover crop rows between crops to reduce evaporation from bare soil, decrease soil erosion, increase soil organic matter, and increase N concentration if legumes are used (Lopes et al. 2011). Cover crops could also play the role of mulch.

Zotarelli et al. (2008) found that the use of SMS-based drip irrigation management for zucchini squash allowed more efficient use of irrigation water and a **reduction in irrigation water use** by 33–80% compared to a typical grower irrigation practices. A subsurface drip irrigation system combined with surface applied fertigation, resulted also in a **reduction of nitrate leaching**, an increase in the nitrogen uptake efficiency, and similar or higher yields compared to other treatments.

Micro-irrigation systems should be used to achieve the **highest returns and yields** while optimizing the use of water and other production inputs. Micro-irrigation systems may use less water when not all of the area is irrigated and when system and **application losses are minimized**, but they should not be managed with the sole intent of saving water; instead, they should be managed to supply the amount of water required by the crop with high frequency. When very frequent irrigations are applied, the essential information for irrigation scheduling is a forecast of the crop water use. An estimation of crop evapotranspiration may be sufficient, either using meteorological information or specific sensors. Minimizing percolation losses should be a main objective of scheduling (Wu, 1995).

**Yields** often (but not always) exceed those obtained by other irrigation methods. This is because, inside the bulb, light, frequent irrigations and fertilizer applications (fertigation) can maintain optimum growth conditions. Irrigation frequency varies from daily to every three or four days.

**Table 13** List of the main advantages and limitations of micro-irrigation systems (from Pereira and Trout, 1999).

| Advantages | Disadvantages |
|---|---|
| It has the potential to **reduce irrigation water use and corresponding operating costs** because water can be applied only where the crop roots develop. This is particularly true for widely spaced crops such as orchards and vineyards or for shallow-rooted crops.<br>It has been shown to **increase the yield and quality of some crops**. This is most likely the result of maintaining near-optimum water and fertility conditions in the root zone.<br>It can **reduce the cost of labor** because the systems need only to be maintained and managed, not tended. Operation usually is accomplished by **automatic timing devices**, but the emitters and system controls should be inspected frequently.<br>A greater control over fertilizer placement and timing through fertigation with micro-irrigation **improves fertilizer efficiency** and **reduces pollution hazards** associated with fertilizers.<br>It usually requires **lower operating pressure and thus less energy than sprinkler systems**.<br>It can **reduce weed growth** and the incidence of some diseases because foliage and much of the soil surface are not wetted. This **reduces costs of labor and chemicals** to control weeds and diseases and reduces related **pollution hazards**.<br>It is less disruptive to field operations because the non-cropped soil between crop rows is not wetted.<br>**Frequent irrigations** maintain soil water content and **keep the salts in the active root zone more diluted**, making it possible to use more saline water than with other irrigation methods.<br>Well-designed micro-irrigation systems can operate efficiently on almost any topography.<br>Problem soils with low infiltration rates, low water-holding capacity, and variable textures and profiles can be irrigated efficiently. | **Equipment costs usually are higher** than for surface irrigation systems and may be higher than for sprinkler systems.<br>Equipment often is complex and requires frequent monitoring to ensure good performance.<br>**Energy costs to pressurize** the system are higher than with surface irrigation and lower than with sprinkler irrigation.<br>Because emitter outlets are very small, they can become clogged by particles of mineral or organic matter. **Clogging reduces discharge rates and the water distribution uniformity**; thus filtration is required in most cases.<br>Because micro-irrigation systems operate at low pressures, varying field topography can result in significant **pressure variations and irrigation non uniformity**.<br>**Salts may concentrate at the soil surface** and between emitters and become a potential hazard. Localized salt accumulation can hinder crop germination. Light rains can leach accumulated salts downward into the root zone.<br>Salts also concentrate below the surface at the perimeter of the wetted bulbs. Too much drying of the soil between irrigations may allow the movement of water and salts back toward the inner bulb. To avoid this damage, **irrigation must be frequent under saline conditions**.<br>If unexpected events (equipment failure, power failure, or water-supply interruption) interrupt irrigation, crop damage may occur quickly because roots use only a small volume of wetted soil. At least 33% of the total potential root zone should be wetted.<br>When a main supply line breaks or the filtration system malfunctions, contaminants may enter the system, resulting in emitter clogging. Secondary filters can be used to protect against these problems. |

Salts in the soil move with the water towards the periphery of the wetted zone. Inside the wetted bulb, where the main root activity occurs, the salt concentration is generally low and not harmful to plants. However, lack of periodic leaching from irrigation or rainfall can result in harmful **soil salt concentrations near the edges**. These salt concentrations can be especially damaging during germination of new crops, or if rainfall moves the accumulated salts back into the active rooting area. Periodic large water applications are required to **leach out salts**.

Use of **subsurface drip irrigation (SDI)** has progressed from being a novelty employed by researchers to an accepted method of irrigation of both perennial and annual crops. Ayars et al. (1999) reviewed the SDI research conducted by scientists at the Water Management Research Laboratory over a period of 15 years. Data are presented for irrigation and fertilization management on tomato, cotton, sweet corn, alfalfa, and cantaloupe for both plot and field applications. Results from these studies demonstrated **significant yield and water use efficiency increases in all crops**. Use of high frequency irrigation resulted in reduced deep percolation and increased use of water from shallow ground water when crops were grown in high water table areas. Uniformity studies demonstrated that after 9 years of operation SDI uniformity was as good as at the time of installation if management procedures were followed to prevent root intrusion.

Similarly, Phene et al. (1987) demonstrated **significant yield increases** in tomatoes with the use of **high frequency SDI** and precise fertility management. Hutmacher et al. (1996) demonstrated yield increases in alfalfa production using SDI systems buried at a depth of 0.7 m. The top soil and the canopy are kept dry, thus reducing weed growth as well as water losses by soil evaporation and surface runoff. Additionally, SDI can be used to control the volume and intensity of applied water and thus limiting percolation losses.

## 4.3. Deficit irrigation strategy

Given the high costs of irrigation development, until now the paradigmatic **irrigation strategy** has been to supply irrigated areas with sufficient water so that the crops transpire at their maximum potential and the full ET requirements are met throughout the season. This approach is increasingly challenged by segments of society in regions where water is scarce, because of both the large amounts of water required by irrigation and the negative effects that such diversions and use have on nature (Fereres and Soriano, 2007).

In recent years, **deficit irrigation (DI)** has been widely investigated as a valuable strategy for dry regions where water is the most limiting factor in crop cultivation (English, 1990; Pereira et al., 2002; Fereres and Soriano, 2007). Deficit irrigation could be defined as an '**optimization strategy**' in which irrigation is applied during drought-sensitive growth stages of a crop, while outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water (Geerts and Raes, 2009). Water restriction is limited to drought-tolerant phenological stages, and so DI requires precise knowledge of crop response to drought stress for each of the growth stages and an assessment of the consequent economic impact of the yield reduction (English and Raja, 1996; Sepaskhah and Akbari, 2005).

Total irrigation application is therefore not proportional to irrigation requirements throughout the crop cycle. Irrigation supply under DI is reduced with respect to maximum crop evapotranspiration (English, 1990). **Reducing ET** result in **a reduction in yield** (Ebel et al., 1993; ICMS, 2013; Greven et al., 2005), because transpiration from crop canopies is tightly coupled with the assimilation of carbon

(Tanner and Sinclair, 1983). A water supply constraint that decreases transpiration below the rate dictated by the evaporative demand of the environment is paralleled by a reduction in biomass production.

Anyway, when water supplies are limiting, the farmer's goal should be to maximize net income per unit water used rather than per land unit, and then to **maximize WP may be economically more profitable** than maximizing yields (English, 1990). DI is somehow a technique aimed at the optimization of economic output when water is limited, and it has been shown experimentally for many crops that **WP increases under DI**, relative to its value under full irrigation (Zwart and Bastiaansen, 2004; Fan et al., 2005).

Figure 22 presents the generalized relationship between yield, irrigation water applied and water productivity for an annual crop. Small irrigation amounts increase crop ET, more or less linearly up to a point where the relationship becomes curvilinear because part of the water applied is not used in ET and is lost. At one point, yield reaches its maximum value and additional amounts of irrigation do not increase it any further. Thus, the WP of irrigation water under DI must be higher than that under full irrigation (Fereres and Soriano, 2007).

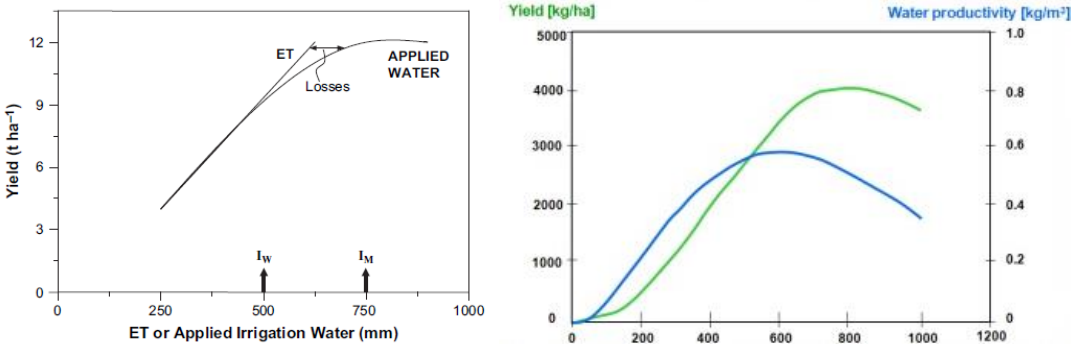


**Figure 22** *Left*: Generalized relationships between applied irrigation water, ETc and crop grain yield. Iw indicates the point beyond which the productivity of irrigation starts to decrease, and Im the point beyond which yield does not increase any further with additional water application (from Fereres and Soriano, 2007). *Right*: generalized relationship between yield and water productivity (Molden, 2003).

In areas where water is the most limiting factor, water demand for irrigation can be reduced and the water saved can be diverted for **alternative uses**. For instance, water saved by DI can be used to irrigate more land, which – given the high opportunity cost of water – may largely compensate for the economic loss due to yield reduction (Kipkorir et al., 2001; Ali et al., 2007).

**Yield responses** to irrigation and to ET deficits have been studied empirically for decades (Vaux and Pruitt, 1983; Stewart and Nielsen, 1990; Howell, 2001). It turned out that it is not only biomass production that is linearly related to transpiration, but the yield of many crops is also linearly related to ET. The design of a DI program must be based on knowledge of this response but the exact characteristics of the response function are not known in advance. Also, the response varies with location, stress patterns, cultivar, planting dates, and other factors. In particular, many crops have **different sensitivities to water stress at various stages of development**, and the DI program must be designed to manage the stress so that yield decline is minimized.

Water deficits, by affecting growth, development, and carbon assimilation, reduce the yield of most annual crops (Hsiao and Bradford, 1983). The reduction in yield by water deficits is caused by a **decrease in biomass production** and/or by a decrease in the **harvest index**. If water deficit increases progressively as the season advances (the so-called 'sustained deficit irrigation' pattern - SDI), water stress develop slowly and allows the plants to adapt to it. Dry matter partitioning is usually not affected and the HI is maintained. The response to SDI described above has been documented extensively in the major field crops and Figure 23 exemplifies the response of maize, wheat, and sunflower.

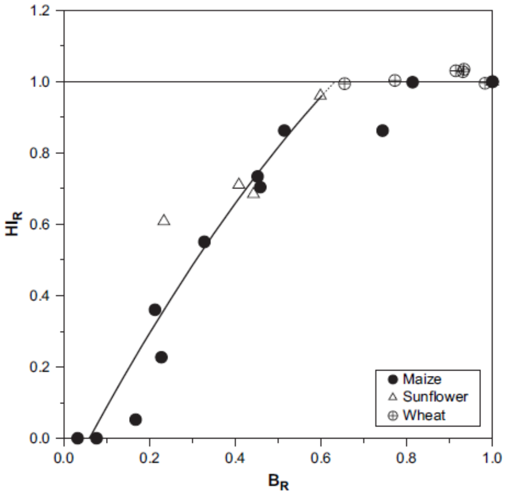


**Figure 23.** Relationship between harvest index (HIR) as a function of biomass production (BR) in response to water deficits, both expressed relative to the values observed under full irrigation (from Fereres and Soriano, 2007).

The literature reviewed suggests that increased WP can be attributed to the following reasons: i) water loss through **evaporation** is reduced; ii) the negative effect of drought stress during specific phenological stages on biomass partitioning between reproductive and vegetative biomass (**harvest index**) is avoided, which stabilizes or increases the number of reproductive organs and/or the individual mass of reproductive organs (filling) (Fereres and Soriano, 2007; Hsiao et al., 2007; Reynolds and Tuberosa, 2008); iii) WP for the net assimilation of biomass is increased as drought stress is mitigated or crops become more hardened; this effect is thought to be rather limited given the conservative behavior of biomass growth in response to transpiration (Steduto et al., 2007); iv) WP for the net assimilation of biomass is increased due to the **synergy between irrigation and fertilization** (Steduto and Albrizio, 2005); this includes cases where irrigation is reduced if fertilizer levels and native fertility are low; v) negative agronomic conditions are avoided during crop growth, such as pests, diseases, anaerobic conditions in the root zone due to water logging, etc. (Pereira et al., 2002).

Reducing irrigation applications over the crop cycle will also **reduce nutrient loss through leaching** from the root zone, resulting in improved ground water quality (e.g. Unlu et al., 2006) and **lower fertilizer needs** on the field. Each DI strategy has its optimum fertilizer level (Tavakkoli and Oweis, 2004; Cabello et al., 2009). Hence, DI is most effective if different management factors are considered in parallel. What is often labeled as the **win–win effect of DI and reduced fertilizer application** (Fox and Rockstrom, 2000, 2003) is the fact that combining DI and optimum fertilizer application leads to a higher yield increase (higher WP) than the sum of the separate yield increases obtained by both factors.

Anyway, one consequence of reducing irrigation water use by DI is the greater **risk of increased soil salinity due to reduced leaching**, and its impact on the sustainability of the irrigation (Schoups et al., 2005).

The use of DI requires that the following **conditions** are met: i) crop response to drought stress should be studied carefully; ii) irrigators should have unrestricted access to irrigation water during sensitive growth stages and a minimum quantity of irrigation water should always be available for application; iii) DI can only be successful if measures are taken to avoid salinization, because leaching of salts from the root zone is lower under DI than under FI. (Ragab, 1996; Sarwar and Bastiaanssen, 2001; Zhang and Oweis, 1999; Kaman et al., 2006; Kang et al., 2002; Fereres and Soriano, 2007; Hsiao et al., 2007).

### 4.3.1. Supplemental irrigation (SI)

In the **humid and sub-humid zones**, irrigation has been used for some time to supplement rainfall as a tactical measure during drought spells to stabilize production. This practice has been called **supplemental irrigation** (Debaeke and Aboudrare, 2004) and, although it uses limited amounts of water due to the relatively high rainfall levels, the goal is to achieve maximum yields and to eliminate yield fluctuations caused by water deficits.

More recently, the term supplemental irrigation has been used in **arid zones** to define the practice of applying small amounts of irrigation water to winter crops that are normally grown under rain-fed conditions (Oweis et al., 1998). This is a form of DI, as maximum yields are not sought. When water resources are limited and rainfall is variable in space and time, crop production is variable and yields are usually low. Supplemental irrigation is then used to augment and stabilize yields (Oweis 1997). Such additions, if well managed, **increase the utilization efficiency of the rainfall** and **irrigation water**. This is particularly true where a winter crop is being supplemented and the alternative use for the water is full irrigation of a summer crop.

Research results showed substantial **increases in crop yield** in response to the application of relatively small amounts of supplemental irrigation in both low and high rainfall areas. Average **rainwater productivity** in the dry areas is about 0.35 kg $m^{-3}$, but it may be increased up to 1.0 kg $m^{-3}$ with improved management and favorable rainfall distribution (Pala and Oweis 2002). Experiences from Syria showed that applying only 50% of the supplementary irrigation needed by rainfed wheat reduces yield by less than 15% while water productivity increases from 10 to 20 kg $ha^{-1}$ $mm^{-1}$ in grain and from 25 to 40 kg $ha^{-1}$ $mm^{-1}$ in total dry matter (Oweis, 1997). The high water productivity of supplemental irrigation is mainly attributed to **alleviating moisture stress during the most sensitive stages** of crop growth. Moisture stress during flowering and grain filling usually causes a collapse in the crop seed filling and reduces yields substantially. When supplementary water is applied before the occurrence of stresses, the plant may produce to its potential (Pala and Oweis 2002).

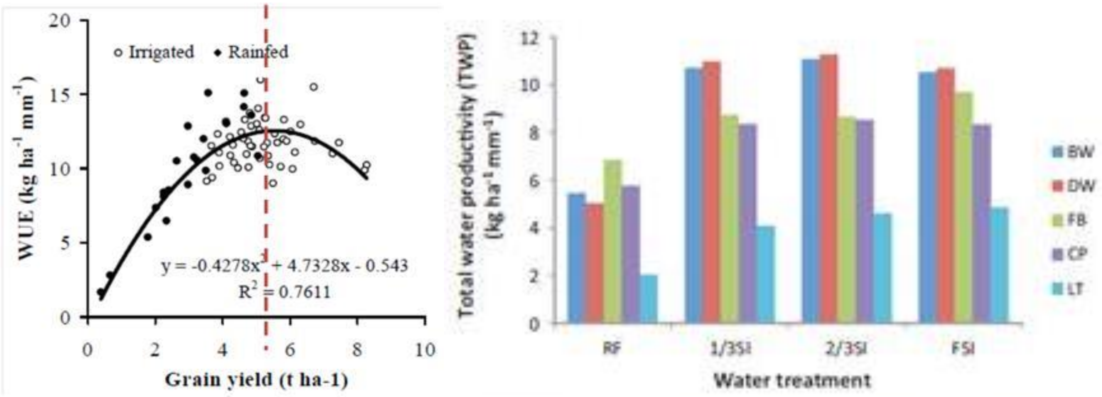


**Figure 24** *Left*: Relationship between WUE and yield for durum wheat under supplemental irrigation in northern Syria (Zhang and Oweis, 1999); *Right*: Mean total water productivity of bread wheat (BW), durum wheat (DW), faba bean (FB), chickpea (CP) and lentil (LT) under different levels of water supply (rainfed – RF, supplemental irrigation – SI, full irrigation - FI) in northern Syria (from Karrau and Oweis, 2012).

### 4.3.2. Regulated deficit irrigation (RDI)

A specific type of DI Is the so-called '**Regulated Deficit Irrigation (RDI)**' which consists of inducing mild to moderate plant water deficits during specific phenological stages by withholding irrigation or by applying less water than plants would use under normal conditions, with the aim of reducing vegetative growth and to improve qualitative aspects of crop production. RDI has had significantly more success in **tree crops and vines** than in field crops for a number of reasons (Fereres et al., 2003). First, economic return in tree crops is often associated with factors such as crop quality, not directly related to biomass production and water use. The yield-determining processes in many fruit trees are not sensitive to water deprivation at some developmental stages (Uriu and Magness, 1967; Johnson and Handley, 2000). Because of their high WP, tree crops and vines can afford high-frequency, micro-irrigation systems that are ideally suited for controlling water application and thus for stress management (Fereres and Goldhamer, 1990).

Trees are subjected to irrigation deficits only at certain stages of development but they generally receive full irrigation outside these periods. The water stress is normally imposed in RDI at stages when reproductive growth is relatively low. Water deficits imposed at these stages also generally **reduce vegetative growth** (and thus pruning costs and agricultural burning potential problems) and may impact on other plant processes, often improving fruit quality (Figure 25).

The imposition of water stress at certain developmental periods could therefore **benefit yield and quality in fruit tree and vine production**. The concept of RDI was first proposed by Chalmers et al. (1981) and Mitchell and Chalmers (1982) to control vegetative growth in **peach** orchards, and they found that savings in irrigation water could be realized without reducing yield. Experiments with RDI have been successful in many fruit and nut tree species such as **almond** (Goldhamer et al., 2000), **pears** (Mitchell et al., 1989), **pistachio** (Goldhamer and Beede, 2004), **citrus** (Domingo et al., 1996; Gonzalez-Altozano and Castel, 1999; Goldhamer and Salinas, 2000), **apple** (Ebel et al., 1995), **apricot** (Ruiz-Sanchez et al., 2000), **wine grapes** (Bravdo and Naor, 1996; McCarthy et al., 2002), and **olive** (Moriana et al., 2003), almost always with positive results.

**Figure 25** Effect of deficit irrigation (on the right) on the reduction of grapevine vegetative growth, with respect to full irrigation (left) (from Wample and Smithyman, 2002).

Thus, there is sufficient evidence at present that supplying the full ET requirements to tree crops and vines may not be the best irrigation strategy in many situations (Fereres and Evans, 2006). One feature of the yield response of tree crops to ET deficits is that, contrary to the linearity observed in annual crops, the response appears to be curvilinear (Moriana et al., 2003). This means that WP is highest at low levels of water application and that DI is the appropriate irrigation strategy. The **RDI response is very dependent on the timing and degree of severity of the water deficits**, as well as on crop load (Marsal and Girona, 1997).

Experience that full irrigation is not the best strategy abounds in many perennial horticultural crops, but in none is it more evident than in **wine grapes**. The quality of wine in semi-arid areas is strongly associated by enologists with water stress (Williams and Matthews, 1990) to the point that, as an example, irrigation of vineyards was forbidden by law in Spain until 1996. Nevertheless, the benefits of RDI to the yield and quality of wine grapes have been clearly demonstrated relative to rain-fed production (Girona et al., 2006).

Among the techniques used for imposing RDI on wine grapes is one that alternates drip irrigation about every 2 weeks on either side of the vine row; this is called **partial root drying (PRD)** (Dry and Loveys, 1998). The PRD technique has its foundation in the root-to-shoot signaling that regulates the plant response to drying soil (Dodd, 2005). Shoot physiological processes are affected by root signalling, including leaf expansion (Passioura, 1988). The control of vegetative growth is of paramount importance in the production of high-quality wine grapes (Loveys et al., 2004), and it has been shown that PRD controls canopy growth and is advantageous over full irrigation in wine production (McCarthy et al., 2002). In practice, the comparisons between PRD and other forms of RDI, which apply the same irrigation levels under field conditions, have not shown any specific advantage of PRD over RDI in terms of production per unit irrigation water in a significant number of experiments (Figure 26) (Fereres et al., 2012; Sadras, 2009).

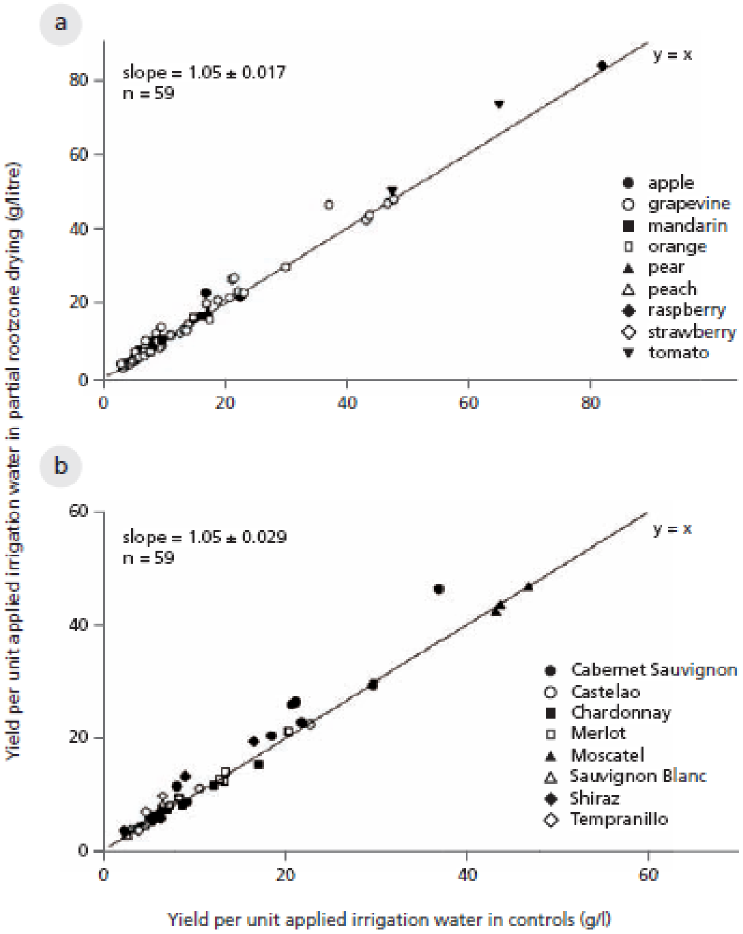


**Figure 26** Comparison of yield per unit irrigation between crops managed with PRD and conventionally irrigated crops (from Sadras, 2009)

## 4.4. Use of treated wastewater

Water supply and water quality degradation are global concerns that will intensify with increasing water demand, the unexpected impacts of extreme events, and climate change; for this reason, worldwide, marginal-quality water will become and increasingly important component of agricultural water supplies, particularly in water-scarce countries (Qadir et al., 2007). One of the major types of marginal-quality water is the **wastewater from urban and peri-urban areas**. In Pakistan 26% of national vegetable production is irrigated with wastewater (Ensink et al., 2004). In Ghana, informal irrigation involving diluted wastewater from rivers and streams occurs on an estimated 11,500 ha, an area larger than the reported extent of formal irrigation in the country (Keraita and Drechsel, 2004).

In the most of these cases, the farmers irrigate with diluted, untreated, or partly treated wastewater. The failure to properly treat and manage wastewater generates adverse health effects. Farmers and their families using untreated wastewater are exposed to health risks from parasitic worms, viruses and bacteria. The potential **health risks and environmental impacts** resulting from wastewater use for irrigation have been well documented (Angelakis et al., 2003). The overarching goals of water reuse in agriculture are to provide an adequate supply of high quality water for growers and to ensure food safety (Dobrowolski et al., 2008).

Therefore, in developed countries, there are **integrated programs for planned reuse of wastewater**, developed by public institutions, which include specific policies for wastewater management in agriculture. Currently, for example, in Israel the integrated programs for reuse of wastewater have permitted that wastewater accounts for 20% of water resources used in the agriculture. In Europe, municipal wastewater treatment has been required by the Directive 91/271/CEE, and the degree of pre-application treatment is an important factor in the planning, design, and management of wastewater irrigation systems (Pedrero et al., 2010).

The **water quality of treated wastewater** depends to a great extent on the quality of the municipal water supply, nature of the wastes added during use, and the degree of treatment the wastewater has received. Wastewater quality data routinely measured and reported at the wastewater treatment plant are mostly for treated effluent disposal or discharge requirements in terms of gross pollution parameters [e.g., biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS)] that are of interest in water pollution control. In contrast, the water characteristics of importance in agricultural and landscape irrigation are specific **chemical elements and compounds that affect plant growth or soil permeability**. Not all these characteristics are measured or reported by wastewater treatment agencies as part of their routine water quality monitoring program.

Historically, the quality of irrigation water has been determined by the quantity and kind of salt present in these water supplies. Although crops vary considerably in their ability to tolerate saline conditions (Maas and Grattan, 1999), in general, as **salinity** increases in the treated wastewater used for irrigation, the probability for certain soil, water, and cropping problems increases. Establishing a net downward flux of water and salt through the root zone (leaching requirement) is the only practical way to manage a salinity problem (Westcot and Ayers, 1985). Under such conditions, good drainage is essential in order to allow a continuous movement of water and salt below the root zone. Long-term use of reclaimed wastewater for irrigation is not generally possible without **adequate drainage**. Where drainage water salinity exceeds crop threshold levels the water can be blended with freshwater. Blending, which can be done before or during irrigation, enables farmers to extend the volume of water available (Rhoades, 1999; Oster and Grattan, 2002).

**Toxicity** due to a specific ion occurs when that ion is taken up by the plant and accumulates in the plant in amounts that result in damage or reduced yield. The ions of most concern in treated wastewater are sodium, chloride, and boron. The source of boron is usually household detergents or discharges from industrial plants. Chloride and sodium also increase during domestic usage, especially where water softeners are used. For sensitive crops, toxicity is difficult to correct without changing the crop or the water supply. The problem is usually accentuated by severe (hot) climatic conditions (Westcot and Ayers, 1985).

In addition to their effects on the plant, **sodium in irrigation water may affect soil structure** and reduce the rate at which water moves into the soil as well as reduce soil aeration. If the infiltration rate is greatly reduced, it may be impossible to supply the crop or landscape plant with enough water for good growth. A permeability problem usually occurs in the surface few centimeters of the soil and is mainly related to a relatively high sodium or very low calcium content in this zone or in the applied water (Westcot and Ayers, 1985). At a given sodium absorption rate (SAR), the infiltration rate increases as salinity increases or decreases as salinity decreases. Therefore, SAR and ECw should be used in combination to evaluate the potential permeability problem. Sometimes, treated wastewaters are relatively high in sodium and the resulting high SAR is a major concern in planning wastewater reuse projects.

The **nutrients in treated municipal wastewater provide fertilizer value** to crop or landscape production but in certain instances are in excess of plant needs and cause problems related to excessive vegetative growth, delayed or uneven maturity, or reduced quality. Nutrients occurring in important quantities include nitrogen and phosphorus and occasionally potassium, zinc, boron, and sulfur (Westcot and Ayers, 1985). The nutrients in reclaimed wastewater can contribute to crop growth, but periodic monitoring is needed to avoid imbalanced nutrient supply.

To avoid health hazards and damage to the natural environment **wastewater must be treated** before it can be used for agricultural and landscape irrigation (Pereira et al., 2002). The effluent for reuse must comply with reuse standards to minimize environmental and health risks (WHO, 2006). With regard to health, the reuse criteria refer mainly to fecal coliform content. Adequate environmental control and effluent reuse requires extensive investment in treatment facilities and disposal and reuse systems. The required quality of effluent will depend on water uses, crops to be irrigated, soil conditions and the irrigation system (Pereira et al., 2002).

Reuse criteria can be relaxed somewhat when **using drip irrigation (DI)** and primarily **subsurface drip irrigation (SDI)** because the **soil acts as a complementary bio-filter** and there is no contact between the effluent and workers or the plant parts above the soil (Oron et al., 1999). An SDI system can reduce the need for costly wastewater treatment, protect against environmental contamination and enhance efficient water use for many crops. This system provides better control of the application rate and distributes effluent uniformly, thereby minimizing groundwater contamination risks. Oron et al. (1999) showed that soil contamination is reduced when using subsurface drip irrigation, besides higher corn yield obtained under SDI. Moreover, a subsurface drip system is installed in the root zone, where effluent meets some or all of the irrigation demand of turfgrass and other landscape plants (Jnab et al., 2001).

In relation to the **agronomic performance of the application of treated municipal wastewater** (TMWW) in irrigated agriculture, Pedrero et al. (2010) reviewed some results obtained by several researchers in Southern Europe. For example, Kalavrouziotis et al. (2005a) studied the effects of the treated municipal wastewater (TMWW) on the **accumulation of heavy metals** in A. cepa (onion) and L. sativa (lettuce), showing that generally higher levels of heavy metals were accumulated in lettuce than in the onion  but without significant differences with the corresponding ones obtained under fresh irrigation water. Similarly, Kalavrouziotis et al. (2008) studied the effects of TMWW on Brassica oleracea, concluding that TMWW should be used for irrigation under a **continuous laboratory control of the wastewater** in order to prevent any undesirable accumulation of toxic metals in the soil and plants, and with **improved wastewater treatment methods** in order to produce effluents having a microbiological load within the WHO allowed limits (WHO, 2006).

Segura et al. (2001) presented the results of a study conducted on melon (C. melo L.) on a sand-mulched soil under greenhouse conditions in a spring cycle (124 days), comparing the application of wastewater with the ground water normally used in irrigation. The use of wastewater to fertigate C. melo had positive effects on the addition of fertilizer since the **application of total N and K was reduced by 40.8 and 17.8%**, respectively. Microbiological analysis of fruits showed no contamination by indicator microorganisms (E. coli) even in fruits in contact with soil.

The **good agronomic attitude** of reclaimed wastewater irrigation in horticulture crops has been also shown in other interesting experiments, such as in Manas et al. (2002) on lettuce (L. sativa L.) and Cirelli et al., (2012) on tomato and eggplant. Palacios et al. (2005) performed a 2-year subsurface drip irrigation (SDI) using reclaimed wastewater irrigation, cultivating alfalfa (M. sativa). Although saline and sodic water was used, irrigation with SDI led to high forage yields, thus demonstrating the feasibility of SDI using a secondary effluent was demonstrated according to the authors.

Aucejo et al. (1997) reported boron **toxicity** in a citrus plantation in Valencia, irrigated with a mix of surface water, groundwater and treated wastewater. However, Reboll et al. (2000) after studying for 3 years the effect of treated wastewater in Navelina orange trees, observed that both growth and fruit quality parameters were unaffected by the high levels of sodium, chloride and boron in wastewater. It was observed that chlorides, sodium and boron foliar concentration did not exceed toxicity levels. Similar results were obtained by Pedrero and Alarcón (2009) evaluating the effects of applying treated wastewater on citrus trees.

Lopez et al. (2006) reported results of the application of TMWW on a drip-irrigated olive orchard grown in a sandy loam soil in southern Italy. Compared to the olive trees grown in rainfed conditions, irrigation caused mitigation of the alternate bearing phenomenon and an **average yield increase** of 50% (about 11 t $ha^{-1}$). Irrigation practice improved fruit characteristics such as weight and flesh to pit ratio which are very important parameters for table olives. With regards to a sustainable soil management, total organic matter (expressed as COD) distributed on the soil by the treated wastewater was, on average, 0.12 t $ha^{-1}$; this amount and the one coming from other organic sources internal to the olive orchard (old leaves, pruning material and grass cover) could produce about 2.3 t $ha^{-1}$ $y^{-1}$ of humus. Faecal coliforms tended to be higher in the irrigated soil, it seemed not to be able to go deep into the soil profile and to spread over the wet area under the dripper. No faecal contamination was recorded on the fruit picked directly from the canopy.

# 5. Energy saving technologies

## 5.1. Variable speed pumps for irrigation

Quite often, the topography of an irrigation district, together with the location of water resources and the need to guarantee a minimum pressure head at the hydrants for appropriate on-farm irrigation, force the designer to plan the installation of a pumping station at the upstream end of the pressurized distribution network. The whole irrigation system (pumping station and irrigation network) is designed to meet the peak irrigation demand. Such an irrigation demand is strongly variable during the irrigation season and the peak is usually limited only to few days. This means that **the pumping station is oversized during most of the irrigation season** (Lamaddalena and Piccinni 1993; Ait Kadi et al. 1998); i.e., during the off-peak periods the pressure head required at the upstream end of the distribution network is much less than that provided by the pumping station. In addition, pumping stations often operate inefficiently (Hla and Scherer, 2001).

All of these imply a much higher energy cost than the other related costs. In fact, **energy consumption** dominates the life cycle cost and can easily reach 90% of the whole life cost of a pumping system (Graham, 2007). Therefore, in principle, there is some important room for energy saving. Some of the inefficiencies may be certainly reduced through appropriate maintenance, while the fact that the pumping station is over-sized for most of the irrigation season may be approached by combining appropriate modeling and variable speed drive technology.

**Variable speed drive (VSD) technology** is used to control the speed of the pump, and consequently to reduce the pressure head of the pump depending on the discharge demanded upstream (Lamaddalena and Piccinni, 1993; Tolvanen, 2008). This technology has the potential to enhance the efficiency of the whole system by consuming the minimum required energy through adjusting the power driving the pump depending on the actual demand rate. Lower flow rates and head also increase pump bearing and seal life, by reducing the hydraulic forces and vibrations/noise acting on the components in motion (e.g. impeller, piston, diaphragm).

**Figure 27** Variable Speed Pump

Nowadays, there are still many barriers to the full implementation of this technology (Pemberton, 2005): short of knowledge about the performance of variable speed pump control; perception that a VSD is more expensive than the classical pump control; concerns about the reliability of the electronic devices. Nevertheless, the technology of variable speed drives has considerably improved during the last years (Pemberton, 2005) and the use of these pumps in irrigation systems has been increasing.

Therefore, the use of this technology **in combination with appropriate modeling** to generate the characteristic curve of the network (i.e., the required pressure head at the pumping station as related to the discharge demanded into the network), deserves more detailed studies in order to better quantify energy saving for on-demand irrigation systems. Moreno et al. (2009) developed a new methodology for obtaining the characteristic pump curves minimizing the pumping station costs. Planells Alandi et al. (2001) proposed a methodology for pumping selection and regulation in water distribution networks.

Several works have been published on this subject in the last few decades on **potential energy savings**. Lamaddalena and Piccinni (1993) showed that using variable speed pumps in two Italian irrigation districts, around **20% of energy** could be saved. Ait Kadi et al. (1998) demonstrated that around **25% of energy** can be saved in an irrigation district in Morocco using the variable speed pump technology. Field tests made by Hanson et al. (1996) on five pumping stations serving different irrigation networks showed that variable speed pumps allow saving from **32 to 56% of energy** compared to classical pumps regulation. More recently, Lamaddalena and Khadi (2012) demonstrated that in comparison with the current pumping station regulation, **energy savings of about 27 and 35%** may be achieved for the two Italian districts (located in the CS area of Capitanata).

## 5.2. Network sectoring and dynamic pressure regulation

In arid and semi-arid regions, one way to achieve improved irrigation efficiency is related with the replacement of the obsolete open channel distribution networks by on-demand pressurized networks. This change appears to be quite effective. **Conveyance efficiencies** are significantly improved from typical values of 60–70% for open channels to values **close to 100% for pressurized networks** (Rodrıguez Dıaz et al., 2008). Furthermore, these new systems allow farmers to use more efficient on-farm irrigation systems such as trickle irrigation or sprinklers since they receive water at their hydrants at suitable pressures.

Another advantage is **demand flexibility**. Open channel flow delivery provides pre-arranged demand, where users request water some time in advance with limited flexibility in its duration and flow (Plusquellec, 2009). Modern pressurized networks are usually designed for on-demand functioning, so water is continuously available to farmers (Rodrıguez Dıaz et al., 2007a; Pulido Calvo and Gutierrez Estrada, 2009). As a result they can apply the right amount of water when required and do not have to wait for rotation and specifically programmed irrigation schedule. Also these systems can be **easily automated** and give farmers the **possibility of remote scheduling**. This has led to water consumption being dramatically reduced in

Southern Spain where their introduction has **reduced water consumption up to 50%** (Rodrıguez Dıaz et al., 2008).

But in return the **pressurized networks require large amounts of energy for their operation**. For example in Spain, where an ambitious modernization plan of irrigation schemes has been carried out, Corominas (2009) reported than while water use has been reduced from 8,250 to 6,500 $m^3$/ha (-21%) from 1950 to 2007, the energy demand was increased from 206 to 1,560 kWh/ha (+657%) in this period. Rodrıguez Dıaz et al. (2009) reported that with pressurized networks energy costs can average 25% of the total management, operation and maintenance (MOM) costs, but in some specific cases this ratio can rise to 50%. Total MOM costs move from average values of 0.02 V $m^{-3}$ for open channel networks to more than 0.10 V $m^{-3}$ for pressurised networks because of not only their energy requirements but also their higher maintenance, operation and amortization costs. In the traditional open channel systems energy costs were not significant as only small elevations of water were required for the distribution channels.

With the modernization process, irrigation districts are moving from an inefficient system in the use of water that is very efficient in its use of energy, to **a more efficient use of water but** clearly with **reduced energy efficiency**. Thus, several authors have highlighted the necessity of reducing the energy requirements **by improving the performance** of the different irrigation network's elements such as the pumping efficiency, optimum network's design, on-farm irrigation systems or using renewable energy resources (Moreno et al. 2007, 2009; Pulido-Calvo et al. 2003; Abadia et al. 2008; Vieira and Ramos 2009; Daccache et al. 2010).

Among existing measures to optimize energy demand in pressurized networks, there are **network sectoring** according to homogeneous energy demand sectors and organizing farmers in irrigation turns, pumping station adaptation to several water demand scenarios, detection of critical points within the network and energy audits (IDAE 2008). Rodriguez Diaz et al. (2009) developed a methodology for evaluating the energy savings measures proposed by IDAE (2008) and tested them in the irrigation district of Fuente Palmera (FP) (Southern Spain). Thus, **potential energy savings** were calculated for each measure. In that study, sectoring was the most effective measure with average potential **savings of around 20%**. This is consistent with other authors' findings (Sanchez et al. 2009; Jimenez Bello et al. 2010).

Carillo Cobo et al. (2011) developed a **methodology for optimal sectoring**, by grouping similar hydrants in homogeneous groups according to the distance to the pumping station and their elevation, using cluster analysis techniques and certain dimensionless coordinates, and using a specific algorithm to search for the best monthly sectoring strategy that accomplishes supplying the actual irrigation demand under minimum energy consumption conditions. This methodology was applied to two Spanish irrigation districts, and results showed that organizing the networks in sectors, **annual energy savings of 5-8%** were achieved, and these savings rose **up to 9-27%**, respectively when the local practices (deficit irrigation) were taken into account. Thus, they confirm that water and energy efficiency need to be considered together.

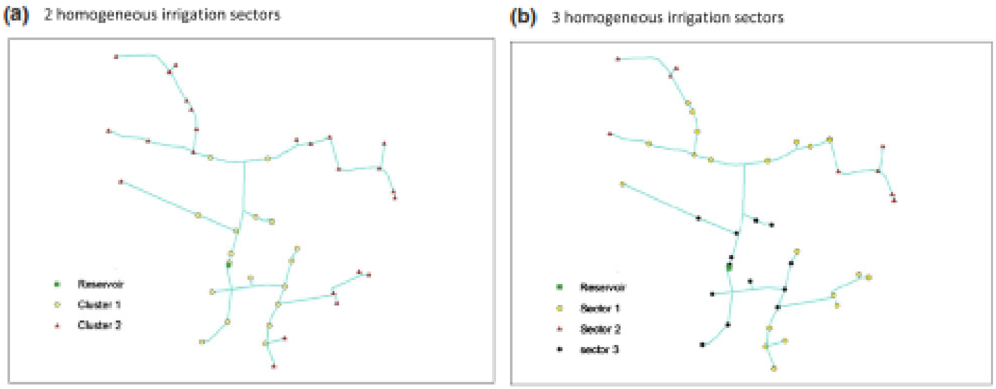


**Figure 28** An example of alternative network sectoring applied to an pressurized irrigation district (from Carillo Cobo et al., 2011)

Diaz et al. (2009) analyzed an Irrigation District in Southern Spain equipped with variable-speed pumps and simulated four alternative management scenarios for several levels of water demand. Results showed that substantial reductions in the power requirements at the pumping station along with **energy saving of up to 27%** could be achieved by adopting techniques such as **pressure dynamic regulation and sectoring**. Moreno et al. (2010a) compared the operational costs of four irrigation networks, two operating on-demand and two on rotational delivery schedule and developed a tool to determine the most appropriate variable-speed pumping station management. Improvements in **energy efficiency between 3.5 and 24.9%** were achieved with higher values occurring when irrigation networks operated under rotation delivery schedule. Moreno et al. (2010b) developed a DSS for analyzing energy saving options on 15 Spanish WUAs and proposed measure to save **around 10% of energy**.

Jimenez-Bello et al. (2010) demonstrated that, in an irrigation system in Spain where water is supplied by a pumping station, the current criteria used to create irrigation sectors do not guarantee that pumping sets work in the most efficient manner, despite the use of variable frequency drives. They developed a methodology, using a genetic algorithm and a hydraulic network model, to group intakes into sectors to minimise energy consumption. They showed that **energy savings around 36%** could be possible, and operational network conditions can be improved by guaranteeing at least the minimum pressures at the hydrants.

# 6. Eco-friendly agronomic practices

## 6.1. Cropping pattern changes

Water available for plant transpiration and biomass production depends upon resource level (soil stored water, rainfall, irrigation) and **crop management systems** (pattern of water use throughout the growing season) including crop/variety choice (Figure 29). The challenge of water management at the **crop level** is to match the time-course (and total amount) of natural and irrigation resources with crop requirements by increasing the resources, moderating plant requirements and/or increasing soil water extraction (Debaeke and Aboudrare, 2004).

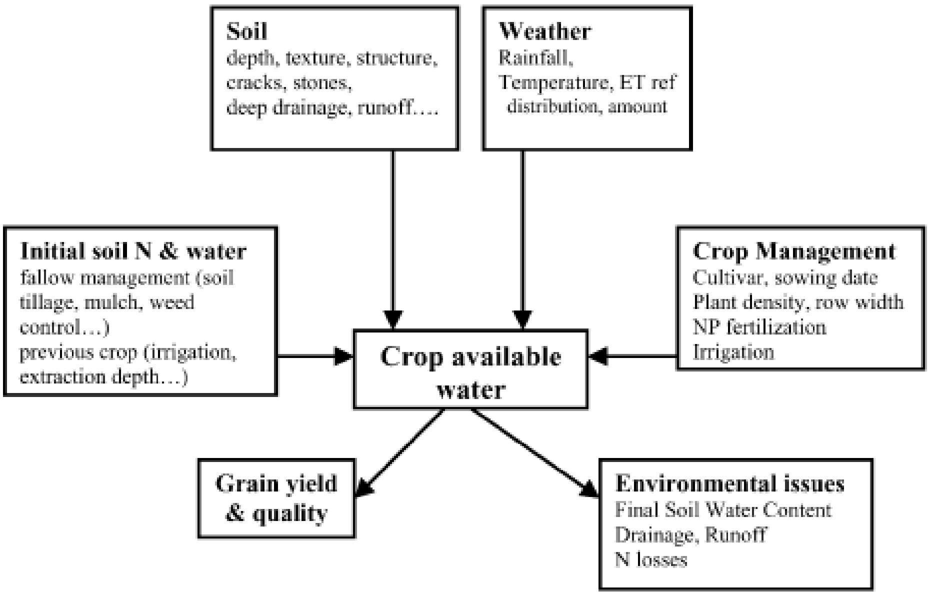


**Figure 29** An example of the determinants of crop available water, crop production and their relation with environmental issues (Debaeke and Aboudrare, 2004)

### 6.1.1. Crop and variety selection

One of the most important crop management strategies under conditions of water limitations is the appropriate **selection of crop species and varieties** adapted to the **timing, amount and frequency of rainfall**. Rainy season and growing season should be matched to optimize the capture of water available for transpiration and to escape water stress during the water-sensitive phases (e.g. choice of autumn-sown crops in Mediterranean regions). Drought escape, whereby a crop completes its life before the onset of terminal drought, is often regarded as the primary strategy of crop adaptation to water-limited environments (Loss and Siddique, 1994). The wide diversity in the length of crop and cultivar growing periods offers ample opportunities for this adjustment. For major field crops, there are many examples where the use of early maturing (or early flowering) cultivars increased and stabilized grain yield, especially in conditions of terminal drought (Woodruff and Tonks, 1983; Stapper and Harris, 1989; Fereres et al., 1993, 1998).

**Improved varieties** well adapted to specific conditions can improve soil water use and increase yield. These varieties should be **tolerant to abiotic stresses** such as cold, drought and heat, and biotic stresses such as diseases and insects (Dakheel et al. 1993). Varieties with **vigorous early growth** and a **deep root system** would use soil water at a rapid rate and would decrease evaporative losses (Gregory 1991).

Selected cultivars **adapted to different rainfall zones** generally combine high yield potential and stress tolerance and hence high yield stability (Nachit et al. 1992). Based on on-farm trials in the highlands of Turkey, the highest yielding wheat variety with recommended cultural practices provided 48% more grain yield than a local variety under recommended practices, while the increase was about six times compared with the local variety under local practices (Durutan et al. 1987). Similarly in the lowlands of Syria, the improved bread wheat varieties Cham 4 and 6, gave 30-51% grain yield increase compared to the older variety Mexipak 65, under different water and N regimes (Oweis et al. 1998). These results also show that improved cultivars may not give increased yields unless **appropriate cultural practices** are applied in a timely manner.

The choice of **drought-tolerant crops (and varieties)** is another means of adaptation to drought-prone environments and of increasing *WUE*. The agronomic traits useful in crop breeding for drought resistance have been well documented in relation with the target environment (Ludlow and Muchow, 1990; Loss and Siddique, 1994; Vannozzi et al., 1999; Sinclair and Muchow, 2001). Ludlow (1989) reviewed three main genotypic adaptations to water-limited environments: (a) drought escape, whereby the crop completes its life before the onset of terminal drought, (b) drought avoidance, where the crop maximizes its water uptake and minimizes its water loss, and (c) drought tolerance, where the crop continues to grow and function at reduced water contents. For instance, the major traits of adaptation for cool season grain legume species in low-rainfall Mediterranean-type environments are early flowering and pod and seed set before the onset of terminal drought. Rapid development, together with early ground cover and dry matter production, allows greater water use in the post-flowering period: examples are pea and faba bean, as compared with other legumes (Siddique et al., 2001).

**Biomass transpiration water use efficiency ($B\_WUE_T$)** is a relatively stable parameter for a given crop in a given environment (Tanner and Sinclair, 1983; Steduto et al., 2007). The value of $B\_WUE_T$ is higher for C4 crops such as maize and sorghum than for C3 crops like sunflower, wheat and legumes (Figure 30). However, $B\_WUE_T$ is higher during periods of low vapor pressure deficit (VPD), as in the cool winter months. Thus, Fereres et al. (1998) measured higher values of WUE for autumn-sown sunflower in Spain and Cooper and Gregory (1987) for chickpea in Syria. In the latter case, $B\_WUE_T$ increased from 19 to 23 kg $ha^{-1}$ $mm^{-1}$ from spring to winter sowing. Similarly, $B\_WUE_T$ could be increased by using early cultivars tolerating low temperatures.

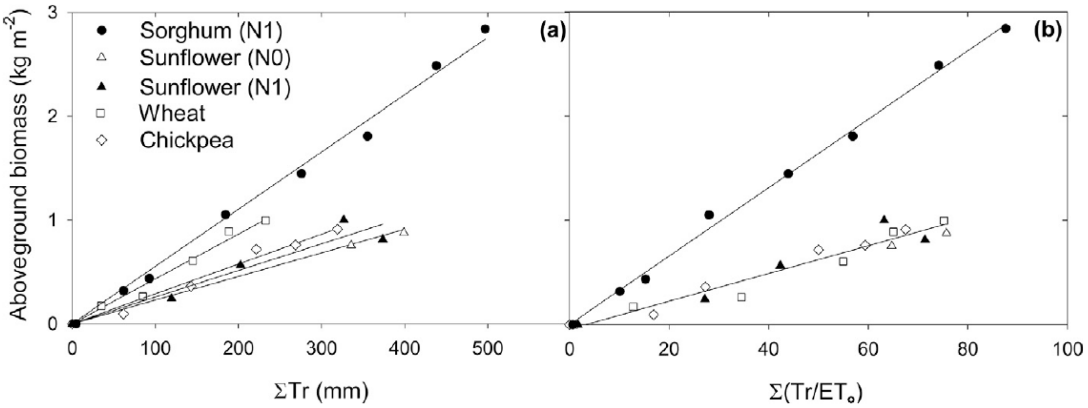


**Figure 30** Relationships (a) between above-ground biomass and cumulative transpiration and (b) between above-ground biomass and cumulative normalized transpiration (with respect to reference evapotranspiration), during the cropping cycle of C3 (sunflower, wheat and chickpea) and C4 species (sorghum) (from Steduto and Albrizio, 2005).

Average **WUE values estimated for most of the crops** are reported in the selected literature for the Continental and Mediterranean area (e.g. Zwart and Bastiaanssen, 2004; Katerji et al., 2008; Karrau and Oweis, 2012; ), although for some crops (like perennial ones) very few information and experimental data are available. The most frequent values of WUE (generally estimated as the ratio between actual yield and crop evapotranspiration) have been observed to fall in the following ranges:

i. for **oilseed, protein and fibre crops** (such as sunflower, soybean, leguminous crops, cotton, etc.) between **0.5-1.0**;
ii. for **C3 cereal crops** (such a winter and spring wheat, barley) between **0.6-1.6**;
iii. for **C4 cereal crops** (such as sorghum and maize) between **0.7-2.7**;
iv. for **industrial crops** (such as sugarbeet) between **6.0-7.0**;
v. for **vegetables** (such as tomato, potato, etc.) between **8.0-20.0**;
vi. for **fruit crops** (such as grape, citrus etc. ) between **16.0-18.0**.

The generally **lower productivity of oilseed and protein crops** (such as sunflower, cotton, faba bean and olive), is consistent with their seed/fruit composition, accounting for higher oil or protein content (rather than starch), which is more expensive in terms of energy needed for biosynthesis. On the other side, **productivity of vegetables and fruit crops is generally higher** than for those with dry yield weight (like grain crops, cotton, sunflower, faba bean), because marketable products are related to fresh weight (vegetables and fruit crops, sugarbeet).

### 6.1.2. Crop management practice (early sowing, crop rationing).

Crop management under water-limited conditions can be referred to two alternative strategies: (a) water-stress alleviation or moderation, by the means of irrigation, and (b) optimal crop water use pattern, by reducing soil evaporation and increasing the contribution of transpiration (e.g. during grain filling period or water-sensitive stages). More rainfall can be captured by better **adjustment of the cropping pattern to the rainfall season**. In semi-arid Mediterranean regions, shifting from summer cereals to winter ones allows the efficient use of winter and spring rainfall (Oweis and Hachum, 2003). Under conditions of water shortages, cultivation strategies can be adopted to accumulate sufficient biomass early in the season without depleting available soil water to the extent that shortages occur later in the season (Debaeke and Aboudrare, 2004). For the most typical grain crops, for example, with a short vegetative phase and an early flowering time, enough water may be left in the soil to guarantee a high harvest index.

Transpiration (T) by annual crops in Mediterranean-type climates is offset or delayed in relation to incoming rainfall. **Earlier sowing** to more closely match incoming rainfall and reduce soil evaporation will increase yield and rainfall-use efficiency (French and Schultz, 1984a; Siddique et al., 1998). Eastham and Gregory (2000) showed that earlier planting of wheat and lupin crops in a Mediterranean-type environment did not affect the total evapotranspiration, but reduced soil evaporation, particularly early in the season before the leaf area of the later-sown crop reached full ground cover. In some cases, this resulted in higher yields and water-use efficiency (and rainfall-use efficiency) of the early-sown crops.

Early sowing of crops is a very important means of **maximizing crop yield and *WUE***. In fact, increasing the early growth of the canopy when the soil surface is usually damp and the vapour pressure deficit is low has proved effective in increasing WUE. Within the concept of improved WUE, water transpired by crops should be increased relative to evaporation from the soil surface. Therefore, directing biomass production into **periods of lowest atmospheric demand** confers an advantage (Gregory 1991, Gupta 1995). In the winter rainfall environment, despite temperature limitations to growth, early sowing (late fall, early winter) allows as much as possible of the crop's growth cycle to be completed within the cool, rainy winter/early spring period (Cooper and Gregory 1987).

As an example, attempts made to persuade farmers to move from spring to winter sowing of chickpea gave 30-70% yield increases (Erskine and Malhotra 1997) (Figure 31). Grain yield increase of 20-25% was obtained by sowing lentil in mid-November instead of early January (Silim et al. 1991, Pala and Mazid 1992b). Winter sowing produces plants with a larger vegetative frame capable of supporting a bigger reproductive structure, leading to greater WUE and increased productivity (Cooper and Gregory 1987). Keatinge and Cooper (1983) reported that WUE of winter-sown chickpea might be more than 100% higher than in the spring-sown crop.

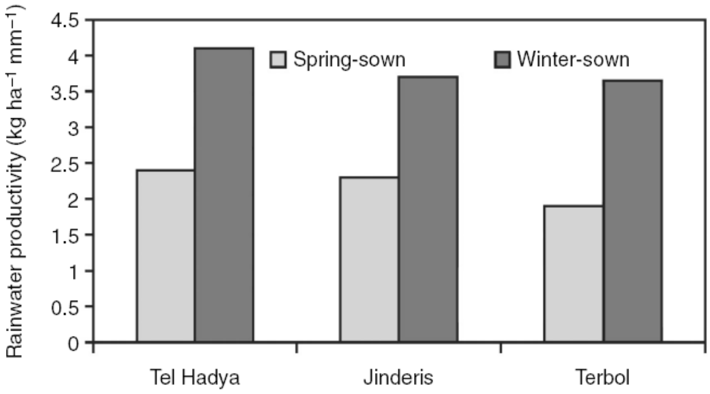
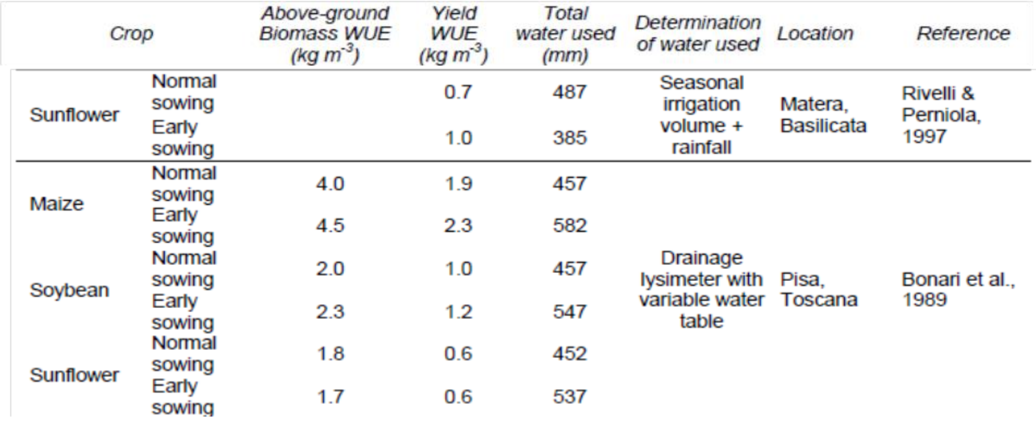


**Figure 31** Rainwater productivity of winter and spring-sown chickpea in Northern Syria (Erskine and Malhorta, 1997)

Early sowing depends also on the tillage/crop rotation system employed. In Western Asia and North Africa (WANA) highland areas, proper fallow tillage practices and sufficient precipitation will improve stand establishment of early sown crops and result in higher yield by extending the period of vegetative growth under cereal-fallow rotation systems (Pala 1991). In the lowlands of the Mediterranean regions, where continuous cropping (pure cereal or cereal-legume rotations) is common, mid-November was found to be an optimum sowing date for cereals (Keatinge et al. 1986; Acevedo et al. 1991), and yield was found to decline by 200-250 kg $ha^{-1}$ for every week delay from the optimum. Pala et al. (2000) reported that wheat grain yield increased by 14% (10-year average, range 0-109%) with early sowing in November compared to late sowing in December. Lentil was even more responsive than wheat. Yield increased by 61% (10-year average, range 0 to 12-fold) by sowing in mid October instead of December. Mean WUE increased by about 10% in wheat and 48% in lentil (Pala et al., 2000).

Bonari et al. (1989) found that an early sowing of ten days increased the yield of 54, 35 and 17% for maize, soybean and sunflower, respectively (Table 14). Hence also biomass and yield water use efficiencies increased significantly in all the crops except of sunflower, although the water use in early sowing was higher than in the normal sowing. Differently, Rivelli and Perniola (1997) dealing with sunflower found that the increase in yield water use efficiency was strictly linked to the decrease in the amount of water used, as effect of a reduced evaporation from the soil.

**Table 14** Effect of early sowing on biomass water use efficiency, yield water use efficiency and total water used (from Todorovic et al., 2007)



| Crop | | *Above-ground Biomass WUE ($kg\ m^{-3}$)* | *Yield WUE ($kg\ m^{-3}$)* | *Total water used (mm)* | *Determination of water used* | *Location* | *Reference* |
|---|---|---|---|---|---|---|---|
| Sunflower | Normal sowing | | 0.7 | 487 | Seasonal irrigation volume + rainfall | Matera, Basilicata | Rivelli & Perniola, 1997 |
| | Early sowing | | 1.0 | 385 | | | |
| Maize | Normal sowing | 4.0 | 1.9 | 457 | Drainage lysimeter with variable water table | Pisa, Toscana | Bonari et al., 1989 |
| | Early sowing | 4.5 | 2.3 | 582 | | | |
| Soybean | Normal sowing | 2.0 | 1.0 | 457 | | | |
| | Early sowing | 2.3 | 1.2 | 547 | | | |
| Sunflower | Normal sowing | 1.8 | 0.6 | 452 | | | |
| | Early sowing | 1.7 | 0.6 | 537 | | | |

The most feasible way to reduce soil evaporation (*E*) is probably to increase the early growth of the crop canopy. Early sowing, together with some plant characteristics (early vigour, crop morphology) and management practices (increased fertilizer input, planting density and reduced row width), is effective in supporting the **reduction of *E/ET*** (Loss and Siddique, 1994; Soltani and Galeshi, 2002). Additionally, because of the rapid canopy closure, **crop competitiveness with weeds** should be increased (thus reducing the weed transpiration component).

However, early planting is not always an advantage (Eastham and Gregory, 2000). If appropriate cultivars are not available, early planting increases the risk of damage by frost during flowering and there is a greater vulnerability to terminal drought due to increased biomass and water use by anthesis, thereby reducing yields (Riffkin et al., 2003).

On the other side, Cooper et al. (1987) pointed out several difficulties in applying these principles in dry areas. Early sowing is **risky if rains are unreliable** and crop failure may result from an initial germination that is not followed by sufficient rainfall. Maximizing ground cover during winter by using high planting densities may conflict with the need to conserve sufficient water for grain filling. Gregory et al. (2000) showed that the scope for reducing *E* depends on soil type, being greatest in clay soils in locations with frequent rain showers and low evaporative demand, and least on sandy soils in regions with sporadic rainfall and high evaporative demand.

Encouraging a more even **seasonal water requirement** is an effective approach when water is plentiful during the first half of the season and becomes short during the second half of the season. Under such conditions, if a dense canopy develops when water is available, it contributes to early crop senescence when water becomes scarcer. Passioura (1976) concluded that the grain yield of wheat growing on a fixed and limiting supply of water can be substantially increased by forcing the plants to save water for post-anthesis growth. Yield and HI increased with the fraction of water transpired after anthesis (Figure 32). When leaf area index (LAI) is kept below 3, transpiration increases linearly with LAI when the soil surface is dry (Ritchie, 1972). Genotypic traits were proposed for wheat by Richards and Passioura (1989) to improve the seasonal pattern of water use.

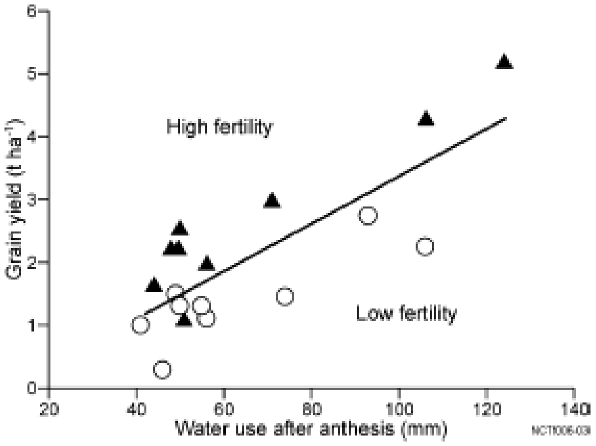


**Figure 32** Relationship between grain yield and water use between anthesis and maturity for barley (from Turner, 2004)

The term '**crop rationing**' was suggested by Debaeke and Nolot (2000) to describe a management option that modifies the seasonal water balance by reducing crop water needs to the amount available from rain and irrigation, based on the early reduction of crop water uptake in order to save water for the most susceptible growth stages. The objective is to save water early in the season to leave sufficient resources for grain filling or at least during the most sensitive periods (e.g. at anthesis, when WUE for grain yield may drop in case of severe water stress).

Reducing crop water requirement could be achieved by **specific crop management strategies**, such as low plant densities, wide inter-rows, plant thinning (or defoliation) and moderate N fertilization resulting in N deficiency during shooting (Debaeke and

Aboudrare, 2004). A crop management solution would be to sow a crop (or a cultivar) with a low LAI at anthesis but covering the soil rapidly, or one with low stomatal conductance which might conserve soil water during the periods when the soil water deficit is still small. Choosing an early flowering cultivar or sowing late may result in similar crop rationing. But as suggested by Fischer (1979) for wheat, the choice of a given precocity or a given level of crop rationing is a compromise between attaining a sufficient biomass and grain number at anthesis without reducing soil water content too markedly at early grain filling. Fereres et al. (1998) showed that winter sowing of sunflower increased *WUE* (because of higher radiation use efficiency) and *T* (because of a higher LAI), and that this approach, which increases total biomass but reduces HI, represented the best compromise anyway; the authors concluded that transpiration should be increased in priority under water-limited conditions.

### 6.1.3. Super-high density plantation (in olive production)

Olive (*Olea europaea* L.) is the most extensive tree crop of the Mediterranean basin and has been traditionally cultivated in marginal areas with low density under rainfall conditions. Olive trees are well known to be resistant to drought, but irrigation can improve yield (Lavee et al., 1990; Girona, 1996; Moriana et al., 2003). **New orchards are drip irrigated and planted at higher densities**, achieving **greater yields** with reduced alternate bearing behavior (Beede and Goldhamer, 1994). The surface covered by these orchards has increased exponentially since the early 1990's, being currently over 100,000 ha worldwide (Fernandez et al., 2013).

The super-high-density (SHD) system (1500–2500 trees per/ha) was developed within the past decade to use over-the-row **mechanical harvesters to reduce the costs** of hand harvesting and to bring orchards into production within only a few years after planting. In order to limit tree size within this system and accommodate the harvester, vegetative vigor of the tree must also be managed. Shifting from medium-high density to super-high density orchards also implies an **increase of input resources needs**. Moreover, farmers' decision for a new investment based in one system or the other is related with the capacity of investment, yield targets and the soil variability and quality.

**Figure 33** A comparison of traditional (left) and super-high density (right) olive cropping systems.

In Spain, for the best super-high-density orchards located on uplands with deep, Vossen et al. (2007) observed an average production around 4.75 tons/ha in the 3rd year, 6.25 tons/ha in the 4th year, and 8.25 tons per acre in the 6th and 7th years after planting. Significant higher yields are reported by Godini et al. (2013) under experimental conditions.

According to Gimenez-Limon (2013), olive farming represents an important source of income and employment in the rural areas of Andalusia (Spain), which is the most important olive oil-producing region in the world. The **rapid development of high-intensity olive farming**, while increasing socio-economic well-being in Andalusian areas, has also endangered environmental sustainability. Some negative impacts of olive growing are briefly summarized below (Beaufoy and Pienkowski, 2000; Gómez-Calero, 2009; EC, 2010; CHG, 2010):

- **Soil erosion**. This problem has been accentuated by the expansion of olive cultivation into soils with unfavourable conditions for agricultural production and aggravated by inadequate management, particularly with regard to the systematic of the natural vegetation land cover (e.g. 52.7% of the Andalusian olive surface has an erosion rate of over 12 t/ha per year).
- **Loss of biodiversity**. One of the peculiarities of traditional olive cultivation systems was the rich biodiversity associated with cultivation. The presence of trees and underbrush in the form of mosaics provided a diversified habitat where large numbers of insects, birds, reptiles and small mammals found shelter. However, olive production intensification (change in cultural practices and increased use of agrochemicals) and specialization (large monoculture areas) has contributed to a decline in the number and diversity of species.
- **Overexploitation of water resources**. Thirty years ago olive farming was almost exclusively rain fed, but the trend towards intensification has meant that today there are 546,425 ha of irrigated olive trees, representing 35.3% of the Andalusian olive grove surface. Although olive trees have low water needs and the use of highly efficient drip irrigation systems is currently widespread, the total pressure exerted on water resources has been significant, as this single crop is currently consuming about 22% of overall water consumption in the Guadalquivir Basin, the main catchment area of the region. As a result, the satisfaction of the demand for water in Andalusia has been put at risk and a wide range of aquifers and surface water bodies are now overexploited.
- **Diffuse water pollution**. The quality of water flowing the olive agro-ecosystems have suffered as a result of the systematic use of chemicals, including herbicides and fertilizers. Problems of diffuse pollution of rivers, reservoirs and aquifers have arisen, generating several health scares that have resulted in the occasional prohibition of consuming water from reservoirs whose feeding basins are covered with olive groves.

Gimenez-Limon et al. (2013) use Data Envelopment Analysis (DEA) techniques and pressure distance functions to contribute a farm-level assessment of the eco-efficiency of a sample of 292 Andalusian olive farmers (Table 15). They distinguish between managerial eco-efficiency and program eco-efficiency, the latter being associated to the different natural conditions prevailing in the three main olive cultivation systems in the region, namely, traditional rain-fed mountain groves, traditional rainfed plain groves and irrigated intensive groves. Their findings show that eco-inefficient management is a widespread practice across olive farmers, mainly due to widespread **technical inefficiency**.

Table 15 Variables considered for the eco-efficiency assessment of different olive cropping systems (from (Gimenez-Limon, 2012).

| | Traditional mountain groves | | Traditional plain groves | | Irrigated intensive groves | | ANOVA test[a] | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | *F*-stat | *p*-value |
| NET INCOME (€/ha) | 701 | 440 | 891 | 634 | 933 | 476 | 5.16 | 0.006*** |
| ENVIRONMENTAL PRESSURES | | | | | | | | |
| Erosion (t/ha) | 27.1 | 15.0 | 8.9 | 6.5 | 9.2 | 6.1 | 104.23 | 0.000*** |
| Biodiversity (adim.) | 0.372 | 0.120 | 0.510 | 0.279 | 0.410 | 0.177 | 73.84 | 0.000*** |
| Pesticides risk (kg rat/ha) | 3,592 | 2,452 | 5,584 | 4,656 | 3,836 | 2,294 | 10.44 | 0.000*** |
| Water use ($m^3$/ha) | 0 | 0 | 0 | 0 | 750 | 329 | 528.74 | 0.000*** |
| Nitrogen ratio (adim.) | 1.260 | 0.679 | 0.987 | 0.894 | 0.912 | 0.741 | 5.16 | 0.006*** |
| Energy ratio (adim.) | 0.227 | 0.091 | 0.242 | 0.139 | 0.335 | 0.137 | 20.50 | 0.000*** |
| NUMBER OF FARMS | | 96 | | 108 | | 88 | | |

[a] The null hypothesis is that the three samples are drawn from the same population.

*** Significance level $p < 0.01$.

A viable strategy to reduce environmental pressure of SHD orchards on water resources is deficit irrigation (DI). **DI strategy could be the best option for SHD olive orchards**, since problems derived from excessive tree vigour, common in this type of orchards, can be minimized by reduced irrigation. Thus, controlling growth may lead to a regular distribution of the incident solar radiation into the canopy (Connor 2006), and helps to keep the trees at a suitable size for the vineyard type straddle-harvesters commonly used in these orchards (León et al. 2007). Substantial water savings can be achieved when a DI strategy is properly chosen and applied, without penalizing yield and sometimes improving quality (Moriana et al. 2003; Tognetti et al. 2006, 2008). Both sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI) are recommended for olive orchards (Moriana et al. 2003; Iniesta et al. 2009; Ramos and Santos 2009).

There are examples of a variety of irrigation strategies applied to olive orchards with high plant densities, from supplementary irrigation (Proietti et al. 2012) to full irrigation (Pastor et al. 2007). The works by Grattan et al. (2006) and Berenguer et al. (2006) explored the convenience of SDI with different levels of irrigation reduction. According to Fernandez et al. (2013) results of an appropriate RDI treatment showed the best balance between water saving, tree vigour and oil production, with a potential 72% water saving as compared to FI, while the corresponding reduction in oil yield was only 26 %.

Grattan et al. (2006) conducted a 2-year study to determine the effects of different quantities of applied water on the growth and water relations of ‘Arbequina’ olive in a super high-density orchard, and they found that there is a rather broad range between irrigation amounts that maximize production (70–75% ETc) and those that maximize quality (35–40% ETc). The optimal amount is somewhere in between and choice will depend upon a number of factors including the desire to achieve quantity over quality or viceversa (Figure 34).

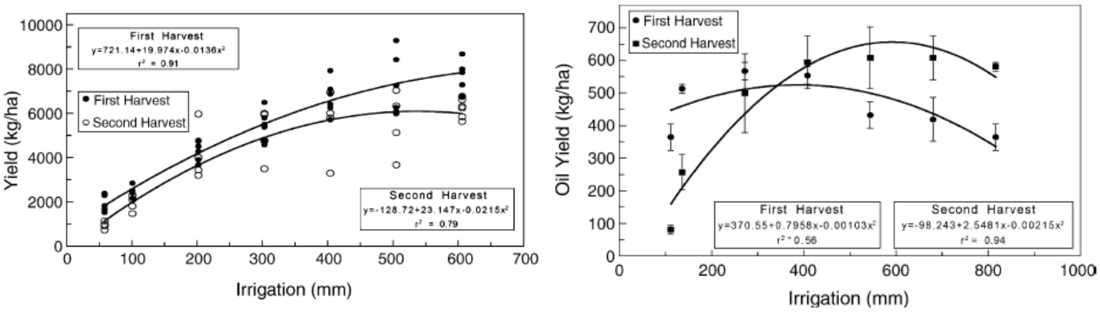


**Figure 34** Olive fruit yield (left) and corresponding oil yield (right) in relation to applied irrigation water, for a SHD olive plantation (from Grattan et al., 2006).

## 6.2. Conservation agriculture and soil management techniques

Worldwide, soil moisture is the main limiting factor in most agricultural systems (Hillel and Rosenzweig, 2002; Debaeke and Aboudrare, 2004). Rainfed agriculture remains the dominant crop and forage production system throughout the world (dry-lands cover more than 50% of the global land surface), and the stability of food and fibre production requires that **precipitation use efficiency** is improved.

In all climates suitable for agriculture, the **water storage capacity of soils** is a crucial property for soil functionality including the productivity function and it is closely correlated with crop yields (Mueller et al., 2010). Modification of the soil surface will lead to changes in the soil water balance in terms of soil water evaporation and infiltration into the soil profile.

**Soil management practices** will ultimately have some effect on how efficiently crops use precipitation as a water supply. Cultivation of agricultural soils has until relatively recently predominantly been achieved by inverting the soil using tools such as the plough. Continual soil inversion can in some situations lead to a degradation of soil structure leading to a compacted soil composed of fine particles with low levels of soil organic matter (SOM). Such soils are more prone to soil loss through water and wind erosion eventually resulting in desertification (Hollande, 2004). This process can directly and indirectly cause a wide range of environmental problems.

In Europe, however, **soil degradation** has only recently been identified as a widespread problem. This may include loss of structure leading to compaction, a decrease in SOM and a reduction in soil organisms, with the subsequent environmental impacts (Figure 35) (Hollande, 2004). Climate change may also exacerbate the problem as rainfall events have become more erratic with a greater frequency of storms and extreme events.

To combat soil loss and preserve soil moisture, soil conservation techniques were developed in USA. ‘**Conservation tillage**’ (CT) involves soil management practices that minimise the disruption of the soil’s structure, thereby minimising erosion and degradation, but also water contamination. Thus, it encompasses any soil cultivation technique that helps to achieve this, including **direct drilling (no-tillage)** and **minimum tillage**. Other husbandry techniques may also be used in conjunction including **cover cropping** and non- or surface incorporation of **crop residues** and this broader approach is termed ‘conservation agriculture’.

On the opposite, the term ‘**conventional tillage**’ defines a tillage system in which a deep primary cultivation, such as mouldboard ploughing, is followed by a secondary cultivation to create a seedbed. Throughout the wetter parts of northern Europe ploughing is still very widely adopted and is a particularly effective method of seedbed preparation on poorly drained soils because it can provide surface drainage and aeration for the topsoil, especially in spring, control weeds and remediate surface compaction.

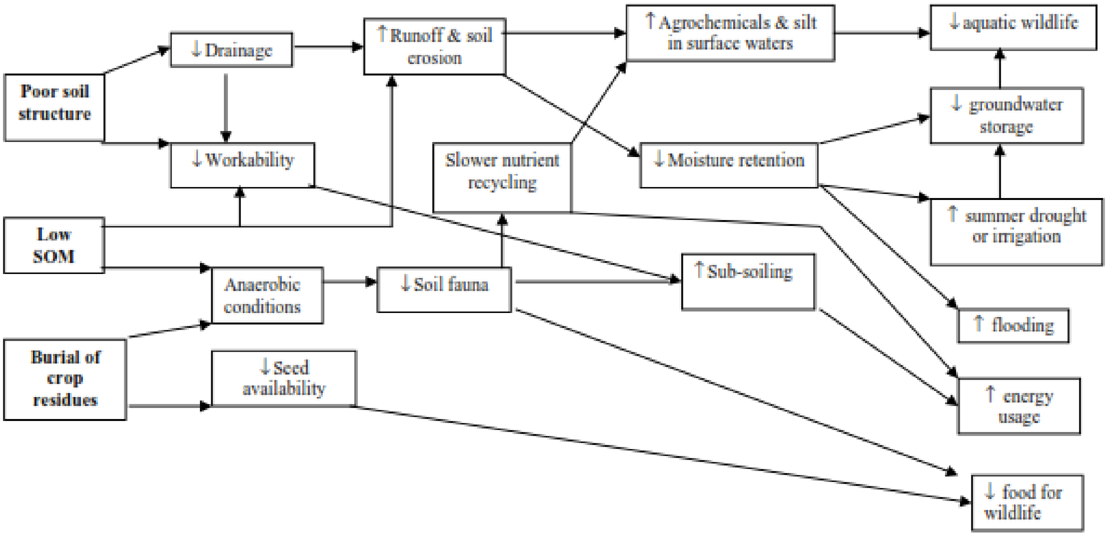
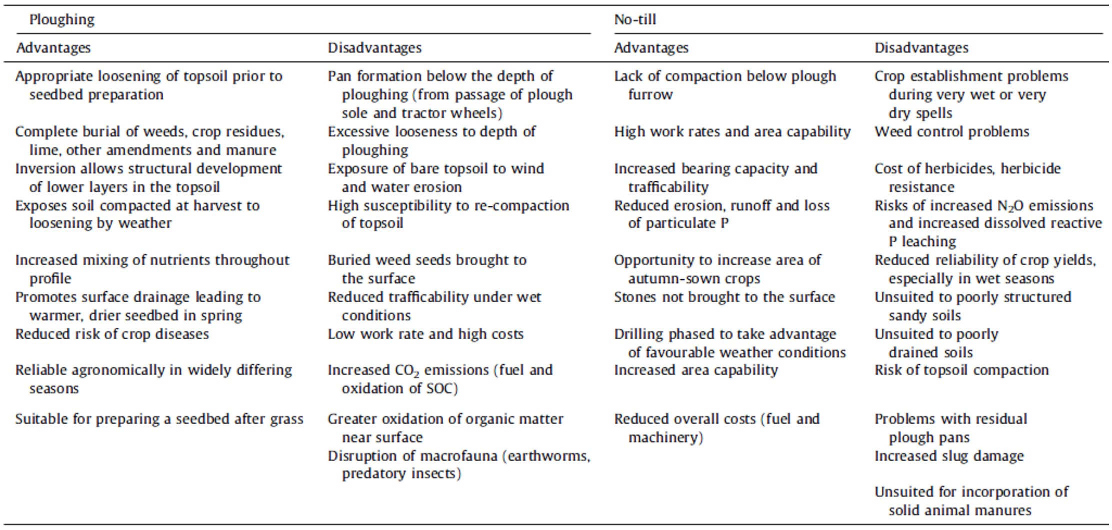


**Figure 35** Processes through which degraded soils affects the environment (from Hollande, 2004).

In south-western Europe the uptake of **no-tillage** is currently increasing because of perceived **environmental advantages and reduced costs**. No-till has generally given equal or higher yields than after ploughing for winter-sown crops. This, combined with savings in tillage costs, especially on larger farms, may act as powerful stimuli to its further adoption. In Mediterranean countries, no-till and the allied preservation of surface residues seem increasingly likely to become standard farming practice because of better economics and improved soil and water conservation.

The relative **advantages and disadvantages of no-tillage and ploughing** depend on a large number of aspects, grouped roughly into agronomic and environmental factors (Tebrugge, 2001). The opinions and choices of farmers related to tillage will be dictated primarily by agronomic factors (Table 16), whereas environmental factors will be relevant to general concerns about soil and landscape protection and climate change. Ploughing may continue to be attractive, especially on smaller farms and where mixed husbandry of crops and animals is practiced, whereas large arable farms may become increasingly well suited to no-till, as well as to intermediate forms of non-ploughing or non-inversion tillage involving reduced depth or intensity of disturbance (Morris et al., 2010).

**Table 16** Relative agronomic advantages and disadvantages of ploughing nad no-till in Europe (from Soane et al., 2012).



| Ploughing | | No-till | |
|---|---|---|---|
| Advantages | Disadvantages | Advantages | Disadvantages |
| Appropriate loosening of topsoil prior to seedbed preparation | Pan formation below the depth of ploughing (from passage of plough sole and tractor wheels) | Lack of compaction below plough furrow | Crop establishment problems during very wet or very dry spells |
| Complete burial of weeds, crop residues, lime, other amendments and manure | Excessive looseness to depth of ploughing | High work rates and area capability | Weed control problems |
| Inversion allows structural development of lower layers in the topsoil | Exposure of bare topsoil to wind and water erosion | Increased bearing capacity and trafficability | Cost of herbicides, herbicide resistance |
| Exposes soil compacted at harvest to loosening by weather | High susceptibility to re-compaction of topsoil | Reduced erosion, runoff and loss of particulate P | Risks of increased $N_2O$ emissions and increased dissolved reactive P leaching |
| Increased mixing of nutrients throughout profile | Buried weed seeds brought to the surface | Opportunity to increase area of autumn-sown crops | Reduced reliability of crop yields, especially in wet seasons |
| Promotes surface drainage leading to warmer, drier seedbed in spring | Reduced trafficability under wet conditions | Stones not brought to the surface | Unsuited to poorly structured sandy soils |
| Reduced risk of crop diseases | Low work rate and high costs | Drilling phased to take advantage of favourable weather conditions | Unsuited to poorly drained soils |
| Reliable agronomically in widely differing seasons | Increased $CO_2$ emissions (fuel and oxidation of SOC) | Increased area capability | Risk of topsoil compaction |
| Suitable for preparing a seedbed after grass | Greater oxidation of organic matter near surface | Reduced overall costs (fuel and machinery) | Problems with residual plough pans |
| | Disruption of macrofauna (earthworms, predatory insects) | | Increased slug damage |
| | | | Unsuited for incorporation of solid animal manures |

**Conventional tillage** roughens the soil surface and breaks apart any soil crust. This leads to increased water storage by increased infiltration into soil as well as increased soil water losses by evaporation compared with a residue-covered surface or an undisturbed surface. Tillage options like breaking of hard pans, deep plowing (Figure 36) and subsoil ripping are able to **increase the soil storage size** (Ehlers and Goss, 2003). Deep plowing can store more water during the rainy periods but, compared with shallow or zero tillage, may **accelerate soil evaporation** during dry periods (Debaeke and Aboudrare, 2004). Ritchie (1971) explained that soil water evaporation is affected by the soil water content of the surface and the degree of plant cover. Tillage moves moist soil to the surface where losses to drying may offset increased infiltration rates. Deep soil ripping with minimum topsoil disturbance promotes **infiltration and deep rooting** of the crop.

In semiarid regions, **bare fallow** (no crop during the growing season) has been considered to be a viable and necessary practice to increase soil water storage. A bare-fallow period can be used to **store water** during one foregone cropping season for the use in the next, but the efficacy of this practice is variable depending on soil depth, structure and texture, weed control and the amount of runoff or soil erosion during the fallow period (Debaeke and Aboudrare, 2004). Improved fallows generally mean the deliberate planting of fast-growing species—usually legumes—that produce easily decomposable biomass and replenish soil fertility, although the magnitude of the yield increment after each successive fallow is variable. However, Stewart and Robinson (1997) have pointed out that only 12–20% of the precipitation in the fallow period is retained in the soil at seeding. O’Leary and Connor (1997a) showed that the amount of water stored in the soil and available to a subsequent crop varied with season, soil type, and management of the fallow land.

### 6.2.1. Conservation agriculture

#### *Conservation tillage*

Conservation tillage (CT) is now commonplace in areas where rainfall causes soil erosion or where preservation of soil moisture because of low rainfall is the objective. World-wide, CT is practised on 45 million ha, most of which is in North and South America but is increasingly being used in other semi-arid and tropical regions of the world (Lal, 2001). **'Minimum'** (or 'reduced') and **'zero'** (or 'no') **tillage** practices are currently spreading throughout the world (Holland 2004; Peigné et al. 2007; Soane et al. 2012).

Reduced tillage corresponds to minimal soil disturbance without soil inversion (in contrast to ploughing). The soil is only worked to a depth of 5–15 cm before seeding. The main goal is to reduce soil disturbance and preserve organic matter (fresh crop residues) at the soil surface or in the first few centimetres of the soil. Zero tillage corresponds to tillage practices without soil disturbance, such as direct seeding into a living crop or mulch. Specific machinery may be used, such as direct seeders, which are comprised of coulter discs or tines for cutting and opening furrows for seeding. In strip or zonal tillage systems, the seedbed is divided between seeding zones that are prepared mechanically or by hand-hoe only where seeds will be planted, and zones that are not ploughed. The undisturbed portion is often also mulched.

**Figure 36** *Left*: conventional tillage (deep ploughing on sloping land). *Right*: zero- tillage and direct sowing on permanent soil cover (from Tebrugge et al., 1999).

Benefits of conservation tillage systems from the ecological point of view are assumed in agricultural practice, administration, advice, and research. Experiences in the application and research of conservation tillage in the US have revealed the beneficial long-term effects of these tillage systems on **soil physical, chemical, and biological properties** (e.g. Hubbard et al., 1994; Karlen et al., 1994). Conservation tillage methods will likely become the favoured approach in many regions of Europe because of economical and ecological influences (Tebrugge and During, 1999) (Figure 37).

In 18 years long-term investigations, Tebrugge and During (1999) compared different tillage options on different soils, and evaluated the effect on the **soil physical properties** most relevant to crop growth and to the protection against undesirable losses of soil and agro-chemicals through erosion and/or leaching. Several soil properties were **improved as a consequence of decreased disturbance and the**

**maintenance of cover by crop residues** in reduced or no-tillage systems. Soils that have undergone long-term no-tillage were characterized by a higher resistance against stress from vehicle load and by a higher stability of aggregates against the impact of raindrops. Lower susceptibility for soil crusting and erosion and a high abundance of vertically oriented continuous earthworm burrows resulted in increased infiltration rates and reduced soil losses. Moreover, losses of agrochemicals via the lateral path may be clearly reduced under no-till conditions.

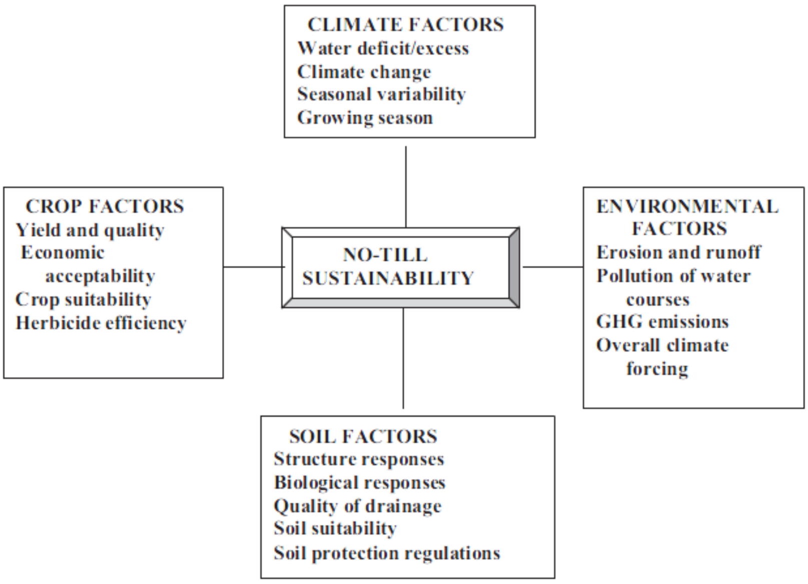


**Figure 37** A summary of climate, crop, soil and environmental factors related to the sustainable uptake of no-till within European regions (from Soane et al., 2012).

Among the important aspects of these practices is the **decreased disturbance to the structure** of the uppermost soil layers (Stavi and Lal 2012). This is achieved through the simultaneous adoption of two essential farm practices: a reduced tillage method of seedbed preparation and permanent soil cover through crop residue management (mulching). The decreased disturbance of the soil profile contributes to maintaining its structure, encouraging activity of soil fauna, which supports agro-ecosystem health (Huggins and Reganold 2008).

One of the most important components of the soil is the organic matter, that strongly influences soil structure, soil stability, buffering capacity, water retention, biological activity and nutrient balance ultimately determining the risk of erosion. Improved soil management practices that **increase the organic matter content** of the soil would have a positive impact on the soil water holding capacity. Hudson (1994) showed that over a wide range of soils, there was an increase in water availability with increases in soil organic matter. Any practice that leads to increases in soil water in the upper portion of the root zone may have a positive impact on **WUE** due to **increased water availability** and improved **nutrient uptake**.

### *Cover crops and mulching (surface residue management)*

**Cover crops** are defined either as additional crops planted on the field post-harvest, or crops intercropped with the main-crop. Continuous cover crops can reduce on-farm erosion nutrient leaching and grain losses due to pest attacks and build soil organic matter and improve the water balance, leading to higher yields (Blanco and Lal 2008; Olson et al. 2010).

**Mulching** by covering the soil with crop or weed residues reduces the amount of solar energy falling on the soil and reduces evaporation, and also reduces runoff and promotes infiltration of rain water in the root zone. Another form of mulching consists of **shallow soil harrowing** to create hydraulic discontinuity between the loosened topsoil and the undisturbed subsoil that limits the upward movement of water.

Covering the surface with mulch or residue has been studied relative to **changes in WUE**. Greb (1966) found that residues and mulches reduce soil water evaporation by reducing soil temperature, limiting vapour diffusion, absorbing water vapour onto mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface. Residue characteristics affect energy balance components and have a large impact on **evaporation fluxes**.

Sauer et al. (1996a) found that the presence of residue on the surface reduced soil water evaporation by 34 to 50% and that creating a 15-cm bare strip increased soil water evaporation by only 7% over the weathered residue cover.

**Figure 38** Photos illustrating some examples of conservation agriculture: (a) mechanized cover crop management before drilling; (b) mechanized crop drilling; (c) wheat growing on dead residue mulch of Gramineae; (d) wheat growing on a living cover crop of alfalfa (source: Scopel et al., 2013).

**Surface water runoff is generally reduced**. Conservation agriculture can induce **higher infiltration rates**, being sometimes almost double of those of conventional systems (Scopel et al., 2013). The improvement of soil infiltration is the result of the increased roughness and complexity of the flow path which slows down the water flow rate across the soil surface and the improved topsoil porosity mainly due to increased macro-fauna activity and less soil crusting. As a result, water is stored more quickly in the soil profile at the beginning of the rainy season in the tropics and during winter and spring in the temperate regions, which can act as a buffer against the effects of an eventual dry spell at the early stage of the crop cycle (Scopel et al. 2004). Also, catch crops can **lower the risk of leaching**, especially when they are intercropped with the main commercial crop (Breland, 1995).

### *Output/input relationship and eco-efficiency indicators*

There is a variable impact of conservation tillage on **yield**. According to Soane et al. (2012), in Europe, it seems that the yields of winter crops with no tillage or reduced tillage are **comparable to conventional tillage** with ploughing, whereas the yields can decrease for spring crops. Intensive research on crop yields with no-till has been conducted in most countries in Europe (Tebrugge, 2001).

In the case of Europe, CT systems in general do not generate yield increases. On average, yields obtained by French farmers on poor and average agricultural lands change little under CT (±10 %) (Agreste, 2008); yields may, however, decrease by about 10 to 20 % on fertile lands under intensive production (Bertrand et al. 2005). Examples of crop yields observed in no-till research in various parts of Europe are reported in Soane et al. (2012). In general no-till gives crop yields within 5% of those obtained with ploughing but soil, crop and weather factors exert important influences.

**Yields of no-till crops tend to approach or exceed those after ploughing as the rainfall decreases** from northern to south-western Europe. For example, in northern Europe no-till yields rarely exceed those after ploughing (e.g. Arvidsson, 2010a), while in areas of extreme aridity in northern Spain barley yields with no-till were sometimes twice those with conventional tillage (Ferna'ndez-Ugalde et al., 2009b).

No-till has been found to have a number of **environmental advantages** in certain circumstances (During et al., 1998) which are not necessarily directly related to the immediate economic factors which influence commercial uptake. Nevertheless, they are likely to have increasing importance as **concerns about soil and landscape** protection assume greater significance. Of particular importance, as yet previously mentioned, are herbicide dispersal, erosion, P dispersal, eutrophication, nitrate leaching and greenhouse gas emissions (Davies and Finney, 2002).

The widespread dependence of no-till on additional and regular **applications of herbicides** has raised apprehension as to the fate of applied herbicides and the environmental consequences. Herbicide usage should be reduced to the minimum consistent with desired level of weed control.

The retention of crop residues on the soil surface can **limit nutrient leaching**, decrease raindrop impact, **protect the soil from water and wind erosion**, increase water retention, and improve soil structure and aeration (Unger et al. 1991; Barros and Hanks 1993; Arshad and Gill 1997; Scopel et al. 2004; Govaerts et al. 2007; Blanco and Lal 2008), with the expected positive effects on crop yields (Smolikowski et al. 1997; Silvertown et al. 2006; Conant 2009) especially where water availability limits production. Thus, the effects of tillage are strictly connected with the effects of mulch or crop residue management.

Several studies showed a significant **decline in nutrient losses** in soils with reduced tillage compared to conventional ploughing (Tebrügge and Düring 1999). The process involved is water infiltration, which occurs mostly in macro-pores and channels, bypassing the soil matrix, so avoiding intensive exchange with the soil and preventing nutrients from being leached, and the peak of N mineralisation is lower when ploughing is abandoned.

**Erosion and runoff** have been identified as important problems throughout Europe needing control, especially in the Mediterranean region (During et al., 1998; Montanarella, 2006). Recent studies, however, suggest that risks of erosion and compaction of European soils have increased as a result of continuing conventional inversion tillage, reductions in soil organic matter and increased mechanization (Tebrugge, 2001). In southern European countries such as Italy, Spain and Portugal, **soil and water conservation** have also been found to be enhanced by the surface residue mulch with no-till due to increased infiltration during winter rainfall and reduced evaporation from the surface in dry summers. In temperate climates, problems of **soil compaction** can occur due to climatic and soil conditions, such as in the northern part of Europe (Soane et al. 2012).

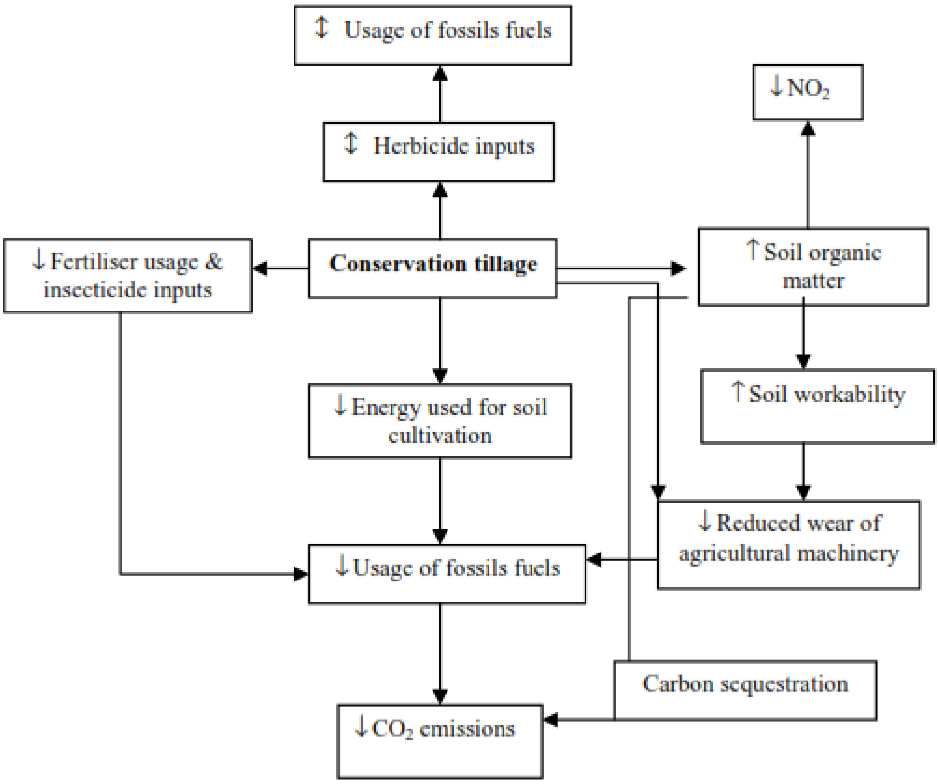


Figure 39 Processes involved in energy consumption and greenhouse-gasses emission under conservation tillage systems (from Soane et al., 2012).

Shifting from conventional to reduced tillage or no-tillage (direct seeding) helps to **reduce energy consumption**. The cultivation of soils through ploughing is the most energy demanding process in the production of arable crops. The diesel fuel used contributes directly to **$CO_2$ emissions** along with that used in the manufacture of the machinery. CT uses less energy: adopting CT was estimated to save 23.8 kg C $ha^{-1}$ per year (Kern and Johnson, 1993). Likewise, a full carbon cycle analysis revealed that the C emissions for conventional tillage, reduced tillage and no-till averaged over corn, soybean and wheat were 69.0, 42.2 and 23.3 kg C $ha^{-1}$per year (West and

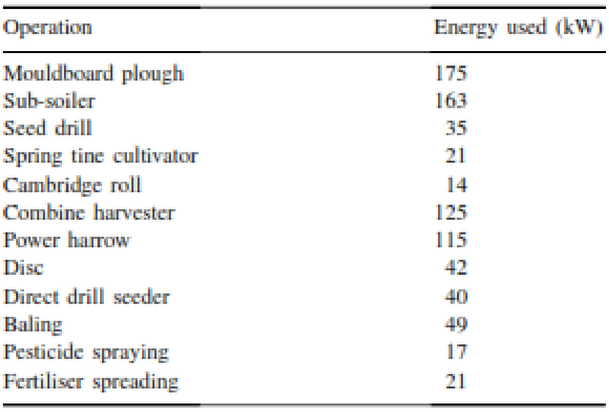
Marland, 2002). Methods of non-inversion soil cultivation (direct drill, disc + drill) clearly have lower energy usage than those based upon ploughing and/or power harrowing (Leake, 2000) (Table 17).

Systems based upon CT may, however, require **additional operations** such as in the creation of a stale seedbed, and may also lead to higher herbicide inputs.

**Fuel used in no-till operations is invariably less** than that used with normal ploughing systems but the difference will depend strongly on the soil type, the depth of ploughing, the number and type of secondary cultivations. The **emission of $CO_2$ and other GHGs** from the production and consumption of tractor fuel is approximately equivalent to 376 kg $CO_2$ per 100 l diesel (Tebrugge, 2001). Therefore, for a range of soil types, an average saving of 40 l $ha^{-1}$ by using no-till in place of ploughing would achieve a reduced emission of 41 kg CO2-C $ha^{-1}$ for each crop season. Tebrugge (2001) claims that no-till has the potential, if adopted on 40% of the EU land area, of reducing CO2 emissions by 4.2 Mt $y^{-1}$ as a result of lower fuel consumption alone.

Donaldson et al. (1996) found that, when the energy usage of two integrated farming systems utilizing CT were compared to conventional systems based upon ploughing, total energy usage was 16 and 26% lower over a 6-year rotation. However, the average yield was lower for comparable crops and consequently the machinery **energy usage per ton of crop** was higher for the integrated approach. In contrast, a detailed C audit in USA revealed that the net C flux averaged across a range of crops was +168 kg C ha-1 for conventional tillage compared to -200 kg C ha-1 for no-till (West and Marland, 2002).

**Table 17** Example of energy used in husbandry operations (Leake, 2000)



| Operation | Energy used (kW) |
|---|---|
| Mouldboard plough | 175 |
| Sub-soiler | 163 |
| Seed drill | 35 |
| Spring tine cultivator | 21 |
| Cambridge roll | 14 |
| Combine harvester | 125 |
| Power harrow | 115 |
| Disc | 42 |
| Direct drill seeder | 40 |
| Baling | 49 |
| Pesticide spraying | 17 |
| Fertiliser spreading | 21 |

Fossil fuels form the basis of many agrochemicals while energy is used in their manufacture, transportation and application. Adoption of **CT can substantially change the crop input requirements** by influencing fertiliser requirements, pest infestation levels and soil moisture. The net carbon (C) production from agricultural inputs can exceed that used by machinery (West and Marland, 2002).

**Fertiliser** is the other main energy input and this can reach 50% of the total energy requirements (Leake, 2000). This can be reduced with CT, because **less nitrate and P is lost by leaching**, crop residues are normally incorporated and there is faster recycling of nutrients by an improved soil biota. However, CT usually requires

**increased use of chemical fertilisers and pesticides** to control weeds and maintain yields (Teasdale et al. 2007). For no tillage systems with direct seeding into mulch, the increase of herbicides is due to destroying the cover crop.

If the full impact of a change in tillage on **carbon (C) budgets** is considered, the energy usage of the whole production process must be evaluated. Intensive soil cultivations break-down SOM producing $CO_2$ thereby lowering the total C sequestration held within the soil. By building SOM the adoption of CT, especially if combined with the return of crop residues, can substantially **reduce $CO_2$ emissions** (West and Marland, 2002). A summary by Tebrugge (2001) of early long-term studies in Canada, Germany, Italy, Spain and Portugal indicated that no-till can be expected to show an **additional accumulation of soil organic carbon** compared to ploughing of 1100, 1500, 800, 800 and 1000 kg C $ha^{-1}$ per year, respectively. A global assessment of 67 long-term experiments, involving 276 paired no-till and ploughed treatments (West and Post, 2002) indicated, at depths usually of 30 cm or less, a mean increase of 570 kg C $ha^{-1}$ per year for no-till compared with ploughing but with considerable variation as has been found in Europe (Soane et al., 2012). In general these initial research results supported the hypothesis that higher SOC at 0–30 cm depth is a valid indication of greater C sequestration after no-till than after ploughing and led to confident predictions that no-till offered an **important method to mitigate anthropogenic $CO_2$ emissions** (Spargo et al., 2008).

Finally, in terms of **economical return and profitability**, tillage suppression may substantially reduce crop production costs, as mechanized tillage is a rather costly technique including fuel, labour and machinery costs. In the intensive grain In Europe, farmers are more concerned by the short-term benefits from applying CT systems such as reduced labour and fuel costs (Lahmar et al. 2006). However, achieving this reduction depends on many factors such as the type of soil, crop and machinery, and the savings may be offset by additional costs due to heavy infestations of weeds, pests and diseases. Such problems may lead farmers to favour specific crops that are more easily managed with CT, such as maize, soybean, canola or to turn back to conventional practices.

### *Effects on Water Uses, WUE and WP*

After the introduction of no-till, changes can be expected in **evaporation** of water from the surface, **infiltration rate** and **hydraulic conductivity** as a result of the different soil physical properties, particularly increased organic matter near the surface and increased vertically orientated macrostructure throughout the profile (Strudley et al., 2008).

Several studies have shown that in CT systems, **water stored in the soil profile** is generally more as compared to conventional ones, due to reduced soil evaporation, increased infiltration and soil conductivity, reduced runoff and deep percolation also due to the increase in the soil organic matter (Hatfield, 2001). After 6 years of no-till on a silty loam soil in Germany, differences in water retention between no-till and ploughed land were very small and crop yields were identical (Vogeler et al., 2009). However, in the semi-arid climate of north-eastern Spain, the much higher barley yields under no-till than conventional tillage in dry years was attributed by Fernandez-Ugalde et al. (2009a,b) to the ability of no-till to increase plant available water.

Johnson et al. (1984) reported that more soil water was available in the upper 1 m under no tillage compared with other tillage practices in Wisconsin. In the Upper Midwest and Canada, there was generally an increase in soil water content under reduced tillage practices. This increase was caused by residue providing a barrier to soil water evaporation and by less disturbance of the soil surface via tillage operations.

Increasing crop residue or adopting no-tillage increases soil water availability and affects crop growth and yield. In Australia, Gibson et al. (1992) found that retaining sorghum stubble on the soil increased the sorghum yield by 393 kg ha due to increased WUE because of a greater amount of water stored in and extracted from the soil profile compared with conventional tillage. They also found that decreasing tillage frequency increased soil water extraction; however, no tillage did not result in the optimum yield or WUE.

The **infiltration rate** of no-till soils is sometimes, but not always, found to be appreciably higher than in ploughed soils. Infiltration rate increases have been observed and have been attributed to protection by residues of the surface from raindrop impact, the stability of aggregates near the surface and continuity between the surface and the sub-surface layers of vertically orientated macro-porosity. These effects are usually attributed to the greater aggregate stability, SOC and protective mulch normally found on no-till soils.

After a preliminary period of establishment, the vertically orientated structure and stabilised earthworm and root channels in no-till soils contribute to **increased hydraulic conductivity**. Increased downward movement of water under no-till and decreased runoff during periods of high rainfall may result in water tables being higher and oxygen concentrations being lower than for ploughed soils under certain circumstances (Soane et al., 2012).

Additionally, it has been shown that in CT, particularly in no-tillage systems, there is usually a larger presence of bio-pores than in CT, that allow an easier **penetration of water and roots** of following crops, thereby allowing an increased exploration of the soil profile (Turner, 2004). If these effects are accompanied by similar higher yields than conventional tillage, there is a resulting improvement in WUE (e.g., De Vita et al., 2007; Hatfield et al., 2001).

**Infiltration rates** under no tillage are increased. In the northern Great Plains, Pikul and Aase (1995) found that infiltration rates were increased because of the protection of the soil surface and that infiltration over 3 h was 52 mm with conventional tillage in a wheat fallow and 69 mm for the annual cropping system with no tillage. They stated that no-tillage has an advantage over tillage because surface cover is maintained, and this reduces the potential for soil crusting and erosion. Aase and Pikul (1995) found that decreasing tillage showed a trend toward improving WUE because of improved soil water availability through reduced evaporation losses.

Soil management practices that increase the soil water holding capacity, improve the ability of roots to extract more water from the soil profile, or decrease leaching losses could all potentially have positive **impacts on WUE**, assuming these changes result in a concurrent increase in crop yield. These practices would affect evapotranspiration rates and potentially increase crop yields, thereby increasing WUE.

Azooz and Arshad (1998) found differences among years when they compared the effects of no tillage and a 75-mm strip till with conventional tillage on the **water use and yield** of barley and canola on a silt loam and a sandy loam soil. In a dry year, there was an increase in yield with no tillage and strip till; however, in a wet year, yield was higher with conventional tillage. Water use efficiency for barley was increased in the dry year by 21% with no tillage and by 18% with strip till in the silt loam; it was increased by 19% with no tillage and by 10% with modified no tillage in the sandy loam compared with conventional tillage. In wet years, WUE was highest with conventional tillage.

Zhang and Qweis (1999) found similar responses for wheat in the Mediterranean region where WUE was increased by agronomic factors that lead to high yields. Despite the interesting results of decades of experiments on CT, there is still a lack of specific research to assess the effects on WUE in Mediterranean environments (Casa, 2007).

### 6.2.2. Use of biodegradable mulches

Benefits of **mulching** on growth and yield of annual and perennial crops have long been recognized (e.g. Shonbeck and Evanylo 1998; Tindall et al. 1991). Mulching with organic or inorganic materials aims to cover soils and forms a physical barrier to limit soil water evaporation, control weeds, maintain a good soil structure, and protect crops from soil contamination. Natural mulches are those derived from animal and plant materials, if properly used they can offer all the benefits of other types of mulches. Natural mulches help also in maintaining soil organic matter and tilth and provide food and shelter for earthworms and other desirable soil biota (Doran 1980).

The use of **plastic mulch** in agriculture has increased dramatically in the last decades throughout the world. This increase is due to benefits such as increase in soil temperature, reduced weed pressure, moisture conservation, reduction of certain insect pests, higher crop yields, and more efficient use of soil nutrients. The use of covering techniques started with a simple system such as mulching, and then row covers and small tunnels were developed and finally plastic houses.

The widespread use of **polyethylene** (the principal type of plastic used today) is due to easy processibility, excellent chemical resistance, high durability, flexibility, and freedom from odor and toxicity. The most commonly used mulch films include low-density polyethylene, linear low-density polyethylene, and high-density polyethylene (Fleck-Arnold 2000).

Regarding the **financial aspects**, using plastic mulch films increases the cost for vegetable production due to material costs of $400–625/ha for normal black plastic mulch film (Lamont 2004b), machines and labor for film application and removal, and also material hauling and landfill tipping fee. The cost of lifting, baling, and disposing polyethylene mulch following cropping depends on the integrity of the film, the length of rows, soil type, distance between bed centers, and availability of suitable machinery; it typically varies from $150 to $240/ha in major vegetable production areas of Australia (Olsen and Gounder 2001).

Most mulch films currently produced from petroleum based plastics cause a considerable **waste disposal problem** (Halley et al. 2001). Plastic requires time-consuming pickup and disposal at the end of the season and its manufacture and disposal entail significant **environmental costs** (Schonbeck 1995). Although recycling may be an option, polyethylene mulches used in vegetable production are contaminated with too much dirt and debris to be recycled directly from the field (Hemphill 1993). Because of high transportation cost and landfill tipping fees, farmers consider on-site burning to be economically more favorable (Lawrence 2007), but mulch films contaminated with fertilizers and pesticides usually generates air pollutants, especially dioxins (EPA 2006).

**Figure 40.** Fresh market tomato grown using polyethylene mulch

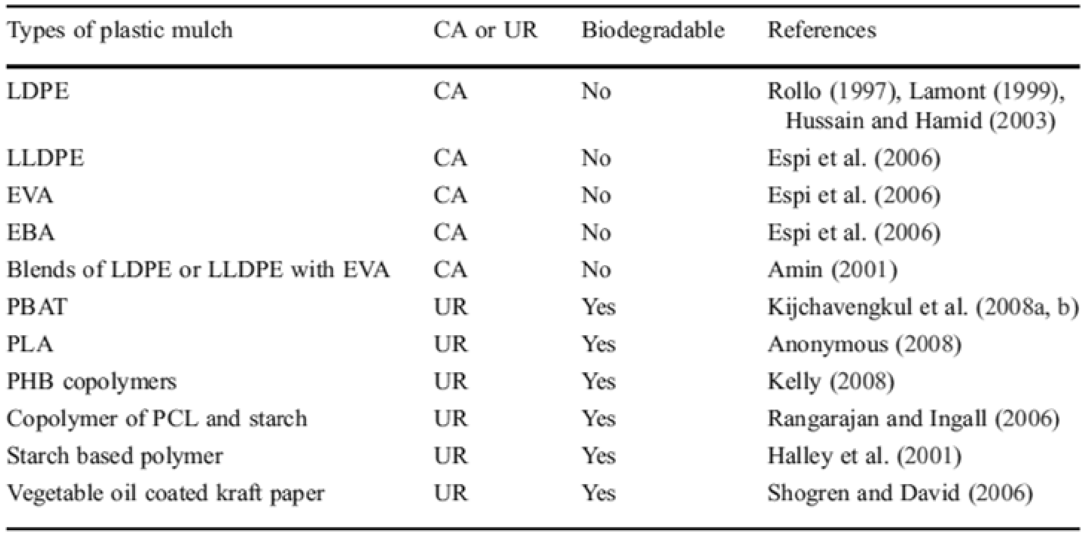
Thus, despite multiple benefits, removal and disposal of conventional polyethylene mulches remains a major agronomic, economic, and environmental constraint, leading to the development of **photodegradable and biodegradable mulches**. The use of biodegradable or photodegradable mulch films may satisfy growing needs to find an alternative to petroleum-based products (Debeaufort et al. 1998; Guilbert et al. 1996; Sorkin 2006) because they do not produce wastes that require disposal (Immirzi et al. 2003; Russo et al. 2004, 2005; Kapanen et al. 2008) and, although the biodegradable mulches are more expensive than the corresponding standard polyethylene-based plastics, this added cost is more than offset by the costs to remove and dispose of the standard plastic mulches.

The development of **environmentally degradable polymeric materials and plastics (EDPs)** was initiated among several other attempts in the early 1980s to address an emerging global plastic waste problem, following decades of fast development and explosive growth of plastic utilization (Selke 1996; Scott 1999). Recently, newer photodegradable products have shown more satisfactory degradation characteristics when tested in different regions.

Biodegradable mulch films can **degrade in the field after plowing**, thus eliminating film recovery and disposal. With material properties similar to those of conventional plastics (Hocking and Marchessault 1994; Steinbuchel and Fuchtenbusch 1998), biodegradable plastics (polyesters) have been developed successfully over the last few years. These include polyhydroxyalkanoates, polylactides, polycaprolactone, aliphatic polyesters, polysaccharides, and copolymer or blend of these.

Nowadays, materials such as polylactic acid, PBS, polycaprolactone, or polybutylene adipate/terephthalate (commercially supplied by BASF under the trade name Ecoflex®), copolymers of PHB, and starch based polymers, are being adopted as biodegradable mulch sheets (Kyrikou and Briassoulis 2007; Shah et al. 2008) (Table 18). **Bioplastics (biopolymers)** obtained from growth of microorganisms or from plants which are genetically engineered to produce such polymers are likely to replace currently used plastics at least in some of the fields (Lee 1996).

**Table 18** Polymeric mulch materials commercially available and currently under research (for more details and references, see Kasirajan and Ngouajio, 2012).



| Types of plastic mulch | CA or UR | Biodegradable | References |
|---|---|---|---|
| LDPE | CA | No | Rollo (1997), Lamont (1999), Hussain and Hamid (2003) |
| LLDPE | CA | No | Espi et al. (2006) |
| EVA | CA | No | Espi et al. (2006) |
| EBA | CA | No | Espi et al. (2006) |
| Blends of LDPE or LLDPE with EVA | CA | No | Amin (2001) |
| PBAT | UR | Yes | Kijchavengkul et al. (2008a, b) |
| PLA | UR | Yes | Anonymous (2008) |
| PHB copolymers | UR | Yes | Kelly (2008) |
| Copolymer of PCL and starch | UR | Yes | Rangarajan and Ingall (2006) |
| Starch based polymer | UR | Yes | Halley et al. (2001) |
| Vegetable oil coated kraft paper | UR | Yes | Shogren and David (2006) |

*CA* = commercially available; *UR* = under research; *LDPE* = low-density polyethylene; *LLDPE* = linear low-density polyethylene; *EVA* = ethylene vinil acetate; *EBA* = ethylene butyl acrylate; PLA = polylactic acid; *PBAT* = poly(butylenes adipate-terephthalate); *PHB* = poly(hydroxilbutyrate); *PCL* = polycaprolactone.

Polylactic acid produced from biorenewable resources, such as corn, has recently been gaining attention for sustainability reasons because the term “biorenewable” refers to materials made from biomass with absorbed carbon dioxide from the atmosphere (Auras et al. 2004). However, its most important property is its **biodegradability**. Laboratory tests with corn starch as a control confirmed the biodegradability of the films (Kijchavengkul et al. 2006, 2008a). Currently, it is used as a sheet, fiber, and modifier for plastics (Muller et al. 2001).

Feuilloley et al. (2005) studied the biodegradability of three different commercial mulch films including **Mater-bi** (Novamont, Novara, Italy); **Ecoflex** (BASF, Ypsilanti,MI, USA) and **Actimais** (SMS Trioplast, Pouance, France). The first conclusions from the study are that a very low degree of biodegradation of the commercial polyethylene films is achieved from these tests and that cross-linked polyethylene micro-fragments are remaining in soil for a very long period of time.

Biodegradable plastic films are converted through **microbial activity** in the soil to carbon dioxide, water, and natural substances; polymers such as poly(lactic acid), poly(butylene adipatecoterephthalate), poly(ε-caprolactone), and starch-based polymer blends or copolymers can degrade when exposed to **bioactive environments** such as soil and compost (Figure 41).

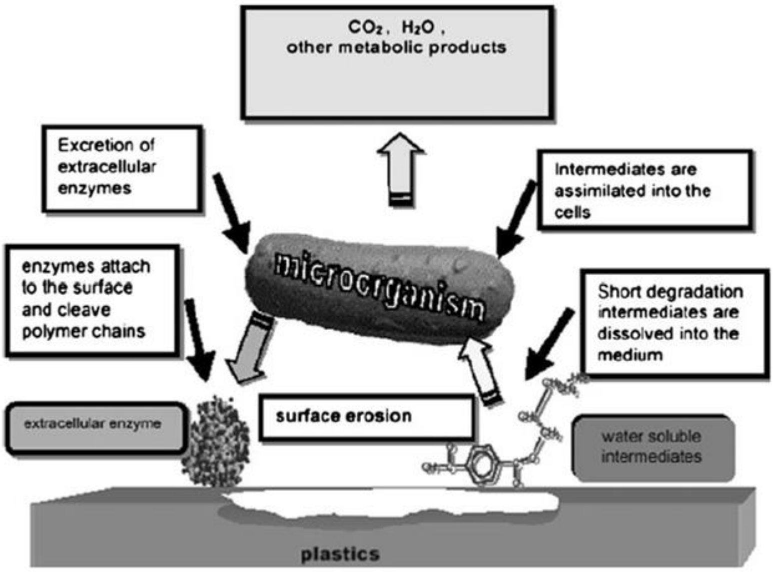


**Figure 41** General mechanism of plastic biodegradation (source Kasirajan and Ngouajio, 2012).

A truly biodegradable material should be destroyed by soil microorganisms, bioassimilated, or mineralized (Feuilloley et al. 2005; Gross and Kalra 2002; Vert et al. 2002). Starch-based polymers have shown enhanced biodegradability but remain too expensive and sometimes too heavy for agricultural applications (Feuilloley et al. 2005; Halley et al. 2001; Olsen and Gounder 2001).

Utilization of plastic mulch in combination with drip irrigation has played a major role in the increases in production of several vegetables (tomato, pepper, eggplant, watermelon, muskmelon, cucumber, and squash), but also applications with field crops could be found in literature. The **benefits of polyethylene mulch** to crop production are well documented and include greater root growth and nutrient uptake (Wein et al. 1993), earlier ripening and a higher yield of fruit (Abdul-Baki et al. 1992), and improved fruit quality (Singh 1992) than plants grown without mulch.

On the other side, the **photo-biodegradable polyethylene** films containing starch are similar to polyethylene films in their ability to **raise soil temperature, preserve moisture, or increase yield**. In addition, photo-biodegradable polyethylenes can be degraded environmentally after field service. The induction periods of four kinds of photo-biodegradable polyethylene films range from 46 to 64 days, which basically satisfies the needs of agricultural cultivation. The photo-biodegradable polyethylene films buried in soil have also **good degradability** (Wang et al. 2004).

Olsen and Gounder (2001) found slightly higher soil temperatures for polyethylene and biodegradable polymer mulches than paper mulch, but **yields** of peppers were **similar for all** three **materials**. The study on the feasibility of using degradable plastic films for horticultural crops production indicated that the silver and black bio-/photo-degradable polyethylene films containing 20% starch degraded after 56, 83, 38, and 33 days when they were mulched in fall, winter, spring, and summer. **The more starch incorporated, the faster the films degraded**.

Lopez et al. (2007) studied the behavior of four biodegradable materials and one linear low-density polyethylene in the open-air cultivation of a Spanish melon cultivar, under Mediterranean environmental conditions during the normal growing season for this crop, and revealed that the use of biodegradable materials produced **similar yields than linear low density polyethylene**, with the biodegradable materials disappeared 5 months after laying, whereas linear low-density polyethylene remained in the ground.

Waterer (2010) studied the field performance of several colors of **corn-starch-based biodegradable mulches** for the production of warm season vegetable crops (sweet corn, zucchini, cantaloupe, pepper, and eggplant) over three cropping seasons. There were no appreciable differences in the soil temperatures or crop growth and **yield responses** on the biodegradable mulches as compared with the same color of standard low-density polyethylene mulch. The biodegradable mulches were easy to apply and were readily incorporated into the soil at the end of the growing season.

Concerning the environmental aspects, all plastic film mulches allow to **reduce N leaching** (Bhella 1988), to **protect the soil from water and wind erosion** and hail damage (Garnaud 1974). The dominant advantage of using polyethylene mulch is its ability to aid in the retention of nutrients within the root zone, thereby permitting more efficient nutrient utilization by the crop (Cannington et al. 1975).

Plastic mulches alter the crop microclimate by changing the **soil energy balance and decreasing the soil water loss** (Liakatas et al. 1986; Tarara 2000). Modification of the crop microclimate results in changes in soil temperature that may affect plant growth and yield (Cooper 1973; Dıaz-Perez and Batal 2002; Ibarra-Jimenez et al. 2006; Lamont 2005). Different types and colors of plastic mulch have characteristic optical properties that change the levels of light radiation reaching the soil, causing increases or decreases in the soil temperature (Ham et al. 1993).

The plastic film is a **barrier preventing soil water evaporation and funnelling excess rainfall away** from the root zone thus keeping the moisture regime in the root zone at more stable levels. This can reduce irrigation demands and help prevent water- or nutrient-related physiological disorder, such as blossom end rot (McCraw and Motes 1991). Evaporation can be significantly reduced depending on the type of mulch (Chakraborty and Sadhu 1994). The water economy achieved by plastic mulching is substantial; all reserves are available for the plants, and consequently, the nutrient supply is also more constant (Lippert et al. 1964).

Associated with the reduction in evaporation losses, **transpiration increases** because both sensible and radiative heat are transferred from the surface of the plastic cover to adjacent vegetation (Allen et al., 1998). Even though the transpiration rates under mulch may increase by an average of 10-30% over the season as compared to using no mulch, the $K_c$ values decrease by an average of 10-30% due to the 50-80% reduction in soil evaporation. A summary of observed reductions in $K_c$, in evaporation, and increases in transpiration over growing seasons is given in table 19 for five horticultural crops (Allen et al., 1998). Besides, crop growth rates and vegetable yields are normally observed to increase with the use of plastic mulches.

Due to the above reasons, in the case of crops under plastic mulches, the FAO Paper 56 suggests that the **crop coefficients** be reduced by 10–30% if applying the single crop coefficient, and by 5–15% the basal crop coefficients (Kcb) if applying the dual crop coefficient (Allen et al., 1998), though highlighting that the effect of this agronomic technique on crop coefficients may be even greater than the reduction suggested in some specific cultural conditions, as in the case of low crop density (Lovelli et al., 2005).

**Table 19** Approximate reductions in $K_c$ and surface evaporation and increases in transpiration for various horticultural crops under complete plastic mulch as compared with no mulch using trickle irrigation (for additional details, see Allen et al., 1998)

| Crop | Reduction in $K_c$ (%) | Reduction in evaporation (%) | Increase in transpiration (%) | Source |
|---|---|---|---|---|
| **Squash** | 5-15 | 40-70 | 10-30 | Safadi (1991) |
| **Cucumber** | 15-20 | 40-60 | 15-30 | Safadi (1991) |
| **Cantaloupe** | 5-10 | 80 | 35 | Battikhi and Hill (1988) |
| **Watermelon** | 25-30 | 90 | -10 | Battikhi and Hill (1986), Ghawi and Battikhi (1986) |
| **Tomato** | 35 | not reported | not reported | Haddadin and Ghawi (1983) |

Interesting experiences on $K_c$ estimation for crops cultivated under plastic mulches have been obtained for the Southern Italy. For example, Lovelli et al. (2005) studied the effects of mulching on water use of muskmelon crop (Figure 42), and observing that: (i) the growing cycle of mulched crop is shorter than of non-mulched one; (ii) the $K_c$ values for mulched are greater at the beginning of the full development phase and immediately after the start of harvesting, while during almost the whole period of harvesting are lower; (iii) the mulched crops as had a rapid and anticipated development manifested the symptoms of an earlier senescence of leaves which resulted in a fast reduction of $K_c$ values. The **higher $K_c$ values** of muskmelon grown under plastic mulches during almost the whole growing cycle are related to the greater vegetative development of mulched crops (confirmed by the greater LAI values). Furthermore, these data indicate how the **duration of phenological phases** of muskmelon is notable **shorter** than that suggested by FAO (Allen et al., 1998), while $K_c$ values obtained were notably higher than those suggested in the FAO documents.

Beside these results, Cantore et al. (2005) found in similar environments that total water used by muskmelon was significantly reduced under mulched conditions (229 *versus* 320 mm, measured with a weighing lysimeter) because of the reduction in seasonal evapotranspiration (due to the reduction of soil evaporation and cycle length); additionally, both above-ground biomass WUE and yield WUE were greatly increased (respectively from 1.7 to 2.8 and from 8.7 to 13.2 kg $m^{-3}$), thus confirming the great **potential of mulching in supporting increases in water productivity**.

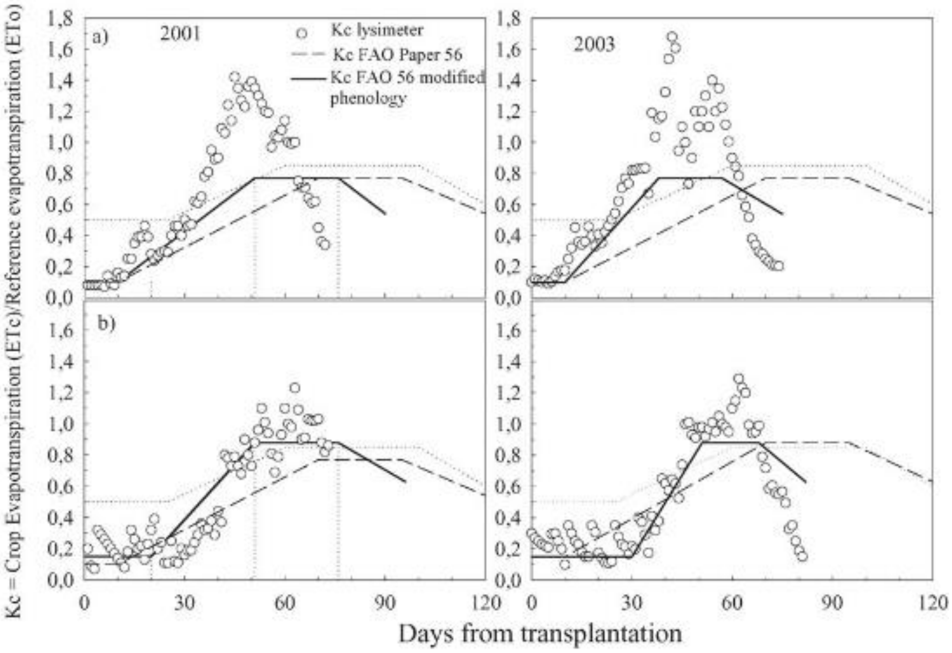


**Figure 42** Relation between estimated and measured (with lysimeter) crop coefficient (Kc) for muskmelon, with (a) and without (b) plastic mulches in two years (from Lovelli et al., 2005).

## 6.3. Organic farming and agro-ecological practices

There is a strongly contrasting, on-going debate around the most appropriate agricultural production practices with which to reach the goal of higher and **sustainable food production** (Wezel et al. 2013). Agricultural options range from high technology-based to ecology-based practices. On the one hand, precision farming or use of genetically modified crops could help match the future food demand. On the other hand, a sum of **agro-ecological practices** are other possible options (Holland 2004), normally integrated in the so-called ‘organic’ farming system.

The shift from traditional agricultural production methods to modern organic production ones would contribute to the **conservation of natural resources**, the maintenance of biodiversity and the preservation of the ecosystem. Organic agriculture is believed to produce significant social, economic and environmental benefits (Morgera et al., 2012); more specifically, the aim of such a system is to reduce the environmental impact, to improve the quality of the products as well as the process effectiveness through enhancing water use efficiency and reducing the use of synthetic fertilizers, pesticides and herbicides (Nilson, 2012).

The term “**agro-ecological practices**” emerged in the 1980s within the development of agro-ecology (Altieri 1995; Wezel et al. 2009). Examples of agro-ecological practices are cover crops, green manure, intercropping, agro-forestry, biological control, resource and biodiversity conservation practices, or livestock integration (Altieri 1995, 2002). Agro-ecological practices contribute to improving the sustainability of agro-ecosystems while being based on various ecological processes and ecosystem services such as nutrient cycling, biological N fixation, natural regulation of pests, soil and water conservation, biodiversity conservation, and carbon sequestration.

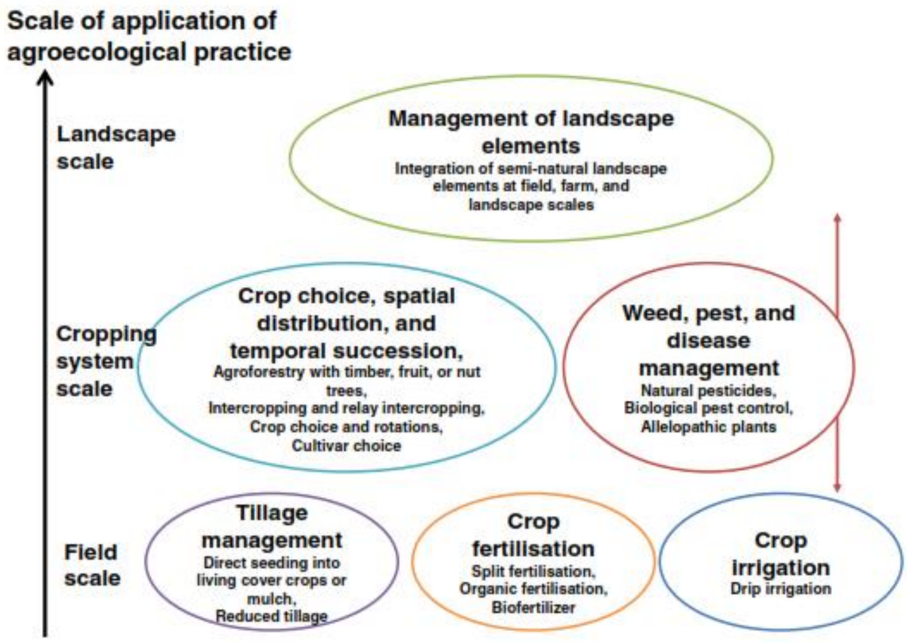


**Figure 43** Different categories of agro-ecological practices and scale of application (from field, to cropping system to landscape) (from Wezel et al., 2013)

According to the analytical framework of Hill and MacRae (1995), an agricultural transition towards a more ‘sustainable’ agriculture can be described according to three stages: i) ‘**efficiency increase’**, which refers to practices that reduce input consumption (e.g. water, pesticides, and fertilisers) and improve crop productivity; ii) ‘**substitution practices**’, that refer to the substitution of an input or a practice (e.g. replacing chemical pesticides by natural pesticides); ‘**re-design of cropping systems**’, which refers to the change of the whole cropping or even farming system.

Among the most relevant **crop management practices** within the agro-ecological approach (Figure 43), it is possible to highlight: (1) practices addressing crop choice, crop spatial distribution, and crop temporal successions; (2) tillage practices; (3) fertilisation practices; (4) irrigation practices; and (5) weed, pest, and disease management practices.

As it has been yet previously mentioned , choosing an adequate **crop** and **cultivar** can help to improve crop resistance to abiotic stresses (such as nitrogen and water deficiencies) (Tilman et al. 2002). Improving water use efficiency in water-scarce conditions (particularly rainfed water) is also possible with relevant **crop rotations** (Pala et al. 2007; Salado-Navarro and Sinclair 2009; Turner 2004). Crop rotations and intercropping with nitrogen-fixing crops, such as groundnuts, beans, and cowpeas will enhance soil fertility and enrich nutrient supply to subsequent crops, leading to increased crop yields (Woodfine 2009).

Rotations also provide an opportunity to **increase water use by a crop**. Roots of some species have the potential to penetrate deeper into the soil than others (Hamblin and Hamblin, 1985), and this may provide ‘biopores’ for a subsequent crop. It has been suggested that both narrow leafed lupin (Lupinus angustifolius) and canola/oilseed rape (Brassica napus) develop ‘biopores’ in the soil that allow easier root penetration by the water and roots of a subsequent crop (Angus et al., 1991;

Cresswell and Kirkegaard, 1995). For example, there is considerable evidence that Lucerne (Medicago sativa) has roots that penetrate deep into the soil over 2–3 years and allow deeper water penetration and deeper root penetration by a subsequent crop (Ward et al., 2002).

Use of **cover crops** is a widely applied agro-ecological practice to limit fertiliser inputs and reduce risk of water contamination due to a decreased risk of leaching (Sanchez et al. 2004), and also to reduce soil or wind erosion. Moreover, in conditions where rainfall events are sporadic and sometimes violent (storms in the Mediterranean climate, for example), cover crops can play an important role by reducing surface runoff and permitting a better water infiltration, possibly gainful for the next crop (Celette et al. 2008; Gaudin et al. 2010).

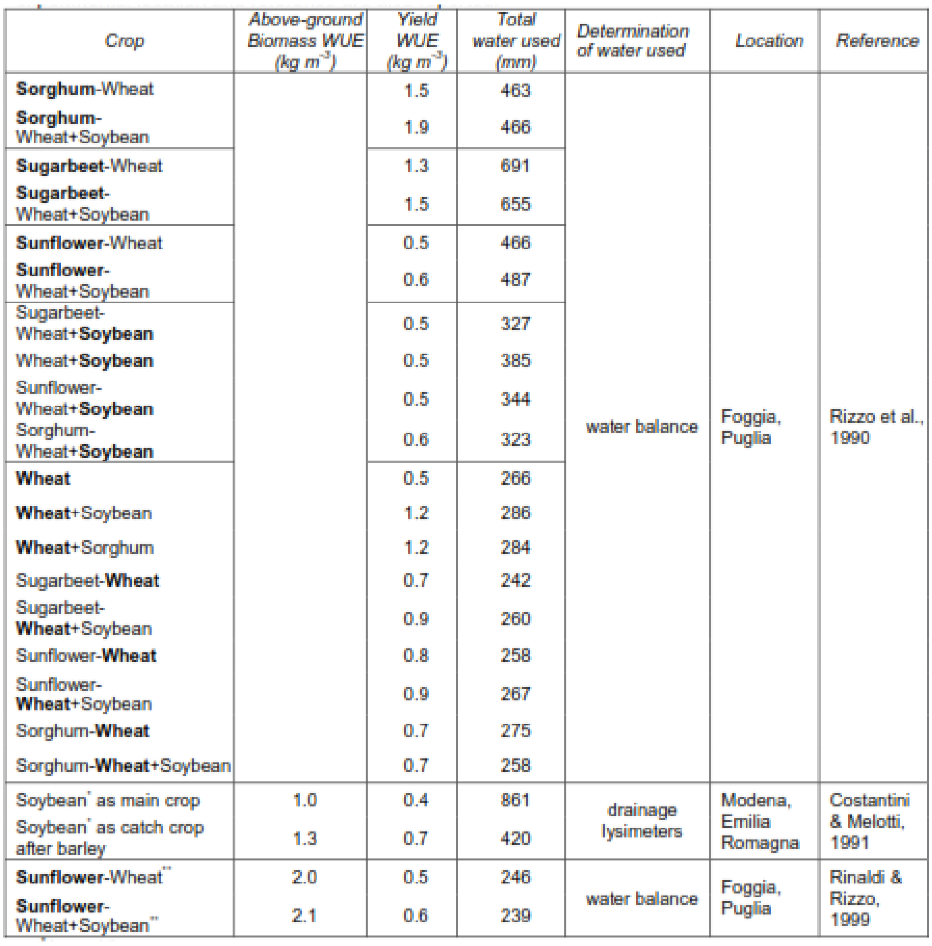
**Intercropping** may be defined as the coexistence of two or more crops in the same field at the same time. Different spatial arrangements of these species are possible; the intensity and type of interactions will depend on the chosen arrangement and associated species (Malézieux et al. 2009). The simplest differentiated crop mixtures (or mixed intercropping) are row and strip intercropping where at least one of the associated crops is planted in a row (or strip) (Figure 44). Other categories sometimes mentioned are associations partially composed of perennial species (e.g. agro-forestry). The intercropping systems are assumed to have potential advantages in productivity, stability of outputs, resilience to disturbance, and ecological sustainability, though they are generally considered harder to manage (Vandermeer 1998). The first interest of intercropping is to improve land productivity by favouring complementarities of associated crops.

**Figure 44** *Left*: 'relay' intercropping of wheat and under-sown clover, to limit nutrient leaching and erosion, to fix nitrogen and to be used as forage. *Right*: olive tree agro-forestry with under-growth of leguminous species, to improve resources use efficiency due to different root systems, better nutrient cycling, legume nitrogen fixation (from Wezel et al., 2013).

Crop rotations and intercropping generally allows improvements of **resources use efficiency**, notably radiation and water use efficiency (Table 20).

Different types of **agro-forestry practices** can be also considered agro-ecological practices since they reduce nutrient leaching, conserve soils, increase diversity of the production system, and produce complementary wood for various uses (e.g. Buck et al. 1998). In Europe, there are different agro-forestry systems that integrate crops and, more generally, woody plants, however, there are also more specialized systems that include fruit or nut tree integration (Figure 43). In some cases, these fruit or nut tree systems are coupled with extensive grazing of meadows below or between the trees.

**Table 20** Effect of crop rotations and intercropping on above-ground biomass WUE, yield WUE, total water used by field sown crops (for additional details, see Todorovic et al., 2007)



| *Crop* | *Above-ground Biomass WUE (kg m$^{-3}$)* | *Yield WUE (kg m$^{-3}$)* | *Total water used (mm)* | *Determination of water used* | *Location* | *Reference* |
|---|---|---|---|---|---|---|
| **Sorghum**-Wheat |  | 1.5 | 463 | water balance | Foggia, Puglia | Rizzo et al., 1990 |
| **Sorghum**-Wheat+Soybean |  | 1.9 | 466 |  |  |  |
| **Sugarbeet**-Wheat |  | 1.3 | 691 |  |  |  |
| **Sugarbeet**-Wheat+Soybean |  | 1.5 | 655 |  |  |  |
| **Sunflower**-Wheat |  | 0.5 | 466 |  |  |  |
| **Sunflower**-Wheat+Soybean |  | 0.6 | 487 |  |  |  |
| Sugarbeet-Wheat+**Soybean** |  | 0.5 | 327 |  |  |  |
| Wheat+**Soybean** |  | 0.5 | 385 |  |  |  |
| Sunflower-Wheat+**Soybean** |  | 0.5 | 344 |  |  |  |
| Sorghum-Wheat+**Soybean** |  | 0.6 | 323 |  |  |  |
| **Wheat** |  | 0.5 | 266 |  |  |  |
| **Wheat**+Soybean |  | 1.2 | 286 |  |  |  |
| **Wheat**+Sorghum |  | 1.2 | 284 |  |  |  |
| Sugarbeet-**Wheat** |  | 0.7 | 242 |  |  |  |
| Sugarbeet-**Wheat**+Soybean |  | 0.9 | 260 |  |  |  |
| Sunflower-**Wheat** |  | 0.8 | 258 |  |  |  |
| Sunflower-**Wheat**+Soybean |  | 0.9 | 267 |  |  |  |
| Sorghum-**Wheat** |  | 0.7 | 275 |  |  |  |
| Sorghum-**Wheat**+Soybean |  | 0.7 | 258 |  |  |  |
| Soybean[*] as main crop | 1.0 | 0.4 | 861 | drainage lysimeters | Modena, Emilia Romagna | Costantini & Melotti, 1991 |
| Soybean[*] as catch crop after barley | 1.3 | 0.7 | 420 |  |  |  |
| **Sunflower**-Wheat[**] | 2.0 | 0.5 | 246 | water balance | Foggia, Puglia | Rinaldi & Rizzo, 1999 |
| **Sunflower**-Wheat+Soybean[**] | 2.1 | 0.6 | 239 |  |  |  |

**Minimum or zero-tillage practices** help reduce energy inputs and thus increase cropping system efficiency. Other advantages are protecting the soil from erosion (organic matter at the soil surface), stocking organic C (less C mineralisation), and favouring soil biodiversity to promote biological activity. For instance, with no-tillage more earthworms were found which increased soil porosity and thus improved water and root penetration into the soil. In organic farming, reduced tillage often results in increasing the machine traffic for weed control, and thus increasing labour time and energy costs (Peigné et al. 2007).

**Organic fertilization** is a way of substituting inorganic fertilizers and of improving the efficiency of fertilization by improving general soil fertility. Application of organic fertilizer causes enhanced soil biological activity and potentially increased soil mineralization. Nevertheless, the constraints of these practices may include higher labour and energy demands, and difficulty in optimizing N availability in soils with organic fertilization as well as in matching plant demand (Sanchez et al. 2004). Moreover, obtaining off farm organic fertilizers might be difficult, expensive, and may even incur undesirable transport and distribution costs (e.g. manure).

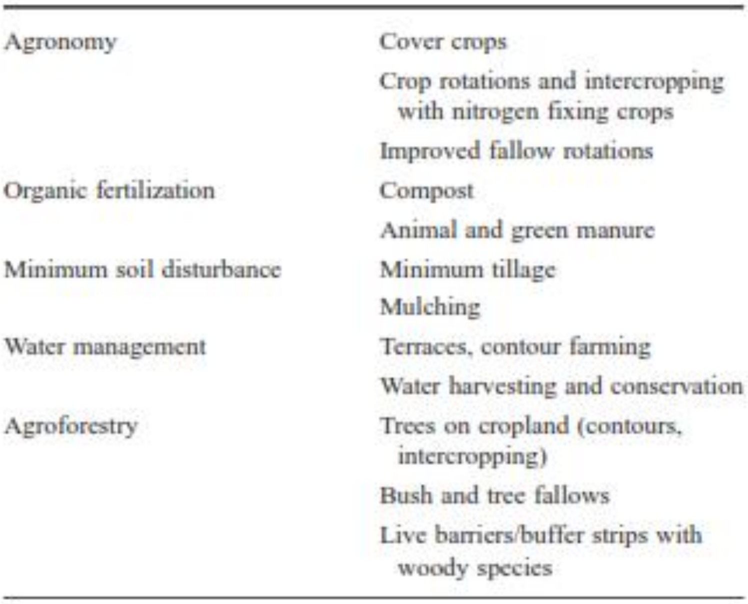
## 6.4. Sustainable land management (in the context of climate change mitigation)

Greater attention is thus being given to **alternative models of agricultural intensification**, and in particular, the potential of sustainable land management technologies. Such practices can generate private benefits for farmers, by improving soil fertility and structure, conserving soil and water, enhancing the activity and diversity of soil fauna, and strengthening the mechanisms of elemental cycling (Branca et al., 2013).

The literature suggests that these benefits can lead to **increased productivity and stability** of agricultural production systems (Lal 1997; World Bank 2006; Woodfine 2009; Pretty 2008). They thus offer a potentially important means of enhancing agricultural returns and food security, as well as reducing the vulnerability of farming systems to climatic risk. At the same time, widespread adoption of sustainable land management has the potential to generate significant public environmental goods in the form of climate change mitigation (FAO 2009, 2010).

The same practices can also deliver significant mitigation co-benefits in the form of removal of atmospheric carbon dioxide by plants and storage of fixed carbon as soil organic matter. The agriculture sector can **contribute to mitigation by reducing greenhouse gas (GHG) emissions**, of which agriculture is an important source, representing 14 % of the global total. Agriculture can also increase the removal of greenhouse gas emissions through sequestration. Soil carbon sequestration was estimated to constitute 89 % of the technical mitigation potential from agriculture (IPCC, 2007).

**Table 21 List of some relevant sustainable land management practices (from Branca et al., 2013).**



| | |
|---|---|
| Agronomy | Cover crops |
| | Crop rotations and intercropping with nitrogen fixing crops |
| | Improved fallow rotations |
| Organic fertilization | Compost |
| | Animal and green manure |
| Minimum soil disturbance | Minimum tillage |
| | Mulching |
| Water management | Terraces, contour farming |
| | Water harvesting and conservation |
| Agroforestry | Trees on cropland (contours, intercropping) |
| | Bush and tree fallows |
| | Live barriers/buffer strips with woody species |

The main benefit of implementing sustainable land management practices is expected to be **higher and more stable crop yields**, **increased system resilience** and, therefore, enhanced livelihoods and food security, and reduced production risk (Pan et al. 2006; Thomas 2008; Conant 2009; Woodfine 2009). According to the review of Branca et al. (2013), sustainable land management practices can increase crop productivity, which is an important component of achieving food security. The review conducted suggests that sustainable land management could have an important role to play in achieving **increases in yield**, although more complete information on their associated costs and their compatibility with specific farming systems and agro-ecologies is needed to effectively judge their merit.

However, agronomy, integrated nutrients, and water management practices are more effective at increasing crop yields in humid than in dry areas. In contrast, the average yield increases observed under tillage and agro-forestry systems are higher in dry areas. These results highlight the **key role of water as a determinant of crop productivity**, and the value of sustainable land management practices in improving the productivity of water use in both humid and dry areas. For example, in more humid areas, effective water management through **terracing and other soil and water conservation measures** will have the effect of reducing soil erosion, therefore increasing soil organic matter and nutrient availability in the root zone. In drier environments, practices that allow plants to make better use of the limited amount of water available prove to be the most productive. **Minimum tillage systems** are found to increase water availability to plants by reducing direct evaporation and improving the hydraulic conductivity of the topsoil and soil surface porosity (Scopel et al. 2001).

Combining the results of the meta-analysis on cereal yield effects with the expected mitigation co-benefits of sustainable land practices from IPCC (2007) estimates, Branca et al. (2013) have highlighted the potential synergies between food security and climate change mitigation. Figure 45 shows a comparison of **yield and mitigation effects** by practice and major agro-ecological zone, indicating that all the sustainable management practices considered can result in yield increases and, at the same time, sequester carbon and reduce GHG emissions, although the relative effects vary considerably by practice and agro-ecological zone. In dry areas, the magnitude of yield effects is greater than those of mitigation. The only exception is water management, which can deliver high levels of food security and mitigation benefits in both dry and humid areas. In contrast, in humid areas, the magnitude of yield and the mitigation effects are more evenly balanced. This finding has important implications for the potential and means of capturing synergies between mitigation and food security.

The higher **potential "mitigation productivity"** (e.g., tons of emissions reduction per hectare) found in humid areas provides an economic basis for supporting higher transaction costs in mitigation crediting programmes—which is key to accessing many forms of climate change mitigation finance. However, dry lands offer another type of potential, since they are characterized by a large number of producers which crop their land in areas where small incremental improvements in management of water resources and soil fertility can lead to large productivity—and ultimately food security—gains. Sustainable land management implemented over a large enough scale, could generate significant mitigation benefits, although requiring mechanisms for efficient crediting and financing adapted to these circumstances.

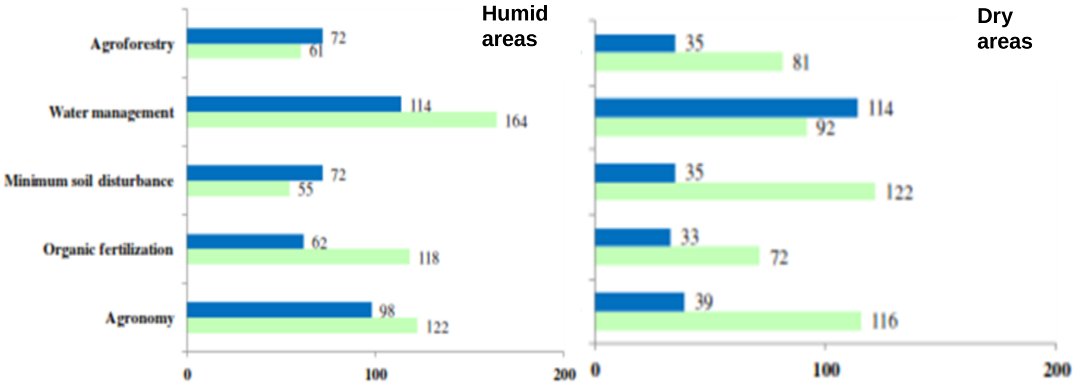


**Figure 45** Effects of sustainable land management practices on climate change mitigation (as GHG reduction in tons of $CO_2$ ha$^{-1}$ year$^{-1}$) and crop yield (average percentage increase) by major agro-ecological zones. All practices result in mitigation and yield increases, but in humid areas the magnitude of these effects are more balanced than in dry ones (from Branca et al., 2013).

# ANNEX - Synthesis of the 'Eco-efficiency Frameworks' for the technologies/practices under evaluation.

### *List of technologies/practices*

| | | |
|---|---|---|
| **Advanced technologies for water supply management** | Remote and automated control of irrigation water supply | **On-farm devices for precision irrigation (automation and sensors)**<br>**Variable Rate Irrigation (VRI)** |
| | Efficient irrigation methods | **Sprinkler irrigation**<br>**Micro-irrigation (drip and subsurface)** |
| | Deficit irrigation strategy | **Supplemental irrigation (SI) and Regulated Deficit irrigation (RDI)** |
| **Energy saving technologies** | | **Variable speed pumps for irrigation**<br>**Network sectoring and dynamic pressure regulation** |
| **Eco-friendly agronomic practices** | Cropping pattern changes | **Crop and variety selection**<br>**Early sowing and crop rationing**<br>**Super high density plantations (for olive farming)** |
| | Conservation agriculture | **Conservation tillage and surface residue management**<br>**Use of biodegradable mulches** |
| | Organic farming | **Agro-ecological practices** |

| **Technology** | **On-farm devices for precision irrigation (automation and sensors)** |
|---|---|
| **Short description** | **Control engineering approaches** is one solution being developed to automate irrigation management, and a generic irrigation control system normally integrates a “decision support system” and the “actuation” devices. **Automatic control** has been applied in almost all engineering fields with great success, although the impact in agriculture, and in particular in precision irrigation, is still limited. In the field of automatic irrigation, **measurements of weather, soil and plant variables** related to the plant water status can provide the information of the consequences of previous actions to calculate the next irrigation dose. Irrigation control can be approached by **adjusting the irrigation application** either: directly from the soil and/or plant response measurements (“sensor-based control”); or from responses simulated using a soil water balance and crop production model (“model-based control”). |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | The given technology/practice addresses productivity improvement by **breakthrough new technologies or practices** to redefine a new efficiency frontier, by producing **more desired outputs** and/or less undesired outputs with **less inputs** |
| **Economic aspects** | For sensor technology (according to Smith et al., 2010; Nilson et al., 2013):<br>- Technology Lifetime: 5-10 years<br>- Investment Cost: 500-2,000 €/ha; payback period: 5-20 years<br>- Operation Cost: 200 €/ha (average annual cost) |
| **Water saving** | Soil-moisture sensor (SMS) may contribute significantly to **water savings**, resulting in **15–51% less irrigation water** applied (depending on irrigation systems). Corresponding **yield** is normally **increased** (up to 11–26% under automated systems), thus resulting in an overall **increase of the irrigation water use efficiency**.<br>The expected increase in both **yield** and **water productivity** components is related to the reduction of irrigation requirements ***(I)***, evaporation ***(E)*** and deep percolation losses ***(DP)***, and thus to the reduction of non-beneficial uses (***NBWU***):<br>$Y = WUE_T\,T = WUE_T\left[C_S\left(\left(\boldsymbol{I} + P + CR + R_{on}\right) - \left(\boldsymbol{E} + T_{weed} + \boldsymbol{DP} + R_{off}\right)\right)\right]$<br>$WP = \frac{Y}{P + CR + \Delta SW + \boldsymbol{I}} = \frac{Y}{(ETc + LF) + \boldsymbol{NBWU}}$ |
| **Energy efficiency** | Given the potential to optimize the water use efficiency, automated irrigation systems reduce associated costs and **minimize the energy input requirement**, while enhancing the crop yield. For example, Marks et al. (2010) reported a range of **15-50% reduction in energy use** with the utilization of the AgriMet technology. Investigation of precision irrigation technologies in the entire state of California concluded in 2 billion kWh energy savings and 1.2 million metric tons reductions in $CO_2$ emissions per year (Marks et al., 2010) |
| **Physical efficiency** | Crop **yield is expected normally to increase** (up to 11–26% depending on irrigation and management systems) |

| | |
|---|---|
| **Environmental impacts** | The technology has the following expected beneficial impacts:<br>- to minimize **water waste due to deep percolation and runoff**<br>- to **reduce the nutrient requirements** of the crop and its **vulnerability to diseases**,<br>- to **reduce environmental pollution** due to the reduced leaching of nutrients applied to the crop with conventional fertilization or fertigation (the technique of supplying fertilizers dissolved in the irrigation water). |
| **Applications/ Innovative character** | There are several **commercial automatic controllers** (*Acclima*, *Watermark*, *Rainbird*, *WaterWatcher*) that regulate soil water content (SWC) based on sensor measurements, and hence operating as closed-loop controllers. These controllers apply irrigation when sensors detect that the measurements are below a certain predefined threshold until another predefined threshold is overcome (**on–off control**). These commercial systems have been compared by Cardenas-Lailhacar et al. (2008, 2010) concluding that, when adequate threshold are defined, all these systems have the **potential to save water** when compared to a traditional time-based irrigation treatment. The authors also showed that, even under dry weather conditions, the incorporation of rain sensors as a feed-forward can save substantial amounts of irrigation water. |
| **Main references** | Cardenas-Lailhacar et al., 2008, 2010; Kim et al. 2008, 2009; McCready et al., 2009; Marks et al. (2010); McCarthy *et al.*, 2011; 2012; Nilson et al., 2013, Pardossi et al., 2009; Peters and Evett 2004, 2008;Romero *et al.*, 2012; Sadler et al. 2002; Smith et al., 2010; Zapata *et al*., 2012; Zotarelli et al., 2008, 2009. |

| Technology | Precision Agriculture (PA) and Variable Rate Irrigation (VRI) |
|---|---|
| **Short description** | **Precision agriculture (PA)** technologies are designed to be able to spatially optimize the use of various inputs for improving or enhancing economic crop production, by considering the site-specific on-farm and on-field variability. This variability can be caused by soil type, crop type, crop condition (stress, etc.) and meteorological conditions (e.g. rainfall). These factors are discussed further in Smith et al. (2009).<br>The **VRI** is a modern agricultural management concept, consisting of hardware and software, allowing the continuous irrigation rate adjustment on individual management zones within the field, consisting of electronically-hydraulically-pneumatically activated valves, controller(s) for the activation and regulation of sprinklers, a motor controller regulating the flow rate, a GPS and a user interface through which field mapping and system set up can be carried out (Perry et al., 2012). |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | The given technology/practice addresses productivity improvement by **breakthrough new technologies or practices** to redefine a new efficiency frontier, by producing **more desired outputs** and/or less undesired outputs with **less inputs** |
| **Economic aspects** | For VRI technology (according to Perry et al., 2012; Grafton IS 2013):<br>- **Technology Lifetime**: (-)<br>- **Investment Cost**: 5,000 – 30,000 € (depending on the size of the center pivot system/number of controlled sprinklers)<br>- **Operation Cost**: Lower pumping costs (15-20%), weed-management costs in non-cropped areas (water and nutrients no longer applied) and fertilizer costs.<br>A significant potential for water savings by **VRI technologies** suggests that they **will become more affordable as irrigation costs increase**, as discussed by Sadler et al. (2005). In addition to cost benefits associated with water charges and reduced pumping costs, VRI allows better strategic use of allocated freshwaters. Technology adoption and higher management levels with the associated nonlinear rises in marginal costs.<br>According to Hedley et al. (2009), the direct value of water savings using VRI was estimated to be 35−149 NZ$/ha under the three contrasting primary productions, a significant saving to the producer. In addition VRI reduced the pollution risk and extraction demand on freshwaters, two of the suite of freshwater ecosystem services, valued at about NZ$30 000/ha. |
| **Water saving** | Hedley and Yule (2009) found significant **potential water savings of 21.8–26.3%** when irrigation water is adjusted for variable soil AWCs and site-specific factors, such as poor drainage. Similarly, computer simulation studies comparing conventional and 'optimized' advanced site-specific zone control by center pivot irrigation have reported **water savings of up to 26 %** (Evans and King, 2012). According to Perry et al. (2012), potential average reductions due to VRI in water use compared to uniform irrigation processes is about **8-20%**.<br>The expected increase in both **yield** and **water productivity** components is related to the reduction of irrigation requirements ***(I)***, evaporation ***(E)*** and deep percolation losses ***(DP)***, and thus to the reduction of non-beneficial uses (***NBWU***):<br>$Y = WUE_T\, T = WUE_T \left[ C_S \left( (\boldsymbol{I} + P + CR + R_{on}) - (\boldsymbol{E} + T_{weed} + \boldsymbol{DP} + R_{off} \right) \right]$ |

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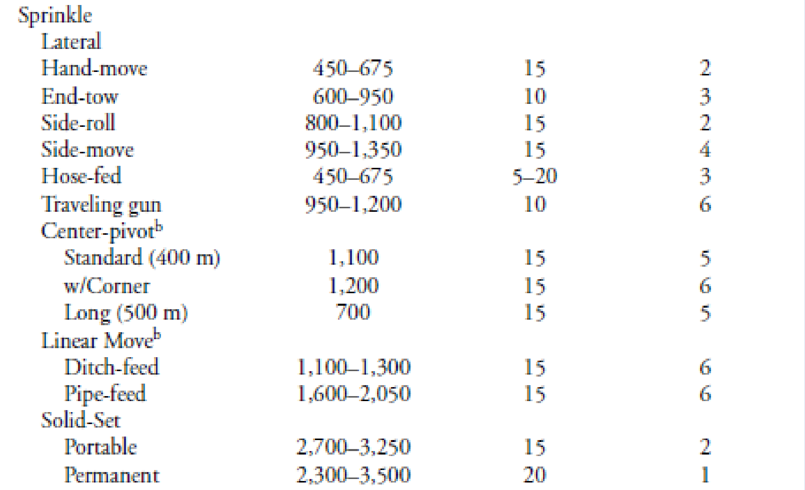
| | $WP = \frac{Y}{P + CR + \Delta SW + \boldsymbol{I}} = \frac{Y}{(ETc + LF) + \boldsymbol{NBWU}}$ |
| **Energy efficiency** | Grafton IS (2013) reports potential **energy savings** of about 5.6%, resulting in 27-77 kg $CO_2$-eq/ha/yr reductions. |
| **Physical efficiency** | |
| **Environmental impacts** | VRI technology has the following expected beneficial impacts (Hedley et al., 2009; Perry et al., 2012; Nilson et al., 2013):<br>- to **minimize water waste due to deep percolation and runoff**<br>- to **reduce the fertilizers/chemicals requirements** of the crop;<br>- to **reduce environmental pollution** due to the leaching of nutrients;<br>- **reduction of weed and disease problems**;<br>- **less energy-related $CO_2$ emissions**.<br>Hedley et al. (2009) have evaluated VRI for three different combinations of crops (pasture, maize and potato) and soils using some performance indicators (irrigation water use per season; drainage and runoff; nitrogen leaching; energy usage per season; irrigation water use efficiency), and they found that VRI **saved 9 − 19 % irrigation water**, with accompanying energy saving; loss of water by **drainage was also reduced by 20 − 29%** using VRI, which **reduced the risk of nitrogen leaching**.<br>Perry et al. (2012) reported 20% reduction in $CO_2$ – equivalents emissions in New Zealand for dairy pasture and corn VRI-irrigated fields. |
| **Applications/ Innovative character** | Research into variable-rate irrigation technology for centre pivot and lateral move irrigation machines has spanned 20 years and produced a number of **commercial systems** (e.g. *Farmscan, Valmont, Zimmatic*). Manufacturers are just starting to offer site-specific controls for linear move sprinkler systems. Kranz et al. (2012) has summarized characteristics of some of the various commercial **site-specific control systems and panels**.<br>A **significant improvement of zone control SS-VRI technology is projected in the future** in relation to: (1) their cost-effectiveness due to higher water and energy costs; (2) regulatory limits on water application amounts; (3) economic incentives in compliance with environmental and other regulations; and (4) demonstrated increased economic returns (Evans et al.; 2013). |
| **Main references** | Evans et al.; 2013; Smith et al., 2009; Perry et al., 2012; Sadler et al. 2005; Hedley and Yule, 2009; Evans and King, 2012; Perry et al., 2012; Kranz et al., 2012; Nilson et al., 2013; Hedley et al., 2009. |

<table>
<tr><th>Technology</th><th>Sprinkler Irrigation</th></tr>
<tr><td>Short description</td><td>One way of improving water use efficiency is to replace gravity-fed irrigation systems such as border check and furrow, with more efficient pressurized systems (Zehnder et al., 2003; Lal, 2004; Playan and Mateos, 2006), because these conversions can offer a significant reduction in water application at the field scale. It seems reasonable to assume that one option for modernization will be **to convert to pressurized irrigation systems in order to generate significant water savings**. Sprinkler irrigation is the method by which pressurized water is ejected through the nozzle of the sprinkler-device and it is sprayed on the land in the form of artificial rain. Small sprinkler heads can operate at low pressures/flow conditions and are suitable when a small radius of throw is required (mini-sprinklers operate at flow rates between 150-300 l/h).</td></tr>
<tr><td>Sector - Stage</td><td>**Agricultural water sector – Water Use (on-farm cropped plots)**</td></tr>
<tr><td>Eco-efficiency scenario</td><td>The given technology/practice addresses productivity improvement by **breakthrough new technologies or practices** to redefine a new efficiency frontier, aiming at producing more output (yield) with a smarter use of the same inputs (if shifting from surface methods).</td></tr>
<tr><td>Economic aspects</td><td>**Initial costs are higher** than for surface irrigation systems. Table 11 contains indicative values for **initial investment costs** (US dollars)**, economic equipment life, and maintenance costs** (% of cost) of different types of sprinkler systems (Pereira and Trout, 1999; Keller, 1992).<br><br><table>
<tr><td>Sprinkle</td><td></td><td></td><td></td></tr>
<tr><td>Lateral</td><td></td><td></td><td></td></tr>
<tr><td>Hand-move</td><td>450–675</td><td>15</td><td>2</td></tr>
<tr><td>End-tow</td><td>600–950</td><td>10</td><td>3</td></tr>
<tr><td>Side-roll</td><td>800–1,100</td><td>15</td><td>2</td></tr>
<tr><td>Side-move</td><td>950–1,350</td><td>15</td><td>4</td></tr>
<tr><td>Hose-fed</td><td>450–675</td><td>5–20</td><td>3</td></tr>
<tr><td>Traveling gun</td><td>950–1,200</td><td>10</td><td>6</td></tr>
<tr><td>Center-pivot[b]</td><td></td><td></td><td></td></tr>
<tr><td>Standard (400 m)</td><td>1,100</td><td>15</td><td>5</td></tr>
<tr><td>w/Corner</td><td>1,200</td><td>15</td><td>6</td></tr>
<tr><td>Long (500 m)</td><td>700</td><td>15</td><td>5</td></tr>
<tr><td>Linear Move[b]</td><td></td><td></td><td></td></tr>
<tr><td>Ditch-feed</td><td>1,100–1,300</td><td>15</td><td>6</td></tr>
<tr><td>Pipe-feed</td><td>1,600–2,050</td><td>15</td><td>6</td></tr>
<tr><td>Solid-Set</td><td></td><td></td><td></td></tr>
<tr><td>Portable</td><td>2,700–3,250</td><td>15</td><td>2</td></tr>
<tr><td>Permanent</td><td>2,300–3,500</td><td>20</td><td>1</td></tr>
</table><br>On average, for sprinkler systems: Technology Lifetime: 15 years; Investment Cost: 2,000 €/ha; Operation Cost: 10% of investment cost.<br>Mechanized sprinkler systems require very little **labor** and are relatively simple to manage. Periodic-move sprinkler systems require only unskilled labor; irrigation management decisions are made by the manager. Fixed sprinkler systems require very little field labor during the irrigation season and may be fully automated.</td></tr>
<tr><td>Water saving</td><td>Converting from flood to pressurized systems result in a **reduction in water application** ranging between 10% and 66%.<br>Attainable average **field application efficiency** are: 65-75% (set-sprinkler), 80-95% (centre pivot), 85-90% (lateral move) (Pereira and Trout, 1999). Properly designed and managed pressurized systems can attain 90% efficiency (Dechmi et al., 2003a, b).<br>Windy and dry conditions may reduce the application efficiency by 5-10%.</td></tr>
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| | The expected increase in both **yield** and **water productivity** components is related to the increase in crop yield ***(Y)*** and evapotranspiration ***(ETc)***; on the other side, the reduction nof both evaporation ***(E)*** and deep percolation losses ***(DP)***, and thus to the reduction of non-beneficial uses (***NBWU***), in respect to the surface irrigation methods.<br>$Y = WUE_T\,\boldsymbol{T} = WUE_T\left[C_S\left(\left(\boldsymbol{I} + P + CR + R_{on}\right) - \left(\boldsymbol{E} + T_{weed} + \boldsymbol{DP} + R_{off}\right)\right)\right]$<br>$WP = \frac{\boldsymbol{Y}}{P + CR + \Delta SW + \boldsymbol{I}} = \frac{\boldsymbol{Y}}{(\boldsymbol{ETc} + LF) + \boldsymbol{NBWU}}$ |
| **Energy efficiency** | **Energy costs for pressurizing water is a significant expense**, depending on the pressure requirements of sprinklers used and power costs. In general, **energy** requirements are **increased 4-5 times** in respect to surface irrigation method.<br>Direct energy inputs are primarily the fuel sources used to operate farm machinery and pumps. Between **23% and 48% of direct energy used for crop production is used for on-farm pumping** (Hodges et al., 1994; Lal, 2004). Where **groundwater** is used for irrigation, **converting to pressurized micro-irrigation systems can decrease energy consumption, with values ranging between** 12% and 44% (Hodges et al., 1994; Srivastava et al., 2003).<br>Batty and Keller (1980) estimated pumping energy needed for different lift heights, and reported that energy required for surface irrigation (MJ/ha m) was 3184 for 0 m lift, 56,250 for 50 m lift and 109,317 for 100 m lift. The energy required was high for hand moved, side roll and center-pivot sprinkle system. In comparison, energy required was low for the trickle system, and was estimated (MJ/ha m) at 20,637 for 0 m lift, 50,118 for 50 m lift and 79,599 for 100 m lift . |
| **Physical efficiency** | **Increase in crop yield** (on average +18-50%) is observed, resulting from improved irrigation uniformity, the control of the irrigation depth, and a flexible irrigation scheduling. |
| **Environmental impacts** | Sprinklers can **leach salts from saline soils** more effectively than surface or micro-irrigation methods.<br>**Irrigation is a very Carbon-intensive practice**. Sloggett (1992) estimated that 23% of the on-farm energy use for crop production in the US was for on-farm pumping. Dvoskin et al. (1976) assessed fuel consumption for lifting irrigation water in several regions of the western US. The **C emission** ranged from 7.2 to 425.1 kg CE/ha for 250 mm of irrigation and from 53.0 to 850.2 kg CE/ha for 500 mm of irrigation. Schlesinger (1999) estimated C emission from irrigation at 220–830 kg CE/ha/year. |
| **Applications/ Innovative character** | Sprinklers are available in **a wide range of characteristics and capacities** and are **suitable for most crops and adaptable to most irrigable soils**. Sprinklers can be adapted to most climatic conditions, but high wind conditions decrease distribution uniformity and increase evaporation losses, especially when combined with high temperatures and low air humidity. Although sprinkling is adaptable to most topographic conditions, large elevation differences result in non-uniform application unless pressure regulation devices are used (Keller and Bliesner, 1990; Giller 1996). |
| **Main references** | Howell, 2003; Zehnder et al., 2003; Lal, 2004; Playan and Mateos, 2006; Pereira and Trout, 1999; Keller, 1992; Dechmi et al., 2003a,b; Hodges et al., 1994; Srivastava et al., 2003; Batty and Keller, 1980; Sloggett, 1992; Schlesinger; 1999; Keller and Bliesner, 1990; Giller 1996. |

## Technology: Micro-irrigation (drip and subsurface)

**Short description**

One way of improving water use efficiency is to replace gravity-fed irrigation systems such as border check and furrow, with more efficient pressurized systems (Zehnder et al., 2003; Lal, 2004; Playan and Mateos, 2006), because these conversions can offer a significant reduction in water application at the field scale. It seems reasonable to assume that one option for modernization will be **to convert to pressurized irrigation systems in order to generate significant water savings**.

**Drip irrigation** systems (surface or sub-surface) utilize a number of point sources for the slow and precise application of water/nutrients directly to the root zones in a controlled flow/pattern that satisfies the peak crop water requirements. **Subsurface drip irrigation (SDI)** is a variation of the conventional surface drip irrigation. SDI systems supply water to crops through buried plastic drip lines with emission points that deliver water underground at a depth where most of the rooting system reside.

**Sector - Stage**

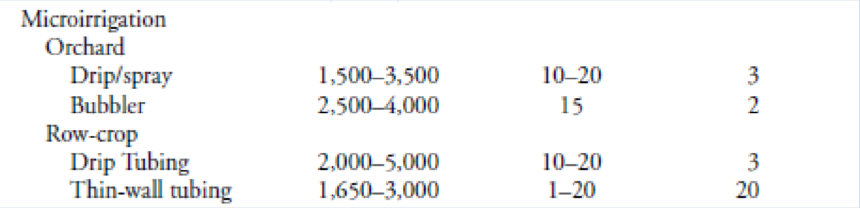
**Agricultural water sector – Water Use (on-farm cropped plots)**

**Eco-efficiency scenario**

The given technology/practice addresses productivity improvement by **breakthrough new technologies or practices** to redefine a new efficiency frontier, aiming at producing more output (yield) with a smarter use of the same inputs (if shifting from surface methods).

**Economic aspects**

The major constraints are the high investment and management costs. **Initial costs are higher** than for surface irrigation systems. Table 11 contains indicative values for **initial investment costs** (US dollars)**, economic equipment life, and maintenance costs** (% of cost) of different types of sprinkler systems (Pereira and Trout, 1999; Keller, 1992).



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|---|---|---|---|
| Microirrigation | | | |
| Orchard | | | |
| Drip/spray | 1,500–3,500 | 10–20 | 3 |
| Bubbler | 2,500–4,000 | 15 | 2 |
| Row-crop | | | |
| Drip Tubing | 2,000–5,000 | 10–20 | 3 |
| Thin-wall tubing | 1,650–3,000 | 1–20 | 20 |

On average, for drip: Technology Lifetime 15 years; Investment Cost 3,000-5,000 €/ha; Operation Cost 10% of investment cost. Slightly higher costs for subsurface drip: Technology Lifetime 15 years; Investment Cost 4,000-6000 €/ha; Operation Cost: 12% of investment cost.

**Equipment costs usually are higher** than for surface irrigation systems and may be higher than for sprinkler systems. Equipment often is complex and requires frequent monitoring to ensure good performance.

Subsurface drip usually requires **specialized tillage operations and equipment**, and also requires special equipment or management to prevent roots from growing into and plugging the emitters.

It can **reduce the cost of labor** because the systems need only to be maintained and managed, not tended. Operation usually is accomplished by automatic timing devices, but the emitters and system controls should be inspected frequently.

It can reduce weed growth and the incidence of some diseases because foliage and much of the soil surface are not wetted. This **reduces costs of labor and chemicals to control weeds** and diseases and reduces related pollution hazards.

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| **Water saving** | **Drip irrigation**, especially in horticultural systems, offers a **high potential to limit water inputs**, to **improve water use efficiency**, and to better match the crop water demand in time and space.<br>This method results in **great water savings** (from 15-45% compared to surface irrigation) because of the high application uniformity and efficiency. Attainable average **application efficiency** are: 85% (trickle and micro-spray), 90% (subsurface drip). Properly designed and managed systems can attain 95% efficiency (Pereira and Trout, 1999).<br>The top soil and the canopy are kept dry, thus **reducing weed growth** as well as water losses by **soil evaporation** (especially with SDI) and surface runoff. Additionally, SDI can be used to control the volume and intensity of applied water and thus **limiting percolation losses**.<br>The expected increase in both **yield** and **water productivity** components is related to the reduction of irrigation requirements ***(I)***, and to the reduction of ***E***, ***Tweed***, ***DP***, ***Roff***, and thus to the reduction of non-beneficial uses (***NBWU***):<br>$Y = WUE_T\, T = WUE_T \left[C_S \, ((\boldsymbol{I} + P + CR + R_{on}) - (\boldsymbol{E} + \boldsymbol{T_{weed}} + \boldsymbol{DP} + \boldsymbol{R_{off}})\right]$<br>$WP = \dfrac{Y}{P + CR + \Delta SW + \boldsymbol{I}} = \dfrac{Y}{(ETc + LF) + \boldsymbol{NBWU}}$ |
| **Energy efficiency** | **Energy costs for pressurizing water is a significant expense**, depending on the pressure requirements and power costs. Anyway, by shifting the irrigation method from sprinkle to mini-sprinkle and from mini-sprinkle to drip-irrigation, **water and energy savings** can be achieved through reducing the water input and pressure requirements. It usually requires lower operating pressure and thus **less energy than sprinkler systems**. |
| **Physical efficiency** | Micro-irrigation systems should be used to achieve the **highest returns and yields** while optimizing the use of water and other production inputs (18-50% yield increase). **Yields** (and **quality**) often (but not always) exceed those obtained by other irrigation methods. This is because, inside the bulb, light, frequent irrigations and fertilizer applications (fertigation) can maintain optimum growth conditions. Irrigation frequency varies from daily to every three or four days.<br>Phene et al. (1987) demonstrated **significant yield increases** in tomatoes with the use of **high frequency SDI** and precise fertility management. Hutmacher et al. (1996) demonstrated yield increases in alfalfa production using SDI systems buried at a depth of 0.7 m. Ayars et al. (1999) reviewed **significant yield and water use efficiency increases under SDI for many crops**. |
| **Environmental impacts** | A greater control over fertilizer placement and timing through fertigation with micro-irrigation **improves fertilizer efficiency** and **reduces pollution hazards** associated with fertilizers.<br>A subsurface drip irrigation system combined with surface applied fertigation, resulted also in a **reduction of nitrate leaching**, an increase in the nitrogen uptake efficiency, and similar or higher yields compared to other treatments.<br>However, lack of periodic leaching from irrigation or rainfall can result in harmful **soil salt concentrations near the edges**. These salt concentrations can be especially damaging during germination of new crops, or if rainfall moves the accumulated salts back into the active rooting area. Periodic large water applications are required to **leach out salts**. |

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| **Applications/ Innovative character** | Corn and soybean farm, switched to drip irrigation and achieved $160/acre (1 acre = 0.4047 ha) reduced costs due to reduced use of fuel, chemicals, fertilizers, labor and cultivation expenses – Nebraska, USA (Drip Irrigation, 2013)<br>Well-designed micro-irrigation systems can operate efficiently on almost any topography. Problem soils with low infiltration rates, low water-holding capacity, and variable textures and profiles can be irrigated efficiently. |
| **Main references** | Zehnder et al., 2003; Lal, 2004; Playan and Mateos, 2006; Pair *et al.;* 1983; Keller and Bliesner, 1990; and Papadopoulos, 1996; Pereira and Trout, 1999; Keller, 1992; Ayars et al., 1999; Drip Irrigation, 2013 |

| **Technology** | **Supplemental Irrigation (SI) and Regulated Deficit Irrigation (RDI)** |
|---|---|
| **Short description** | Deficit irrigation (DI) could be defined as an ‘**optimization strategy**’ in which irrigation is applied during drought-sensitive growth stages of a crop, while outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water (Geerts and Raes, 2009).<br>The term **supplemental irrigation** has been used in arid zones to define the practice of applying small amounts of irrigation water to winter crops that are normally grown under rain-fed conditions to augment and stabilize yields (Oweis et al., 1998). Such additions, if well managed, **increase the utilization efficiency of the rainfall** and **irrigation water**.<br>Another specific type of DI Is the so-called ‘**Regulated Deficit Irrigation (RDI)**’ which consists of inducing mild to moderate plant water deficits during specific phenological stages by withholding irrigation or by applying less water than plants would use under normal conditions, with the aim of reducing vegetative growth and to improve qualitative aspects of crop production. RDI has had significantly more success in **tree crops and vineyards** than in field crops for a number of reasons (Fereres et al., 2003). |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | ‘Deficit irrigation’ practices address productivity improvement by **moving along the efficiency frontier**, but with associated increase in riskiness, and aim to produce **less outputs (yield)** but with **much less inputs (water)** |
| **Economic aspects** | DI is somehow a technique aimed at the **optimization of economic output** when water is limited (Zwart and Bastiaansen, 2004; Fan et al., 2005). In areas where water is the most limiting factor, water demand for irrigation can be reduced and the water saved can be diverted for **alternative uses**. For instance, water saved by DI can be used to irrigate more land, which – given the high opportunity cost of water – may largely compensate for the economic loss due to yield reduction (Kipkorir et al., 2001; Ali et al., 2007).<br>**Economic return in tree crops and vineyards** is often associated with factors such as **crop quality**, not directly related to biomass production and water use. Because of their high WP, tree crops and vineyards can afford high-frequency, micro-irrigation systems that are ideally suited for controlling water application and thus for stress management (Fereres and Goldhamer, 1990). |
| **Water saving** | It is demonstrated under several conditions and crop types, that RDI practices allow substantial **reduction in total water application** together with a maximization of **water productivity**.<br>Deficit irrigation, apart from reducing the irrigation applications (***I***), is expected to reduce soil evaporation (***E***), weed’s transpiration (***Tweed***), and also to limit deep percolation (***DP***):<br>$Y = HI\ \frac{\boldsymbol{B}}{\boldsymbol{T}}\left[C_S\left(\left(\boldsymbol{I} + P + CR + R_{on}\right) - \left(\boldsymbol{E} + \boldsymbol{T_{weed}} + \boldsymbol{DP} + R_{off}\right)\right)\right]$<br>Thus, the expected increase of the **water productivity** at field-farm level is related to the effect on both yield (***Y***) relative to the corresponding reduction in water application (***I*** *and* ***ΔSW***) as well as on some non-beneficial uses:<br>$WP = \frac{\boldsymbol{Y}}{P + CR + \Delta\boldsymbol{SW} + \boldsymbol{I}} = \frac{\boldsymbol{Y}}{(\boldsymbol{ETc} + LF) + \boldsymbol{NBWU}}$ |

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| **Energy efficiency** | Energy savings are expected in relation to the reduction of irrigation applications and related pumping. |
| **Physical efficiency** | In the case of SI, research results showed substantial **increases in crop yield** in response to the application of relatively small amounts of supplemental irrigation. Average **rainwater productivity** in the dry areas is about 0.35 kg $m^{-3}$, but it may be increased up to 1.0 kg $m^{-3}$ with improved management and favorable rainfall distribution (Pala and Oweis, 2002).<br>In the case of RDI, **reducing ET** result in **a reduction in yield**, but in most cases, the **quality** of the production (e.g. sugar content) tends to be equal or even superior to rain-fed or full irrigated cultivation.<br>Each DI strategy has its optimum fertilizer level, so DI is most effective if different management factors are considered in parallel, and often there is a **win–win effect of DI and reduced fertilizer application** (Fox and Rockstrom, 2000, 2003). |
| **Environmental impacts** | Reducing irrigation applications over the crop cycle **reduce nutrient loss** through leaching from the root zone, resulting in **improved ground water quality** and **lower fertilizer needs** (e.g. Unlu et al., 2006).<br>Anyway, one consequence of reducing irrigation water use by DI is the greater **risk of increased soil salinity due to reduced leaching**, and its impact on the sustainability of the irrigation (Schoups et al., 2005). |
| **Applications/ Innovative character** | The concept of RDI was first proposed by Mitchell and Chalmers (1982) to control vegetative growth in **peach** orchards. Experiments with RDI have been successful in many fruit and nut tree species such as **almond, pears, pistachio, citrus, apple, apricot, wine grapes, and olive**, almost always with positive results. For example, the quality of wine in semi-arid areas is strongly associated by enologists with water stress, and the benefits of RDI to the yield and quality of wine grapes have been clearly demonstrated relative to rain-fed production (Girona et al., 2006). |
| **Main references** | English, 1990; Pereira et al., 2002; Fereres and Soriano, 2007; Geerts and Raes, 2009; Zwart and Bastiaansen, 2004; Fan et al., 2005; Kipkorir et al., 2001; Ali et al., 2007; Fox and Rockstrom, 2000, 2003; Unlu et al., 2006; Schoups et al., 2005; Girona et al., 2006; Mitchell and Chalmers, 1982. |

| Technology | Variable Speed Pumps |
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| **Short description** | **Variable speed drive (VSD) technology** is used to control the speed of the pump, and consequently to reduce the pressure head of the pump depending on the discharge demanded upstream (Lamaddalena and Piccinni 1993; Tolvanen 2008). This technology has the potential to enhance the efficiency of the whole system by consuming the minimum required energy through adjusting the power driving the pump depending on the actual demand rate.<br>Lower flow rates and head also increase pump bearing and seal life, by reducing the hydraulic forces and vibrations/noise acting on the components in motion (e.g. impeller, piston, diaphragm). |
| **Sector - Stage** | **Agricultural water systems – Distribution networks (secondary networks)** |
| **Eco-efficiency scenario** | Variable Speed Pumps are particularly useful when the high fluctuations of water demand could be expected during the working hours of the system. |
| **Economic aspects** | Technology lifetime: 15 years<br>Investment cost: 30,000 €<br>Operational cost: The use of energy consuming control valves can potentially be eliminated and hence, operating cost might be reduced. |
| **Water saving** | Water saving is due to the reduced levels of overall dynamic head, leakages will be minimized and water savings might be achieved. |
| **Energy efficiency** | Several works have been published on this subject in the last few decades on **potential energy savings**. Lamaddalena and Piccinni (1993) showed that using variable speed pumps in two Italian irrigation districts, around **20% of energy** could be saved. Ait Kadi et al. (1998) demonstrated that around **25% of energy** can be saved in an irrigation district in Morocco using the variable speed pump technology. Field tests made by Hanson et al. (1996) on five pumping stations serving different irrigation networks showed that variable speed pumps allow saving from **32 to 56% of energy** compared to classical pumps regulation. More recently, Lamaddalena and Khadi (2012) demonstrated that in comparison with the current pumping station regulation, **energy savings of about 27 and 35%** may be achieved for the two Italian districts. |
| **Physical efficiency** | |
| **Environmental impacts** | Minimization of energy consumption. Water savings. |
| **Applications/ Innovative character** | |
| **Main references** | Lamaddalena and Piccinni 1993; Lamaddalena and Khadi, 2012; Ait Kadi et al. 1998; Hla and Scherer 2001. |

| Technology | Network sectoring and dynamic pressure regulator |
|---|---|
| Short description | **Pressurized networks require large amounts of energy for their operation**. For example in Spain, where an ambitious modernization plan of irrigation schemes has been carried out, Corominas (2009) reported than while water use has been reduced from 8,250 to 6,500 $m^3$/ha (-21%) from 1950 to 2007, the energy demand was increased from 206 to 1,560 kWh/ha (+657%) in this period.<br>**Network sectoring** supports energy demand optimization in pressurized networks according to homogeneous energy demand sectors and organizing farmers in irrigation turns, pumping station adaptation to several water demand scenarios, detection of critical points within the network and energy audits. |
| Sector - Stage | **Agricultural water systems – Distribution networks (secondary networks)** |
| Eco-efficiency scenario | Sectoring of irrigation networks into smaller operational units |
| Economic aspects | |
| Water saving | **Conveyance efficiencies** are significantly improved from typical values of 60–70% for open channels to values **close to 100% for pressurized networks** (Rodrıguez Dıaz et al., 2008). Furthermore, these new systems allow farmers to use more efficient on-farm irrigation systems such as trickle irrigation or sprinklers since they receive water at their hydrants at suitable pressures.<br>These systems can be **easily automated** and give farmers the **possibility of remote scheduling**. This has led to water consumption being dramatically reduced in Southern Spain where their introduction has **reduced water consumption up to 50%** (Rodrıguez Dıaz et al., 2008).<br>**Network sectoring** does not contribute directly to water saving while **dynamic pressure regulators** can reduce water use due to leakage and improve the overall functioning (efficiency) of irrigation devices downstream. |
| Energy efficiency | According to Rodriguez Diaz et al. (2009), sectoring is the most effective measure with average potential **energy savings of around 20%**. This is consistent with other authors' findings (Sanchez et al. 2009; Jimenez Bello et al. 2010). Carillo Cobo et al. (2011) developed a methodology for optimal sectoring, and results showed that organizing the networks in sectors, **annual energy savings of 5-8%** were achieved, and these savings rose **up to 9-27%**, respectively when the local practices (deficit irrigation) were taken into account.<br>According to Diaz et al. (2009), **energy saving of up to 27%** could be achieved by adopting techniques such as **pressure dynamic regulation and sectoring**. Jimenez-Bello et al. (2010) showed that **energy savings around 36%** could be possible, and operational network conditions can be improved by guaranteeing at least the minimum pressures at the hydrants. |
| Physical efficiency | |
| Environmental | Minimization of energy consumption. Water savings. |

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| **impacts** | |
| **Applications/ Innovative character** | |
| **Main references** | Rodrıguez Dıaz et al., 2008, 2009; Corominas, 2009; Carillo Cobo et al. (2011); Jimenez-Bello et al. (2010) |

| **Technology** | Crop and variety selection |
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| **Short description** | One of the most important crop management strategies under conditions of water limitations is the appropriate **selection of crop species and varieties** adapted to the **timing, amount and frequency of rainfall**. For major field crops, there are many examples where the use of early maturing (or early flowering) cultivars increased and stabilized grain yield, especially in conditions of terminal drought (Woodruff and Tonks, 1983; Stapper and Harris, 1989; Fereres et al., 1993, 1998). **Improved varieties** well adapted to specific conditions can improve soil water use and increase yield. These varieties should be **tolerant to abiotic stresses** such as cold, drought and heat, and biotic stresses such as diseases and insects (Dakheel et al. 1993). Varieties with **vigorous early growth** and a **deep root system** would use soil water at a rapid rate and would decrease evaporative losses (Gregory 1991).<br>In the case of **irrigated areas**, the objective is to select the cropping pattern that could assure the highest economic return under specific pedo-climatic and socio-economic scenario. |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | Productivity is expected to be improved by **addressing system inefficiencies through a best practice** for a certain level of input and risk. The goal is to **produce more desired outputs** with a **smarter use of the same inputs**. |
| **Economic aspects** | Depends on cropping pattern |
| **Water saving** | The choice of drought-tolerant crops (and varieties) is a mean of adaptation to drought-prone environments and of **increasing *WUE***. The value of $WUE_T$ is higher for C4 crops such as maize and sorghum than for C3 crops like sunflower, wheat and legumes. However, $WUE_T$ is higher during periods of low vapor pressure deficit (VPD), as in the cool winter months. Similarly, $WUE_T$ could be increased by using early cultivars tolerating low temperatures. At the plant/crop level, **yield** is expected to increase in relation to the potential increase of the **harvest index** (***HI***) and **water use efficiency** (***WUE***). The selection of crop/varieties with vigorous early growth and/or deep rooting system, so with higher crop competitiveness, allows to reduce soil **evaporation** (***E***) and weed's transpiration (***Tweed***), and also to limit deep percolation (***DP***):<br>$$Y = \boldsymbol{WUE_T}\, T = \boldsymbol{HI}\, \frac{Y}{T}\, T = HI\, \frac{B}{T} \left[C_S \left(\left(I + P + CR + R_{on}\right) - \left(\boldsymbol{E} + \boldsymbol{T_{weed}} + \boldsymbol{DP} + R_{off}\right)\right)\right]$$<br>Thus, the expected impact on the **water productivity** at field-farm level is relative to the increase in yield (***Y***), to the more efficient use of rainfall pattern (***P***) and to the possible reduction of some non-beneficial uses (soil evaporation, weed's transpiration):<br>$$WP = \frac{\boldsymbol{Y}}{\boldsymbol{P} + CR + \Delta SW + I} = \frac{\boldsymbol{Y}}{(ETc + LF) + \boldsymbol{NBWU}}$$ |
| **Energy efficiency** | Depends on cropping pattern |

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| **Physical efficiency** | Increase in **yield and/or water productivity**. Selected cultivars adapted to different rainfall zones generally combine high yield potential and stress tolerance (Nachit et al. 1992). |
| **Environmental impacts** | Depends on cropping pattern |
| **Applications/ Innovative character** | Based on on-farm trials in the highlands of Turkey, the highest yielding wheat variety with recommended cultural practices provided 48% more grain yield than a local variety under recommended practices, while the increase was about six times compared with the local variety under local practices (Durutan et al. 1987). Similarly in the lowlands of Syria, the improved bread wheat varieties Cham 4 and 6, gave 30-51% grain yield increase compared to the older variety Mexipak 65, under different water and N regimes (Oweis et al. 1998). |
| **Main references** | Woodruff and Tonks, 1983; Stapper and Harris, 1989; Fereres et al., 1993, 1998; Dakheel et al. 1993; Gregory 1991; Nachit et al. 1992; Oweis et al. 1998. |

| **Technology** | **Early sowing and crop ‘rationing’** |
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| **Short description** | More rainfall can be captured by better **adjustment of the cropping pattern to the rainfall season**. Transpiration (T) by annual crops in Mediterranean-type climates is offset or delayed in relation to incoming rainfall. **Earlier sowing** to more closely match incoming rainfall and reduce soil evaporation will increase yield and rainfall-use efficiency (French and Schultz, 1984a; Siddique et al., 1998). The term ‘**crop rationing**’ describe a management option that modifies the seasonal water balance by reducing crop water uptake in order to save water for the most susceptible growth stages. Reducing crop water requirement could be achieved by **specific crop management strategies**, such as low plant densities, wide inter-rows, plant thinning (or defoliation) and moderate N fertilization resulting in N deficiency during shooting (Debaeke and Aboudrare, 2004). |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | Productivity is expected to be improved by **addressing system inefficiencies through a best practice** for a certain level of input and risk. The goal is to produce **more desired outputs** with a **smarter use of the same inputs** |
| **Economic aspects** | |
| **Water saving** | Early sowing, together with some management practices (increased fertilizer input, planting density and reduced row width), is effective in supporting the **reduction of *E/ET*** (Loss and Siddique, 1994; Soltani and Galeshi, 2002). Additionally, because of the rapid canopy closure, **crop competitiveness with weeds** should be increased (thus reducing the weed transpiration component). If crop cycle and development are optimized under the given climatic conditions, a **reduction** in water **deep percolation** could be expected, thus reducing the ‘non-consumptive’ fraction. Directing biomass production into **periods of lowest atmospheric demand** confers an advantage (Gregory 1991; Gupta 1995).<br>At the plant/crop level, **yield** is expected to increase in relation to the potential increase of the **harvest index** (***HI***) and the lower vapour pressure deficit (***VPD***) of the environment:<br>$Y = \boldsymbol{HI}\,\frac{B}{T}\,\frac{(ET - E)}{\boldsymbol{VPD}}$<br>According to several experiments, yield is expected to increase because of the increase in **water use efficiency** (***WUE***), together with a potential reduction in soil **evaporation** (***E***), weeds’ transpiration (***Tweed***) and deep percolation (***DP***):<br>$Y = \boldsymbol{WUE_T}\,T = \boldsymbol{HI}\,\frac{B}{T}\left[C_S\left(\left(I + P + CR + R_{on}\right) - \left(\boldsymbol{E} + \boldsymbol{T_{weed}} + \boldsymbol{DP} + R_{off}\right)\right)\right]$<br>Thus, the expected impact on the **water productivity** at field-farm level is relative to the increase in yield (***Y***), to the more efficient use of rainfall pattern (***P***) and to the possible reduction of some non-beneficial uses (soil evaporation, weeds’ transpiration, deep percolation):<br>$WP = \frac{\boldsymbol{Y}}{\boldsymbol{P} + CR + \Delta SW + I} = \frac{\boldsymbol{Y}}{(ETc + LF) + \boldsymbol{NBWU}}$ |
| **Energy** | |

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| **efficiency** |  |
| **Physical efficiency** | Early sowing of crops is a very important mean of **maximizing crop yield and *WUE***. In fact, increasing the early growth of the canopy when the soil surface is usually damp and the vapour pressure deficit is low has proved effective in increasing WUE.<br>E.g. Bonari et al. (1989) found that an early sowing of ten days increased the yield of 54, 35 and 17% for maize, soybean and sunflower, respectively. Hence also biomass and yield water use efficiencies increased significantly in all the crops except of sunflower, although the water use in early sowing was higher than in the normal sowing. |
| **Environmental impacts** |  |
| **Applications/ Innovative character** | In semi-arid Mediterranean regions, shifting from summer cereals to winter ones allows the efficient use of winter and spring rainfall (Oweis and Hachum, 2003). Under conditions of water shortages, cultivation strategies can be adopted to accumulate sufficient biomass early in the season without depleting available soil water to the extent that shortages occur later in the season (Debaeke and Aboudrare, 2004).<br>Eastham and Gregory (2000) showed that earlier planting of wheat and lupin crops in a Mediterranean-type environment did not affect the total evapotranspiration, but reduced soil evaporation, particularly early in the season before the leaf area of the later-sown crop reached full ground cover. In some cases, this resulted in higher yields and water-use efficiency (and rainfall-use efficiency) of the early-sown crops. |
| **Main references** | French and Schultz, 1984a; Siddique et al., 1998; Debaeke and Aboudrare, 2004; Loss and Siddique, 1994; Soltani and Galeshi, 2002; Gregory 1991; Gupta 1995; Oweis and Hachum, 2003; Eastham and Gregory, 2000. |

| **Technology** | **Super-High Density (SHD) plantations (in olive farming)** |
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| **Short description** | In olive oil production, **new orchards are drip irrigated and planted at higher densities**, in order to achieve greater yields with reduced alternate bearing behavior (Beede and Goldhamer, 1994). The super-high-density (SHD) system (1500–2500 trees per/ha) was developed within the past decade to use over-the-row **mechanical harvesters to reduce the costs** of hand harvesting and to bring orchards into production within only a few years after planting. In order to limit tree size within this system and accommodate the harvester, vegetative vigor of the tree must also be managed. |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | |
| **Economic aspects** | Shifting from medium-high density to super-high density orchards also implies an **increase of input resources needs**. Moreover, farmers' decision for a new investment based in one system or the other is related with the capacity of investment, yield targets and the soil variability and quality. |
| **Water saving** | A viable **strategy to reduce environmental pressure of SHD orchards** on water resources is **deficit irrigation (DI)**. DI strategy could be the best option for SHD olive orchards, since problems derived from excessive tree vigour, common in this type of orchards, can be minimized by reduced irrigation<br>There are examples of a variety of **irrigation strategies applied to olive orchards with high plant densities**, from supplementary irrigation (Proietti et al. 2012) to full irrigation (Pastor et al. 2007). According to Fernandez et al. (2013) results of an appropriate RDI treatment showed the best balance between water saving, tree vigour and oil production, with a **potential 72% water saving as compared to FI**, while the corresponding reduction in oil yield was 26 % only.<br>The expected impact on **water productivity** components is related to the increase in yield (***Y***) and irrigation requirements ***(I)***, reduction of the evaporation losses ***(E)*** *and transpiration from weeds* (***Tweed***), and thus to the reduction of non-beneficial uses (***NBWU***):<br>$Y = WUE_T\,T = WUE_T\left[C_S\,((\boldsymbol{I} + P + CR + R_{on}) - (\boldsymbol{E} + \boldsymbol{T_{weed}} + DP + R_{off})\right]$<br>$WP = \frac{\boldsymbol{Y}}{P + CR + \Delta SW + \boldsymbol{I}} = \frac{\boldsymbol{Y}}{(ETc + LF) + \boldsymbol{NBWU}}$ |
| **Energy efficiency** | |
| **Physical efficiency** | Yield increase per hectare (Godini et al., 2011; Vossen et al., 2007). In Spain, for the best super-high-density orchards located on uplands with deep, Vossen et al. (2007) observed an average production around 4.75 tons/ha in the 3rd year, 6.25 tons/ha in the 4th year, and 8.25 tons per acre in the 6th and 7th years after planting. Significant higher yields are reported by Godini et al. (2013) under experimental conditions. |
| **Environmental impacts** | The rapid development of high-intensity olive farming, while increasing socio-economic well-being of olive producers, has also endangered environmental sustainability, and some negative impacts have been |

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| | reported (Beaufoy and Pienkowski, 2000; Gómez-Calero, 2009; EC, 2010; CHG, 2010):<br>- **Soil erosion**, accentuated by the expansion of olive cultivation into soils with un-favourable conditions for agricultural production and aggravated by inadequate soil management,<br>- **Loss of biodiversity**, with respect to traditional olive cultivation systems was the rich biodiversity associated with cultivation;<br>- **Overexploitation of water resources**, by shifting from rainfed production to high-intensity systems (e.g. this single crop is currently consuming about 22% of overall water consumption in the Guadalquivir Basin, the main catchment area of the region Andalusia, in Spain);<br>- **Diffuse water pollution**, as a result of the systematic use of chemicals, including herbicides and fertilizers, with arising problems of diffuse pollution of rivers, reservoirs and aquifers. |
| **Applications/ Innovative character** | The surface covered by these orchards has increased exponentially since the early 1990's, being **currently over 100,000 ha worldwide** (Fernandez et al., 2013).<br>Gimenez-Limon et al. (2013) use Data Envelopment Analysis (DEA) techniques and pressure distance functions to contribute a farm-level assessment of the eco-efficiency of a sample of 292 Andalusian olive farmers. |
| **Main references** | Fernandez et al., 2013; Gimenez-Limon et al., 2013; Proietti et al. 2012; Pastor et al. 2007; Grattan et al., 2006; Beaufoy and Pienkowski, 2000; Gómez-Calero, 2009; EC, 2010; CHG, 2010; Godini et al., 2011; Vossen et al., 2007. |

| **Technology** | **Conservation tillage and surface residue management** |
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| **Short description** | To combat soil loss and preserve soil moisture, soil conservation techniques were developed in USA. ‘**Conservation tillage**’ (CT) involves soil management practices that minimise the disruption of the soil’s structure, including **direct drilling (no-tillage)** and **minimum tillage**. Other husbandry techniques may also be used in conjunction including **cover cropping** and non- or surface incorporation of **crop residues** and this broader approach is termed ‘conservation agriculture’. Cover crops are defined either as additional crops planted on the field post-harvest, or crops intercropped with the main-crop. **Mulching** by covering the soil with crop or weed residues reduces the amount of solar energy falling on the soil and reduces evaporation, and also reduces runoff and promotes infiltration of rain water in the root zone. |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | Conservation tillage aims at introducing new technologies and practices **to redefine the efficiency frontier**, to obtain **more desired outputs and less undesired outputs with less inputs** |
| **Economic aspects** | In terms of **economical return and profitability**, tillage suppression may substantially reduce crop production costs, as mechanized tillage is a rather costly technique including fuel, labour and machinery costs. |
| **Water saving** | Surface water **runoff is generally reduced**. Changes can be expected in **infiltration rate** and **hydraulic conductivity** as a result of the different soil physical properties, particularly increased organic matter near the surface and increased vertically orientated macrostructure throughout the profile (Strudley et al., 2008). Covering the surface with mulch or residue affect energy balance components and have a large impact on **evaporation fluxes**. Any practice that leads to increases in soil water in the upper portion of the root zone may have a positive impact on **WUE** due to **increased water availability** and improved **nutrient uptake**.<br>Conservation tillage can affect yield in relation to its effect on transpiration (***T***), that can be improved in relation to the increase of the fraction of water stored in the soil (***Cs***) and to the increase of effective precipitation (***P***).<br>$Y = WUE_T\, T = HI\, \frac{B}{T} \{\boldsymbol{C_S} [(I + \boldsymbol{P} + CR + R_{on}) - (\boldsymbol{E} + T_{weed} + \boldsymbol{DP} + \boldsymbol{R_{off}})]\}$<br>At field scale, if yield is kept at the same levels of conventional tillage, the strategy aims at **improving water productivity** by increasing water storage and effective rainfall, by optimizing crop evapotranspiration (***ETc***), beside the reduction of non-beneficial water uses (soil evaporation ***E***, deep percolation ***DP*** and surface runoff ***Roff***):<br>$WP = \frac{Y}{\boldsymbol{P} + CR + \Delta \boldsymbol{SW} + I} = \frac{Y}{(\boldsymbol{ETc} + LF) + \boldsymbol{NBWU}}$ |
| **Energy efficiency** | Shifting from conventional to reduced tillage or no-tillage (direct seeding) helps to **reduce energy consumption**. CT uses less energy: adopting CT was estimated to save 23.8 kg C ha$^{-1}$ per year (Kern and Johnson, 1993). Likewise, a full carbon cycle analysis revealed that the C emissions for conventional tillage, reduced tillage and no-till averaged over corn, soybean and wheat were 69.0, 42.2 and 23.3 kg C ha$^{-1}$per year (West and Marland, 2002). |
| **Physical** | There is a variable impact of conservation tillage on **yield**. According to |

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| **efficiency** | Soane et al. (2012), in Europe, it seems that the yields of winter crops with no tillage or reduced tillage are **comparable to conventional tillage** with ploughing, whereas the yields can decrease for spring crops. Yields of no-till crops tend to approach or exceed those after ploughing **as the rainfall decreases** from northern to south-western Europe (Fernandez-Ugalde et al., 2009b). |
| **Environmental impacts** | Experiences in the application and research of conservation tillage in the US have revealed the beneficial long-term effects of these tillage systems on **soil physical, chemical, and biological properties** (e.g. Hubbard et al., 1994; Karlen et al., 1994).<br>The most important environmental impacts are related with (Breland, 1995; During et al., 1998; Tebrügge and Düring 1999; Montanarella, 2006; West and Marland, 2002):<br>- protect the soil from **water and wind erosion and runoff**<br>- reduced tillage operations  and **energy consumption** (for soil cultivation)<br>- reduced or stable **fertilizers applications**<br>- reduced **nutrient losses** and **agro-chemicals leaching**<br>- reduction in **surface runoff and erosion**<br>- reduced **CO2 (and other GHG) emission**<br>- risk of **increased N2O emission**<br>- risk of increased **environmental pollution** (due to higher **herbicides** applications) |
| **Applications/ Innovative character** | Conservation tillage (CT) is now commonplace in areas where rainfall causes soil erosion or where preservation of soil moisture because of low rainfall is the objective. **World-wide, CT is practised on 45 million ha**, most of which is in North and South America but is increasingly being used in other semi-arid and tropical regions of the world (Lal, 2001). ‘Minimum’ (or ‘reduced’) and ‘zero’ (or ‘no’) tillage practices are currently spreading throughout the world (Holland 2004; Peigné et al. 2007; Soane et al. 2012). |
| **Main references** | Soane et al., 2012; Fernandez-Ugalde et al., 2009b; Breland, 1995; During et al., 1998; Tebrügge and Düring 1999; Montanarella, 2006; West and Marland, 2002; Lal, 2001; Holland 2004; Peigné et al. 2007. |

| Technology | Use of biodegradable mulches |
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| Short description | Utilization of plastic mulch in combination with drip irrigation has played a major role in the increases in production of several vegetables (tomato, pepper, eggplant, watermelon, muskmelon, cucumber, and squash), but also applications with field crops could be found in literature. The **benefits of polyethylene mulch** to crop production are well documented and include greater root growth and nutrient uptake (Wein et al. 1993), earlier ripening and a higher yield of fruit (Abdul-Baki et al. 1992), and improved fruit quality (Singh 1992) than plants grown without mulch. Despite multiple benefits, removal and disposal of conventional polyethylene mulches remains a major agronomic, economic, and environmental constraint, leading to the development of **photodegradable and biodegradable mulches**. Biodegradable mulch films can degrade in the field after ploughing, thus eliminating film recovery and disposal. |
| Sector - Stage | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| Eco-efficiency scenario | The technique aims at **reduce undesired outputs** with a **smarter use of the same inputs**, by moving along the same efficiency frontier. |
| Economic aspects | Using **plastic mulch films** increases the cost for vegetable production due to material costs of US$ 400–625/ha for normal black plastic mulch film (Lamont 2004b), machines and labor for film application and removal, and also material hauling and landfill tipping fee (typically varies from US$ 150-240/ha, according to Olsen and Gounder 2001). Its manufacture and disposal entail significant **environmental costs** (Schonbeck 1995). |
| Water saving | Plastic mulches alter the crop microclimate by changing the **soil energy balance and decreasing the soil water loss** (Tarara 2000) and may affect plant growth and yield (Ibarra-Jimenez et al. 2006; Lamont 2005). The plastic film is a barrier **preventing soil water evaporation**. Associated with the reduction in evaporation losses, **transpiration increases** because both sensible and radiative heat are transferred from the surface of the plastic cover to adjacent vegetation (Allen et al., 1998). In combination with drip irrigation and appropriate scheduling methods**,** mulching supports the **reduction of excessive deep percolation**.<br>Mulching is effective in increasing yield through its effect on both the transpiration **(*T*)** and the possible **improvement of the transpirational *WUE*** ($\boldsymbol{WUE_T}$);<br>$$Y = \boldsymbol{WUE_T}\,\boldsymbol{T} = HI\,\frac{\boldsymbol{B}}{\boldsymbol{T}}\left[C_S\left(\left(I + P + CR + R_{on}\right) - \left(\boldsymbol{E} + \boldsymbol{T_{weed}} + \boldsymbol{DP} + R_{off}\right)\right)\right]$$<br>At field scale, the strategy aims at **improving water productivity** by increasing actual yield (***Y***), optimizing crop evapotranspiration (***ETc***), beside the reduction of non-beneficial water uses (soil evaporation ***E***, weed transpiration ***Tweed***, deep percolation ***DP***):<br>$$WP = \frac{\boldsymbol{Y}}{P + CR + \Delta SW + I} = \frac{\boldsymbol{Y}}{(\boldsymbol{ETc} + LF) + \boldsymbol{NBWU}}$$ |
| Energy efficiency | |
| Physical efficiency | The dominant advantage of using mulch is its ability to aid in the retention of nutrients within the root zone, thereby permitting more **efficient nutrient utilization** by the crop (Cannington et al. 1975). Improved efficiency of water and nutrient uptake (also due to greater root growth) result in **yield increase** and **earliness of ripening**. |

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| **Environmental impacts** | The photo-biodegradable polyethylene films buried in soil have **good degradability** (Wang et al. 2004). Olsen and Gounder (2001) found that the silver and black bio-/photo-degradable polyethylene films containing 20% starch degraded after 56, 83, 38, and 33 days when they were mulched in fall, winter, spring, and summer. Lopez et al. (2007) studied the behaviour of four biodegradable materials and revealed that biodegradable materials produced disappeared 5 months after laying, whereas linear low-density polyethylene remained in the ground.<br>Concerning other environmental aspects, all plastic film mulches allow to **reduce N leaching** (Bhella 1988) and to **protect the soil from water and wind erosion** and hail damage (Garnaud 1974). |
| **Applications/ Innovative character** | Feuilloley et al. (2005) studied the biodegradability of three different commercial mulch films including **Mater-bi** (Novamont, Novara, Italy); **Ecoflex** (BASF, Ypsilanti,MI, USA) and **Actimais** (SMS Trioplast, Pouance, France). Olsen and Gounder (2001) found slightly higher soil temperatures for polyethylene and biodegradable polymer mulches than paper mulch, but **yields** of peppers were **similar for all** three **materials**. Lopez et al. (2007) studied the behavior of four biodegradable materials and and revealed that the use of biodegradable materials produced **similar yields than linear low density polyethylene**, with the biodegradable materials disappeared 5 months after laying, whereas linear low-density polyethylene remained in the ground. |
| **Main references** | Wein et al. 1993; Abdul-Baki et al. 1992; Singh 1992; Wang et al. 2004; Feuilloley et al. (2005); Kasirajan and Ngouajio, 2012; Olsen and Gounder (2001). |

| **Technology** | **Organic farming (agro-ecological practices)** |
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| **Short description** | **Organic agriculture** is believed to produce significant social, economic and environmental benefits (Morgera et al., 2012); more specifically, the aim of such a system is to reduce the environmental impact, to improve the quality of the products as well as the process effectiveness through enhancing water use efficiency and reducing the use of synthetic fertilizers, pesticides and herbicides (Nilson, 2012). To reach the goal of higher and **sustainable food production** a sum of agro-ecological practices are considered as possible options (Wezel et al. 2013). The term "**agro-ecological practices**" emerged in the 1980s within the development of agro-ecology. Examples of agro-ecological practices are cover crops, green manure, intercropping, agro-forestry, biological control, resource and biodiversity conservation practices, or livestock integration (Altieri 1995, 2002). |
| **Sector - Stage** | **Agricultural water sector – Water Use (on-farm cropped plots)** |
| **Eco-efficiency scenario** | Organic farming practices address productivity improvement by **Introducing/spreading new technologies or practices** to redefine a new efficiency frontier. Organic farming aims to produce less outputs with much less inputs |
| **Economic aspects** | Among the constraints of these agro-ecological practices it is included the **possible higher labour and energy demands**, together with the difficulty in optimizing N availability in soils with organic fertilization as well as in matching plant demand (Sanchez et al. 2004). |
| **Water saving** | Choosing an adequate crop and cultivar can help to improve crop resistance to **abiotic stresses** (such as nitrogen and water deficiencies) (Tilman et al. 2002). Improving **water use efficiency** in water-scarce conditions (particularly rainfed water) is also possible with relevant crop rotations (Pala et al. 2007; Turner 2004). Agro-ecological practices help to improve water infiltration and **water storage**, and to **reduce soil evaporation** with cover crops or mulch. |
| **Energy efficiency** | - reduced application of chemical fertilizers (organic fertilizers);<br>- reduction in energy inputs with minimum or zero tillage;<br>- higher management needs and labour demand (e.g. intercropping, agro-forestry, weed control, etc.);<br>- higher machine traffic for weed control;<br>- higher energy costs for organic fertilization (e.g. obtaining off farm organic fertilizers might be difficult, expensive, and may even incur undesirable transport costs). |
| **Physical efficiency** | The organic systems are assumed to have **potential advantages in productivity, stability of outputs, resilience to disturbance, and ecological sustainability**, though they are generally considered harder to manage (Vandermeer 1998). Although **yield reduction** is normally observed (with respect to conventional systems), products are expected to show **higher quality** at market level. Crop rotations and intercropping generally allows improvements of **resources use efficiency**, notably radiation and water use efficiency. Possible difficulties in optimizing N availability in soils with organic fertilization as well as in matching plant demand, and consequent risk of nutrient leaching. |
| **Environmental** | The shift from traditional agricultural production methods to modern organic production ones would contribute to the **conservation of natural** |

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| **impacts** | **resources**, the maintenance of biodiversity and the preservation of the ecosystem. Agro-ecological practices contribute to improving the **sustainability of agro-ecosystems** while being based on various ecological processes and ecosystem services such as nutrient cycling, biological N fixation, natural regulation of pests, soil and water conservation, biodiversity conservation, and carbon sequestration.<br>Among the expected impacts (Morgera et al., 2012):<br>- **stabilization of yields** (cultivar choice);<br>- improved **land productivity** (e.g. intercropping), but loss of cropped land for the main crop;<br>- improved **resources use efficiency** (crop/variety selection, appropriate crop rotations, intercropping);<br>- enhancement of **soil fertility** with nitrogen-fixing crops;<br>- favouring **soil biodiversity**;<br>- **protecting the soil from erosion** due to higher organic matter at the soil surface;<br>- **reduction of soil/water pollution and $CO_2$/$NO_2$ emissions** (48-66% $CO_2$ reductions compared to conventional practices);<br>- cover crops limit fertiliser inputs and **reduce risk of water contamination** due to a decreased risk of leaching. |
| **Applications/ Innovative character** | Examples of application: i) 6.3 million ha are under certified organic management (3.9% of total agricultural area) with 13 billion € retail sales in the EU Union (2005); ii) biologically integrated farming systems, California, USA, 1993-2000 (Morgera et al., 2012; Swezey and Broome, 2000). |
| **Main references** | Morgera et al., 2012; Vandermeer 1998; Swezey and Broome, 2000; Wezel et al. 2013; Altieri 1995, 2002 |

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