NILE BASIN INITIATIVE
Initiative du Bassin du Nil

IN-FIELD WATER MANAGEMENT IN IRRIGATED AGRICULTURE: *ADAPTABLE BEST PRACTICES*

Nile Basin Initiative – NELSAP
Regional Agricultural Trade and Productivity Project (RATP)

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IN-FIELD WATER MANAGEMENT IN IRRIGATED AGRICULTURE: ADAPTABLE BEST PRACTICES

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Nile Basin Initiative (NBI)
Nile Equatorial Lakes Subsidiary Action Programme (NELSAP)
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About this Training Manual

The Nile Basin Initiative (NBI) is a partnership of the riparian states (Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda**,** Eritrea is participating actively in the NBI as an observer) that seeks to develop the river in a cooperative manner, share substantial socioeconomic benefits, and promote regional peace and security through its shared vision of "sustainable socioeconomic development through the equitable utilisationof, and benefit from, the common Nile Basin water resources". NBI's *Strategic Action Program* is made up of the *Shared Vision Program (SVP) and Subsidiary Action Programs (SAPs).* The SAPs are mandated to initiate concrete investments and action on the ground in the *Eastern Nile (ENSAP) and Nile Equatorial Lakes sub-basins (NELSAP).*

NELSAP through its sub basin programs implements pre-investment programs in the areas of power, trade and development and natural resources management. As part of its pre-investment framework, the Regional Agricultural Trade and productivity Project (RATP), in concert with the NELSAP, intends to promote and disseminate best practices on water harvesting and small scale irrigation development as a contribution towards agricultural development in the NEL Countries. NELSAP has previously implemented completed a project called Efficient Water Use for Agriculture Project (EWUAP). One of the recommendations of EWUAP was the need to develop Training/Dissemination materials on "*adoption of low cost technologies for water storage, conveyance, distribution, treatment and use for agriculture that can be adapted by communities and households of the rural and peri-urban poor*". This Training Manual is the initiative of NELSAP, for that purpose.

This Training Manual provides insights as to how to save water used in irrigation, particularly at field level. It is meant to improve the skills of engineers, technicians, extension workers, managers and practitioners of irrigated agriculture, especially those working in smallholder irrigation in Africa. More specifically, the manual equips the reader with knowledge on how to (i) identify causes and sources of water losses in irrigation, (ii) develop and apply agronomic measures that save water and/or increase productivity of the same water, (iii) plan and apply various techniques that improve water use efficiency in irrigated agriculture, and (iv) implement modern and innovative ways of improving water productivity in irrigated agriculture. This Manual is meant to inform, educate, enhance knowledge and practice, targeting smallholder irrigation in the NEL region. The information contained here may not be exhaustive and thus, readers are encouraged to seek further information from references cited in this publication and elsewhere.

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Glossary of Key Terms

Term	Definition/Brief description
Actual crop evapo-transpiration	The actual crop evapotranspiration, denoted as ETca, is the sum total of actual evaporation and transpiration from a crop grown under prevailing conditions. Under optimal growth conditions, ETca equals potential ETc.
Agricultural water management (AWM)	The holistic management of water for agriculture (crops, trees, live-stock) in the continuum from rain fed systems to irrigated agriculture. It includes irrigation and drainage, soil and water conservation, rainwa-ter harvesting, agronomy, in-field water management, integrated water-shed management and all relevant aspects of the management of water and land.
Available water	The amount of water held in a soil that plants can use.
Available water hold-ing capacity	The total amount of water a soil profile can hold for plant uptake. It depends on soil depth, texture, structure and organic matter content.
Blue water	The proportion of rainfall which flows on or beneath soil surface to accumulate in rivers, streams, springs, swamps, lakes, ground water, aquifers or into storage structures such as dam, ponds and tanks, and which is extractable as liquid fresh water.
Coefficient of varia-tion (CV)	A mathematical measure of the variability of runoff from year to year. It is the ratio of standard deviation of annual inflow to the mean annu-al inflow
Conservation farming	The holistic application of conservation tillage alongside other agro-nomic practices (e.g. manuring, crop rotations, mulching) to reduce labour and preserve the natural state of the soil. Also called conserva-tion agriculture.
Consumptive use	Water consumption that withdraws or abstracts and uses water without generating return flows. It includes water used by plants in evaporation and transpiration processes or crop consumptive use.
Crop coefficient (Kc)	Factor representing the relationship between crop evapotranspiration and reference crop evapotranspiration.
Crop evapotranspira-tion (E_{TC})	The evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions.
Crop water depletion	The amount of water depleted in the process of crop production by transpiration (T), evaporation from soils, and field ponds or channels (E). Originating from rainfall (green water), irrigation (blue water) or a combination of both, it is a consumptive use as the water is no longer available for other use because it has evaporated, transpired, or been incorporated into crops
Crop water require-ment (ET_{crop})	The depth of water needed to meet the evapotranspiration require-ments of a disease-free crop, growing in large fields under non-re-stricting soil conditions and achieving full production potential under the given growing environment. It is synonymous with Crop evapo-transpiration (E_{TC}).

Term	Definition/Brief description
Crop water use efficiency	The ratio of crop yield (Y) to the amount of water depleted by the crop in the process of evapotranspiration (ET) or the consumptive use of the crop.
Crop yield	The harvested production per unit of harvested area for crop products.
Drainage	The process of managing and/or removing excess surface water and controlling water logging from shallow water tables.
Drip Irrigation (trickle irrigation)	A planned irrigation system in which water is applied directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, perforated pipe) operated under low pressure with the applicators being placed either on or below the surface of the ground.
Drip irrigation kit	A package comprising the core components required to install a drip irrigation system. Other components and materials that are readily available at the point of installation are usually not part of the kit unless special qualities of the components are desired.
Effective rainfall (P_{eff})	That part of the total rainfall that can be beneficially used by crops.
Evaporation (E)	The amount of water that leaves a water surface or land as vapour. Evaporation can be beneficial or non-beneficial. Non-beneficial evaporation includes that from open water bodies (tanks, ponds, reservoirs, canals) and from bare soil.
Evapotranspiration (ET)	The sum of water lost from an area through the combined effects of evaporation from the ground surface and transpiration from the vegetation.
Fertigation	The application of liquid fertilizer through an irrigation system.
Field capacity (FC)	The maximum amount of water held in a soil, measured a few days after it has been thoroughly soaked and allowed to drain freely.
Flood irrigation	The application of irrigation water where the entire surface of the soil is covered by ponded water.
Gravity-fed irrigation	Irrigation in which water is available or made available at a higher level so as to enable supply to the land by gravity flow.
Green water	The proportion of infiltrated rainfall stored in the soil profile that is available for root water uptake by plants. It includes water expended in evaporation, interception and transpiration and constitutes the main water resource used in rain fed agriculture.
Groundwater	Water that exists beneath the earth's surface in underground streams and aquifers.
Hydraulic conductivity	The rate at which water can pass through a soil material, usually measured under saturated conditions to ensure water is moving through the soil via gravity and positive head pressure.
Infiltration	Entry, absorption and downward movement of water into the soil
Infiltration capacity	Limiting rate at which falling rain can be absorbed by a soil surface in the process of infiltration.
Infiltration rate	The rate at which water enters the soil profile. Infiltration rate can be relatively fast, especially as water enters into pores and cracks of dry soil. As the soil wets up and becomes saturated, the infiltration rate slows to the point where surface runoff occurs.
Interception	Catching and holding of rainfall above the ground surface by leaves, stems and residues of plants

Term	Definition/Brief description
Interflow	Movement of soil water through a permeable layer in a down slope direction parallel with the ground surface, also called through flow
Irrigation	Any process, other than by natural precipitation, which supplies water to crops or any other cultivated plants.
Irrigation efficiency	The ratio of irrigation water consumed in the process of irrigation to the water delivered from the supply source, or the percentage of water delivered to the field that is used beneficially.
Irrigation moderniza-tion	A process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes combined with institutional re-forms, with the objective to improve resource utilisation(labour, water, economic, environmental) and water delivery service to farms
Mulching	The practice of covering cropped land with a layer of loose material such as dry grass, straw, crop residues, leaves, compost inorganic cov-ers.
Overland flow	Water flowing over a sloping ground surface to join a channel or stream
Percolation	Movement of water downward through the pores of the soil.
Perennial (crop)	A plant that lives for three or more years and which normally flowers and fruits at least in its second and subsequent years.
Permanent wilting point (PWP)	The soil water content at which water is no longer available to plants, which causes them to wilt because they cannot extract enough water to meet their requirements.
pH	A measure of acidity or alkalinity of a liquid. A pH of 7.0 is neutral; a pH less than 7.0 is acidic; a pH greater than 7.0 is alkaline.
Precision Agriculture (PA)	An integrated information- and production-based farming system that is designed to increase long term, site-specific and whole farm produc-tion efficiency, productivity and profitability while minimising unin-tended impacts on wildlife and the environment
Rain fed agriculture	Agricultural systems whereby natural rainfall is the predominant source of water for growing crops, trees or pasture on that field. It also includes crops grown with flood flows harvested from excess rainfall runoff.
Runoff	Water that flows away from a catchment after falling on its surface in the form of rain.
Salinity	Soils having high concentration of soluble salts
Saturation	The moisture content at which all soil pores are completely water-filled.
Seepage	Water leaking from the ground or a dam embankment. Also described as the flow of water through the soil pores under a pressure gradient.
Semi-arid	Fairly dry climate with average annual rainfall of about 300-700 mm, with high variability in rainfall.
Silt	Sediment made up of fine particles carried or laid down by moving water.
Soil and water conser-vation (SWC)	Activities that maintain or enhance the productive capacity of land in areas affected by or prone to soil erosion.
SRI - (System of rice intensification)	A package of growing rice in paddies, which includes intermittent wetting and drying, planting younger seedlings and other agronomic practices which result in higher rice yields while using less water.

Term	Definition/Brief description
Stream flow	Flow or discharge of water that moves along a river or channel (m^3/s).
Sub-humid	A humid climate with average annual rainfall of roughly 700-1000 mm.
Supplemental irrigation	The application of a limited amount of water to the crop when rainfall fails to provide sufficient water for plant growth to increase and stabilize yields.
Surface runoff	Excess rainfall which runs off the surface of the land, it includes both overland flow and stream-flow
Surface sealing	When soil forms a sort of clay cement after rain, because the finest grains clog the soil pores, preventing water infiltration. Also called clogging up
Surge irrigation	A technique in which water is applied to furrows (or borders) intermittently during a single irrigation set.
Sustainable land management (SLM)	The use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions.
Terrace	A piece of land whose slope steepness and/or length has been reduced by either construction works, or by creating barriers across the slope, so as to absorb and/or reduce surface runoff
Tillage	Preparation of the land for planting, or all the operations undertaken to prepare a seed bed in agriculture
Transpiration	Water that is taken up by plants from the soil and then lost to the air through small openings in the leaves of plants.
Transpiration ratio	The ratio of the amount of water transpired to the amount of dry matter produced by a crop.
Water application efficiency (E_a)	The ratio of water applied as net increase in soil moisture in the crop root zone to the total amount of water applied at the field level.
Water budget (water balance)	Balance of inflow and outflow of water per unit area or unit volume and unit time taking into account net changes of storage
Water conservation	The control, protection, storage, management and utilisation of water resources in such a way as to optimise productivity
Water control	The physical control of water by measures such as conservation practices on the land, channel improvements, and installation of structures for reducing water velocity and trapping sediments.
Water conveyance efficiency (E_c)	The ratio of water delivered to a farm or field at the pipe/canal outlet, to the amount taken/diverted from some source.
Water harvesting	Activities where water from rainfall and/or surface runoff is collected, diverted, stored and utilised.
Water logging	State of land where the water table is located at or near the surface resulting in poorly drained soils, adversely affecting crop production
Water management	The regulation, control, conservation, harvesting and use of water for agriculture. It includes efficient or economical utilisation of available water for agriculture and other purposes.
Water productivity (WP)	An efficiency term quantified as the ratio of product output (goods and services) to water input. It is expressed in term of yields (physical WP), income (economic WP) or environmental services (environmental WP).

Term	Definition/Brief description
Water storage capacity	Maximum capacity of soil to hold water against the pull of gravity, also called field capacity.
Water storage efficiency (Es)	A measure of the fraction of irrigation water that is stored in the crop root zone compared to the water needed in the root zone prior to irrigation.
Water table	Upper limit of the ground water
Water use efficiency	The ratio of water used in crop evapotranspiration (ET_o) to crop yield
Water withdrawal	The gross amount of water extracted from any source, either permanently or temporarily, for a given use, including irrigation. It can be either diverted towards distribution networks or directly used.

1. INTRODUCTION

1.1 What is In-field water management?

In-field water management includes the delivery, application, control, scheduling and management of water used in crop production, alongside other agronomic practices that improve the water productivity of an agricultural system. Thus, in-field water management can be for rain fed crop production (see Training Manual 4 of these series), or irrigated agriculture. There are several possible approaches to improve the water management at field level. For instance, drip and sprinkler irrigation are preferable to less efficient surface irrigation methods such as border, basin or furrow. In-field water management also includes agronomic practices as well as improvements in irrigation technologies and irrigation scheduling, which may be adapted for more-effective and rational use of limited water supplies. New irrigation and innovative water management approaches may be adopted, which are not necessarily based on full crop water requirement, but ones designed to ensure the optimal use of allocated water. Examples include supplemental irrigation, deficit irrigation or technologies such as the system of rice intensification (SRI) as well as greenhouse farming. Thus, this particular Manual describes in-field water management practices that could help reduce losses of water and/or increase the efficiency of its use, especially in smallholder irrigated agriculture.

1.2 Why improve irrigation water management

Irrigated agriculture is responsible for producing about 40% of food and agricultural products worldwide, but it takes up just 17% of agricultural land. In Africa, it has been stated that about 70-80% of mobilized water resources (piped water, canals, wells) is used in irrigation. Furthermore, with growing population, water availability per capita is declining and the water made available to irrigation will face ever steeper competition from other sectors. Declining water resources and limited clean water availability will make it difficult to satisfy food requirements in the future. In the arid and semi arid zones, water scarcity is a major problem and will get ever more severe in future. Where irrigation schemes have been developed, irrigation efficiencies are sometimes as low as 20% due to losses in conveyance, application, and irrigation technologies that are wasteful of water (Figure 1.1). There is therefore need to improve the overall irrigation efficiencies, and in-field water management provides a set of techniques which are easy to implement at the farm level.

Figure 1.1 (a) Surface irrigation uses too much water *(Photo by Bancy Mati)*

(b) Excessive irrigation wastes water *(Photo by Omar el Seed)*

1.3 Efficiency terms used in irrigated agriculture

Various terms exist to describe how efficiently irrigation water is applied and/or used by the

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crop. However, these values are often difficult to measure in the field. They also vary over time and with operating conditions. The specific efficiencies across each component of an irrigation system are described as follows:

1.3.1 Irrigation efficiency

Irrigation efficiency (Ei), indicates overall, how well the available water supply is utilised and managed in the full spectrum of irrigation, based on different evaluation methods and indicators. Irrigation efficiency is thus the percentage of water delivered to the field that is used beneficially, across all beneficial irrigation processes. It is determined as follows:

$$\mathbf{E_i = (W_b/W_f) \times 100}$$

Where,
E_i = Irrigation efficiency, as a percent
W_b= Water used beneficially
W_f = Water delivered to field.

Irrigation efficiency is more broadly defined than water application efficiency in that irrigation water may have more uses than simply satisfying crop water requirements. Other beneficial uses could include salt leaching, crop cooling, pesticide or fertilizer applications, or frost protection. Water lost to percolation below the root zone due to non-uniform application or over-application water runoff from the field, wind drift and spray droplet evaporation all reduce irrigation efficiency. For a thorough assessment of the irrigation system performance, other types of efficiencies are determined.

1.3.2 Water conveyance efficiency

Water conveyance efficiency (Ec), is the ratio of water delivered to a farm or field at the pipe/canal outlet, to the amount taken from some source. It depicts a measure of how efficiently a given amount of water leaving a source is delivered to the irrigated field. The difference between the two amounts represents the seepage and evaporative losses incurred en route from source to field. It depicts the efficiency of water transport in to the field. It is associated with canal networks, water courses and field ditches. It is also applicable where water is conveyed in channels from a well to the individual fields. It is calculated as the percentage of source water that reaches the field, as follows:

$$\mathbf{E_c = (W_f/W_d) \times 100}$$

Where
E_c=Water conveyance efficiency, per cent
W_f= Water delivered to the irrigated field (at the field supply channel)
W_d=Water diverted from source.

Conveyance efficiency is generally a concern for irrigation systems that supply a group of farmers through a system of canals and open canals. Ec can be considered to be 100% in piped water delivery systems where there are no leaks. Conveyance efficiency mainly depends on the length of the canals, the soil type or permeability of the canal banks and the condition of the canals. Large irrigation schemes lose more water than small schemes due to the longer canal systems. From canals in sandy soils more water is lost than from canals in heavy clay soils. When canals are lined with bricks, plastic or concrete, water losses through seepage are drastically reduce. However poor maintenance of canals e.g. bund breaks are not repaired properly, or rodents burrow through the structure, a lot of water can be lost. Table 1 provides some indicative values of the conveyance efficiency (Ec), considering the length of the canals and the soil type in which the canals are dug.

The level of maintenance is not taken into consideration: bad maintenance may lower the values of Ec by as much as 50%.

Table 1.1: Indicative values of the conveyance efficiency (Ec) for various canals

Canal lining	**conveyance efficiency (%)**			
	Earthen canals			**Lined canals**
Canal length/Soil type	**Sand**	**Loam**	**Clay**	
Long (>2000m)	60	70	80	95
Medium(200-2000m)	70	75	85	95
Short (<200m)	80	85	90	95

1.3.3 Water application efficiency

The *water application efficiency* (Ea), sometimes called *field application efficiency* or *on-farm application efficiency*, is the ratio of water applied as net increase in soil moisture in the crop root zone to the total amount of water applied at the field level. It depicts the fraction of the water volume applied to a farm or a field that is "consumed" by a crop, relative to the amount applied. Thus, it is a measure of how efficiently water delivered to the field is applied to the crop. It gives an indication of how well an irrigation system performs its primary task of getting water to the plant roots. Water application efficiency is depicted as a percentage of water delivered to the field that is used by the crop, calculated as follows:

$$Ea = (Ws/Wf) \times 100$$

Where
Ea=Water application efficiency, per cent
Ws= Water stored in the root zone of the plants
Wf= Water delivered to the irrigated field (at the field supply channel).

After the water reaches the field supply channel, it is important to apply the water as efficiently as possible, hence the need for Ea. It is easy to manipulate Wf so that Ea can be nearly 100 percent. However, it is possible to have a high Ea yet the irrigation water is poorly distributed such that the crop suffers moisture stress in one part of the field and water logging in another. It is also possible to have nearly 100 percent Ea but have crop failure if the soil profile is not filled sufficiently to meet crop water requirements. An irrigation system can be operated in such a ways as to achieve nearly 100 percent Ea if Wf is sufficiently low. Increasing Ea in this manner totally ignores the need for irrigation uniformity. For Ea to have practical meaning, Wc needs to be sufficient to avoid undesirable water stress.

Water application efficiencies below 100 per cent can also be due to seepage losses from the field distribution channel and deep percolation below the crop root zone. Sometimes, in case of very small fields, there may be runoff losses at the tail end of borders and furrows. In general, water application efficiency decreases as the amount of water applied during each irrigation increases. However, very small irrigations may not fill the root zone adequately and may reduce crop yields, and in the long run give rise to salt problems due to inadequate leaching. Water application efficiency sometimes is incorrectly used to refer to the amount of water delivered to the surface of the soil in an irrigated field by a sprinkler system. Water losses can occur after reaching the soil surface, leading to overestimation of the application efficiency.

There is much evidence that, in a given climate, the growth of many crops is directly related to the amount of water they transpire. The field application efficiency (Ea) mainly depends on the irrigation method and the level of farmer discipline. Some indicative values of the average field application efficiency (Ea) are given in Table 1.2.

Table 1.2: Range of application efficiencies for various irrigation systems

Irrigation system	**Application efficiency range (%)**
Surface Irrigation	
Basin	60 – 95
Border	60 – 90
Furrow	50 – 90
Surge	60 – 90
Sprinkler Irrigation	
Hand-move	65 – 80
Travelling Gun	60 – 70
Center Pivot & Linear	70 – 95
Solid Set	70 – 85
Micro Irrigation	
Point source emitters	75 – 95
Line source emitter	70 – 95

(Source: Rogers at al, 1997)

** Efficiencies can be much lower due to poor design or management. These values are intended for general system type comparisons and should not be used for specific systems.*

1.3.4 Water storage efficiency

Water storage efficiently (Es), is a measure of the fraction of irrigation water that is stored in the crop root zone. The concept of water storage efficiency is useful in evaluating how completely the water needed prior to irrigation has stored in the root zone during irrigation. It is determined as follows:

$$Es = (Ws/Wn) \times 100$$

Where
Es=Water storage efficiency, per cent
Ws=Water stored in the zone during irrigation
Wn= Water needed in the root zone prior to irrigation.

It has been started that small irrigation may lead to high water application efficiencies, yet the irrigation practice may be poor. Water storage efficiency becomes important when water supplies are limited or when excessive time is required to secure adequate penetration of water into the soil. Also, when salt problems exist, the water storage efficiency should b kept high to maintain a favourable salt balance. Water losses include surface runoff and deep percolation. If a center pivot is equipped with a properly designed nozzle package and operated using best management practices and irrigation scheduling, these losses can be negligible. However, for many systems, these losses can be large and result in poorly distributed or non-uniform irrigation. The use of the water storage efficiency term is discouraged because of the difficulty in determining the crop root zone and because Es can be very low while sufficient water is provided to the crop.

1.3.5 Water distributing efficiency

Water Distribution Efficiency (Ed) indicates the degree of uniformity in the amount of the water infiltrated into the soil. It can also be defined as the uniformity in depths applied at the surface based on a measure for sprinkler systems. It is therefore determined as the percentage of the average application depth delivered to the least-watered part of the field. This is calculated as follows:

$$\mathbf{E_d = [1-(y/d)] \times 100}$$

Where
Ed = Water distribution efficiency, per cent
y = Average absolute numerical deviation in depth of water stored from average depth stored during the irrigation
d = Average depth of water stored along the run during the irrigation.

This equation is identical to the expression used for determining uniformity coefficient for sprinkler irrigation.

Generally, high uniformity is associated with the best crop growth conditions since each plant has an equal opportunity to access applied water. Non-uniformity results in areas that are under-watered or overwatered. Not only the application of the right amount of water to the field but also its uniform distribution over the field is important. Permissible lengths of irrigation runs are controlled to a large extent by the uniformity of water distribution which is possible for a given soil and irrigation management practice. Water distribution efficiency indicates the extent to which water is uniformly distributed along the run.

1.3.6 Distribution uniformity

Distribution Uniformity (Ud), is the percentage of average water application amount received in the least-watered quarter of the field. It is calculated as follows:

$$\mathbf{U_d = (L_q/X_m) \times 100}$$

Where,
Ud = Distribution Uniformity
Lq = Average low-quarter depth of water infiltrated
Xm= Average depth of water infiltrated (or caught).

The distribution uniformity gives an indication of the magnitude of the distribution problem. It is less tedious to determine than the Ed.

1.3.7 Water use efficiency

The water utilisationby the crop is generally described in terms of water use efficiency (kg/ha.cm or q/ha.cm). It can be defined in terms of (i) crop water use efficiency and (ii) field water use efficiency. These are calculated as follows:

a) **Crop water use efficiency** - is the ratio of crop yield (Y) to the amount of water depleted by the crop in the process of evapotranspiration (ET) or the consumptive use of the crop.

$$\textbf{Crop water use efficiency} = {}^{Y}\!/_{ET}$$

b) **Field water use efficiency** - is the ratio of crop yield (Y) to the total amount of water used in the field or Field water requirement (WR).

$$\textbf{Field water use efficiency} = {}^{Y}\!/_{WR}$$

From these two equations, it follows that water use efficiency can be improved by either by increasing crop yield or by decreasing the water requirement. The magnitude of crop yields also depends on such plant factors as gains due to photosynthesis verses losses due to diseases and pests. Hence, water use efficiency can be influenced by externalities like pest and diseases, the choice of crop and the varieties used as well as prevailing environment, e.g. improvement of the water, air and nutrient supply to the roots, and of light and carbon diode supply to foliage. The crop yield itself can be defined in terms of total growth (i.e.) dry production) or in terms of marketable product. Of the two indices for water use efficiency, the concept o crop water use efficiency is of fundamental interest while field water use efficiency is of greater practical importance.

1.3.8 Scheme irrigation efficiency

Scheme irrigation efficiency is that part of the water pumped or diverted through the scheme inlet which is used effectively by the plants. The scheme irrigation efficiency
(E) can be calculated, using the following formula:

$$E = {}^{(E_c \times E_a)}/_{100}$$

Where,
E = Scheme irrigation efficiency (%)
Ec = Conveyance efficiency (%)
Ea = Field application efficiency (%)

A scheme irrigation efficiency of 50-60% is good; 40% is reasonable, while a scheme Irrigation efficiency of 20-30% is poor. At the field scale, large amounts of water are not used productively, i.e. they are lost through evaporation, runoff and deep percolation. In hot tropical zones, the long-term seasonal amounts of water lost without being used productively often range between 400 and 1,000 mm, concentrated in a limited period of 70–140 days. This substantial amount of water could hypothetically produce 4,000–10,000 kg grain/ha if used effectively for transpiration, e.g through efficient irrigation methods.

1.3.9 Project efficiency

Project efficiency indicates the effective use of the irrigation water that is stored in the soil and is available for consumptive use by crops. When the delivered water is measured at the farm head gate (or well) it is called farm irrigation efficiency, when measured in the field it is designated as field irrigation efficiency; and when measured at the point of diversion from the canal or the main source of supply it may be called project efficiency.

1.3.10 Operational efficiency

Operational efficiency is the ratio of the actual project efficiency compared to the operational efficiency of an ideally designed and managed system using the same irrigation method and facilities. Low operational efficiencies indicate management or system design problems, or both

1.3.11 **Economic (irrigation) efficiency**

Economic efficiency is the ratio of the total production (net or gross profit) attained with the operating irrigation system, compared to the total production expected under ideal conditions. This parameter is a measure of the overall efficiency, because it relates the final output to input.

1.4 Consumptive water use

Consumptive water use is water consumption that withdraws or abstracts and uses water without generating any return flow. The water abstracted is no longer available for other uses because it has evaporated, been transpired, been incorporated into products and crops, been consumed by humans and livestock, or otherwise removed from freshwater resources. Losses of water during transport between points of abstraction and points of use (for example leakage from distribution pipes) are excluded from consumptive water use. For irrigated agriculture consumptive use is equivalent to evapotranspiration (ET) or crop water use.

1.5 Crop water use efficiency

Crop water-use efficiency is a physiological index, which is a measure of the response of the crop to irrigation, not in percentage terms, but as total biomass produced (above-ground dry matter) per unit mass of water taken up by the crop. Since, over 90 percent of the water taken up by plants in the field is normally transpired, crop water-use efficiency is in effect the reciprocal of what has long been known as the *transpiration ratio*. The latter is defined as the ratio of the amount of water transpired to the amount of dry matter produced (tonnes per tonne). That ratio can be of the order of 1000 or more in a dry climate of high evaporative demand.

An alternative way to characterize crop water-use efficiency is in terms of the marketable crop produced per unit volume of water. This expression is identical to the above-ground biomass in the case of crops grown and harvested for forage, but it is quite different where the marketable product is only the fruit, seed or fibre. Generally, but not always, the yield of such products is proportional to total growth, hence also to transpiration. Water use efficiency alone is not a sufficient indicator to define the performance of an irrigation system. Indicators of high water losses and operational inefficiencies need to be factored in irrigation planning. Thus, water productivity provides a more realistic indicator of the effectiveness of water to bear production and the economic benefits of the entire irrigation system.

1.6 Water productivity

Water productivity is an efficiency term quantified as a ratio of product output (goods and services) over water input. The output could be biological goods or products such as crop (grain fodder) or livestock (meat, egg, fish) and can be expressed in term of yields, nutritional value or economic return. The output could also be an environment service or function. Crop water productivity or water use efficiency (WUE) expressed in kg/m^3 is expressed in terms of production or marketable product (e.g. kilograms of grain) per unit of water input needed to produce that product (cubic meters of water). The water used for crop production is referred to as crop evapotranspiration. This is a combination of water lost by evaporation from the soil surface and transpiration by the plant, occurring simultaneously. Values of WUE for cereals at field level, expressed with evapotranspiration in the denominator, can vary between 0.10 and 4 kg/m^3. Water productivity can be at different scales and for a mixture of goods and services.

There are three major expressions of water productivity, identified as;

(i) The amount of carbon gain per unit of water transpired by the leaf or by the canopy (photosynthetic water productivity);

(ii) The amount of water transpired by the crop (biomass water productivity); and

(iii) The yield obtained per unit t of water transpired by the crop (yield water productivity).

Water productivity can also be described in terms of the following terms:

(i) Physical water productivity relates the amount of agricultural produce to water use – "more crop per drop".

(ii) Economic water productivity relates the economic benefits obtained per unit of water.

(iii) Water productivity has also been used to relate the use of water in agriculture for more nutrition, jobs, better welfare, and a better.

(iv) Environment: It should be recognized that water is just one factor affecting agricultural productivity, and that water productivity gains relate all benefits derived to water, even though many other factors impact productivity. Water productivity is particularly appropriate where water is scarce compared to other resources involved in production.

2. IRRIGATION WATER LOSSES

2.1 Causes of water losses in irrigation

The design of irrigation systems, improvements made during land preparation, water application methods, cropping systems, agronomic management, care and skills of the irrigator are major factors that influence how efficiently an irrigation scheme operates. Loss of irrigation water may occur in the conveyance and distribution systems, while poor water distribution in irrigated fields as well as deep percolation losses can occur resulting in lower efficiencies. Sometimes water losses may occur due to surface runoff at the tail end of irrigation borders and furrows. The losses can be held to a minimum by adequate planning of the irrigation system, proper design of the irrigation method, adequate land preparation and efficient operation of the system. Irrigation water losses, include air losses, canopy losses, soil and water surface evaporation, runoff, and deep percolation. The magnitude of each loss is dependent on the design and operation of each type of irrigation system. Ground evaporation may be an important component early in the season, before the crop canopy covers the surface and in hot climates.

2.2 Water losses in surface irrigation

Losses of water are highest under surface irrigation than other methods of water application. The losses include runoff, deep percolation, ground evaporation and surface water evaporation. Runoff losses can be significant if tail water is not controlled and reused. Although use of tail water reuse pits could generally increase surface application efficiency, many surface irrigators use a blocked furrow to prevent runoff. Usually the lower portion of the field is levelled to redistribute the tail water over that portion. While runoff may be reduced to near zero, deep percolation losses may still be high with this practice.

2.3 Water losses from canals

Canals remain the most commonly used structures for delivery of irrigation water in Africa. But canals are prone to water losses due to damage and poor design, or other reasons. Thus, only portion of the water diverted from a source (river, well) and used for irrigation reaches the root zone of the plants. Some of the water is lost during transport through the canals and in the fields (Figure 2.1). Thus, only a fraction of the water is used efficiently. In canal based irrigation schemes, water losses from the canal are caused by:

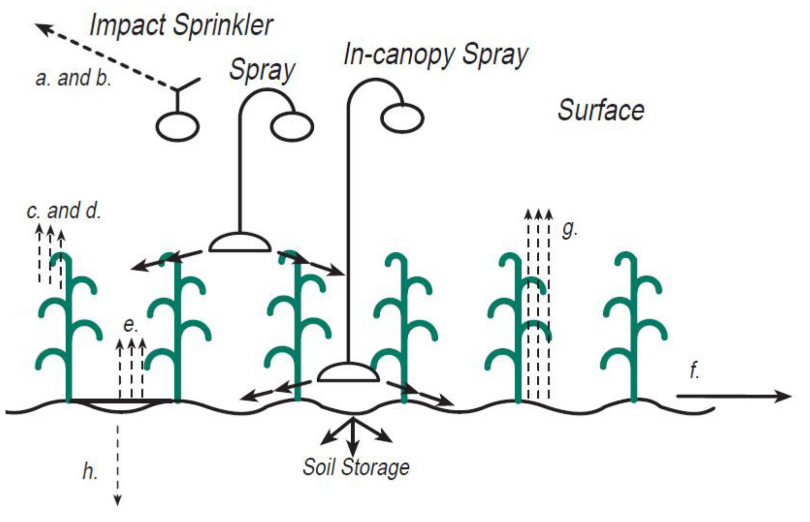
- Evaporation from the water surface
- Deep percolation to soil layers underneath the canals
- Seepage through the bunds of the canals
- Overtopping the bunds
- Bund breaks
- Runoff in the drain
- Rat/mole holes in the canal bunds
- Water uptake by aquatic weeds.

Figure 2.1 (a) Water is lost through poorly maintained canals *(Photos by Bancy Mati)* **(b) Poor land levelling results in improper wetting and water losses**

2.4 Sprinkler irrigation losses

Air losses include drift and droplet evaporation. Air losses can be very large if the sprinkler design or excessive pressure produce a high percentage of very fine droplets. Drift is normally considered to be water particles that are removed from the target area, while droplet evaporation would be the loss of water by evaporation directly from the drop of water while in flight. Direct movement and droplet evaporation vary, but the general estimate of droplet evaporation is small, probably less than 1percent of the output. Total air loss under properly-operating sprinklers and low wind conditions is likely to be in the 1 to 3 percent, although it can have higher values.

Canopy losses include losses due to water held on the plant (foliage interception) and canopy evaporation during the irrigation. Water evaporation from the wetted surface of the plant does reduce transpiration by the plant (Figure 2.2). However, evaporation from a free water surface is faster than transpiration through plant stomata.



Legend

Air losses
a. drift
b. droplet evaporation

Canopy losses
c. canopy evaporation
d. foliage interception

Surface losses
e. surface water evaporation
f. surface runoff
g. soil evaporation

Deep percolation losses
h. deep percolation

Figure 2.2: Irrigation water loss and storage locations
(Source: Rogers at al, 1997)

In sprinkler irrigation, water movement as runoff or redistribution of the surface water, deep percolation, and ground evaporation are usually considered to be negligible. Any runoff from the field or deep percolation would reduce application efficiency by a percentage of the total application amount. Runoff of up to 60 percent of the application amount has been measured for in-canopy sprinkler heads on sloping ground.

2.5 Determining water losses in irrigation

2.4.1 Field water balance

The field water balance in an irrigated system is a key parameter of the efficiency of in-field water management. One of the most critical factors is evapotranspiration (ET), which has great impact on water losses, depending on various complex factors. The methods for calculating potential evapotranspiration (ETp) can be very simple (empirically based), requiring only monthly average temperature data, or very complex, requiring daily data on maximum and minimum temperature, solar radiation, humidity and wind speed, as well as vegetation characteristics (Figure 2.3).
The crop water balance in an irrigated system can be expressed as:

$$\mathbf{P + Irr + Ron = Roff + (E+I+T) + D + \Delta S}$$

Where:
P=Rainfall
Irr= Irrigation
Ron=Run-on from adjacent upslope land
Roff=Runoff from field
E=Evaporation
I=Interception losses
T=Transpiration losses
D=Deep percolation
ΔS= Change in water content in soil during time step
(E+T+I)=Green water flow. Amount of water used for production of biomass.

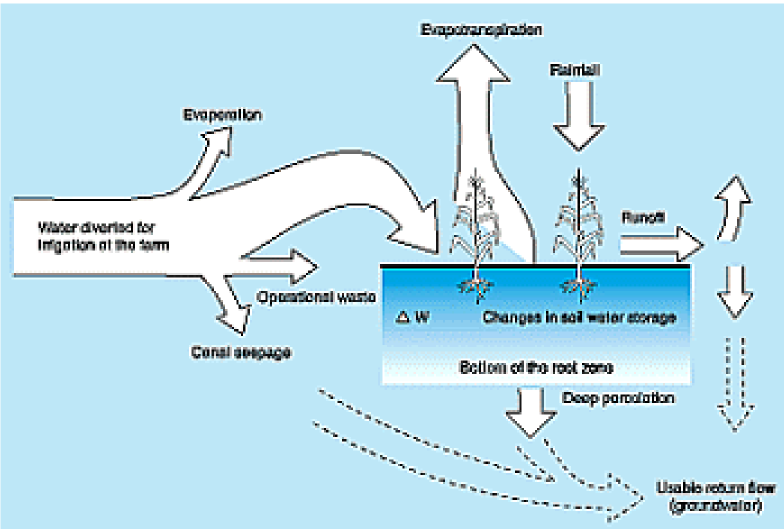


Figure 2.3: Illustration of the water balance of a field

If runoff and direct evaporation of free water are prevented, and if evaporation from the soil surface is minimised and weeds are effectively controlled; and if, furthermore, water is applied in measured quantities commensurate with crop requirements so as to avoid excessive percolation, all the losses can be reduced to less than 20 percent of the water applied. Irrigation efficiency can then attain or even exceed 80 percent.

2.4.2 Agronomic efficiency of water use

The agronomic efficiency of water use (Fag) is an index that depicts the efficiency of water o be converted to biomass. The overall agronomic efficiency of water use is calculated as follows:

$$\mathbf{Fag} = {}^{P}/_{U}$$

Where

P = Crop production (total dry matter or the marketable product, as the case may be), and

U = the total volume of water applied.

As only a fraction of the applied water is actually absorbed and utilised by the crop, it is necessary to consider the various components of the water applied or U, which is calculated as follows:

$$\mathbf{U = R + D + E_p + E_s + T_w + T_c}$$

Where

R = the volume of water lost by runoff from the field,

D = the volume drained below the root zone (deep percolation),

E_p = the volume lost by evaporation during the conveyance and application to the field

E_s = the volume evaporated from the soil surface (mainly between the crop rows),

T_w = the volume transpired by weeds, and

T_c = the volume transpired by the crop.

All these volumes pertain to the same unit area.

Accordingly:

$$\mathbf{Fag = P/(R+D+E_p+E_s+T_w+T_c)}$$

Under surface irrigation, as commonly practiced in smallholder irrigation schemes, excessive water application often results in considerable runoff, evaporation from open water surfaces and transpiration by weeds. These losses commonly amount to 20 percent or even 30 percent of the water applied. In addition, the loss of water due to percolation below the root zone may be of the order of 30 percent or even 40 percent of the water applied. Consequently, the fraction actually taken up by the crop is often below 50 percent and may even be as low as 30 percent. Furthermore, the yield attainable can be greatly enhanced by judicious selection of crops and varieties, optimal fertilization and tillage and proper timing of planting and harvesting. All in all, the agronomic efficiency of water use in irrigated farming can be significantly increased relative to the low efficiency characteristic of traditional practice.

2.4.3 Crop Coefficient

The Crop Coefficient (Kc), is a characteristic of a crop that depicts how much a given crop consumes water, or its evapotranspiration rate. In order to determine the crop water requirement

ETcrop, the reference crop evapotranspiration, ETo, must be multiplied by the crop factor, Kc. The crop factor (or "crop coefficient") varies according to the growth stage of the crop. There are four growth stages to distinguish:

(i) initial stage: when the crop uses little water;

(ii) crop development stage, when the water consumption increases

(iii) mid-season stage, when water consumption reaches a peak;

(iv) late-season stage, when the maturing crop once again requires less water.

Table 2.1 shows the number of days which each crop takes over a given growth stage. However, the length of the different crop stages will vary according to the variety and the climatic conditions where the crop is grown.

Table 2.1: Crop Coefficients (Kc) for grain crops commonly grown in sub-Saharan Africa

Crop	Initial stage	(days)	Crop dev. stage	(days)	Mid-season stage	(days)	Late season	(days)	Season average.
Cotton	0.45	(30)	0.75	(50)	1.15	(55)	0.75	(45)	0.82
Maize	0.40	(20)	0.80	(35)	1.15	(40)	0.70	(30)	0.82
Millet	0.35	(15)	0.70	(25)	1.10	(40)	0.65	(25)	0.79
Sorghum	0.35	(20)	0.75	(30)	1.10	(40)	0.65	(30)	0.78
Grain/small	0.35	(20)	0.75	(30)	1.10	(60)	0.65	(40)	0.78
Legumes	0.45	(15)	0.75	(25)	1.10	(35)	0.50	(15)	0.79
Groundnuts	0.45	(25)	0.75	(35)	1.05	(45)	0.70	(25)	0.79

Source: FAO, 1986

3. AGRONOMIC MANAGEMENT OF IRRIGATED FIELDS

3.1 Maximising crop water use efficiency

To maximise crop water-use efficiency, it is necessary both to conserve water and to promote maximal growth. The former requires minimising losses through runoff, seepage, evaporation and transpiration by weeds. The latter task includes planting high-yielding crops well adapted to the local soil and climate. It also includes optimizing growing conditions by proper timing and performance of planting and harvesting, tillage, fertilization and pest control.

3.1.1 Farming practices that enhance water use efficiency

Raising water-use efficiency requires good farming practices as follows:

(i) Select most suitable and marketable crops and varieties for the region.

(ii) Use optimal timing for planting and harvesting.

(iii) Use optimal tillage (avoid excessive cultivation).

(iv) Practise soil conservation for long-term sustainability (Figure 3.1- a).

(v) Use appropriate insect, pest, parasite and disease control (Figure 3.1- b).

(vi) Apply manures and green manures where possible and fertilize effectively (preferably by injecting the necessary nutrients into the irrigation water).

(vii) Avoid progressive salinisation by monitoring water-table elevation and early signs of salt accumulation, and by appropriate drainage.

(viii) Irrigate at high frequency and in the exact amounts needed to prevent water deficits, taking account of weather conditions and crop growth stage.

Figure 3.1 (a) Irrigation on a slope should be terraced to conserve water *(Photos by B. Mati)*

(b) Pest control of irrigated fields improves water use efficiency

3.1.2 Soil fertility management

The management of soil fertility is of utmost importance to irrigated agriculture. The soil should be capable of providing adequate supply of nutrients in correct proportions, resulting in sustained high crop yields. In addition, a fertile soil has good rooting depth, good aeration and good water holding capacity, adequate amounts of organic matter, the right pH balance and no adverse soil-borne pests and diseases. Soil fertility management is the holistic improvements made to a soil and its ability to produce crops, including water management and weed control. It also includes soil nutrient management, such as adding manure and fertilizers to the soil in the right amounts to provide the required plant nutrients for vigourous crop growth (Figure 3.2). The availability of nutrients (macro and micro) in the soil is one way of achieving water conservation resulting in higher yields and improving water productivity. It also includes addition of fertilizer to supply one or more plant nutrients essential for improving the productivity of crops.

Fertilizers are divided into two groups; are inorganic and organic. In both types, fertilizers typically provide both macro nutrients and micro-nutrients. Macronutrients are the elements consumed in larger quantities and are present in plant tissue. They include: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). Micronutrients, on the other hand are consumed in smaller quantities and are present in plant tissue on the order of parts per million (ppm). They include: boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). These minerals can also be obtained from organic sources through nutrient cycling. Both organic and inorganic fertilizers are needed in irrigated agriculture especially since cropping can be rather intense.

Figure 3.2 (a) Manure application is water conservation *(Photos by B. Mati)* **(b) Fertilizer application to improve water productivity**

3.2 Crop and variety selection

Crops vary considerably in their water demand, drought resistance, drought avoidance, yield levels and economic returns of marketable produce. The choice of crop variety is just as important. For any given crops, there are huge disparities between various cultivars. There are varieties with a short growing season, with high water efficiency, high yielding cultivar, disease resistant ones and so on. Cultivars and ecotypes are selected not only for their water-use efficiency but also for their hardiness and drought resistance and yield levels.

3.2.1 Selecting and managing crops to use water more efficiently

The characteristics to guide the selection of opportune crop types and cultivars for improving water use efficiency in irrigated agriculture can be summarized as:

(i) Crops that grow in hot seasons when evaporation rates high and rainfall is inadequate. These are variously know as drought resistant or drought evading crops. They also require less water for irrigation. Examples include millets, sorghum, certain maize cultivars and various tree crops e.g. mango, papaya, guava.

(ii) Rapid-growing plants, preferably those with low water requirements, as they shorten the time in which water is needed for irrigation e.g. spices like parsley, vegetables like kale and carrots, and various types of African traditional vegetables.

(iii) High-yielding crop varieties that require no appreciable increase in water supply, for example, non-aromatic rice cultivars, various tomato cultivars, beans and vegetables.

(iv) Plants whose leaf morphology inhibits excessive transpiration when there is water stress. For example, pineapple plants close their stomata during the day when evapotranspiration losses are greatest; they consume less water than do plants that open their stomata during the day.

(v) Plants with a high marketable value or huge profit margins should be selected to improve the economic productivity of water (Figure 3.3).

Figure 3.3 (a) Irrigated parsley (a spice), grows quickly, has high market value *(Photos by B. Mati)*

(b) Irrigated carcade (a herb), has high economic value, hence water productivity

3.2.2 Use of drought resistant varieties

Different agronomic adaptation practices are applicable to different farming systems and agro-climatic zones, including drought tolerance for adaptation to climate change. Many research institutions have developed various crop varieties suitable for specific climatic zones. For instance, research institutions have developed crop variety drought-tolerant crops such as maize, sorghum and cowpea, NERICA rice and traditional vegetables. The adoption of direct seeding pre-germinated seed, either by broadcasting or drum seeding, into flooded paddy fields can reduce the crop cycle by 10-45 days. Suitable drought resistant crop varieties can be distinguished by;

- Short-stemmed varieties with limited leaf surface area can minimise transpiration,
- Deep, prolific root systems enhance moisture utilisation, and
- Quick-maturing varieties are important in order that the crop may develop prior to the hottest and driest part of the year and mature before moisture supplies are completely exhausted.

Examples of crop tolerances for various weather conditions are shown in Table 3.1.

Table 3.1: Crops with tolerance to various stresses

Tolerance Characteristics	Crop Type
High temperature tolerance	Cotton, groundnut, chillies, mango
Drought resistance	Millet, barley, chickpeas, sorghum, bullrush millet, gram mung bean, cassava, castor bean, sesame, groundnut (Spanish variety), pigeon peas, sunflower
Lower temperatures	Wheat, potato, sugar, tomato, safflower, carrots, cabbage, kale
Excessive wetting	Rice, cassava, yam
Wide climatic tolerance	Maize, beans, groundnut, sweet potato, sugar cane, papaya, tobacco, banana

3.2.3 Use of high yielding crop varieties

High yielding crops are varieties that have been improved through plant breeding and other scientific methods, such that their production per unit area far exceeds that of the original basic varieties. The seeds and planting stock for most high yielding varieties are available commercially. They carry names such as hybrids and improved varieties. In irrigated agriculture, the use of high yielding varieties is normally recommended so as to achieve optimum productivity of water. The higher the yields, the more improved is the irrigation efficiency. There are many research institutions around the world developing high-yielding crop varieties, of almost all types of crops, including those grown under irrigation. Moreover, introduction of improved crop varieties should consider the local community's eating habits, cultural practices, agro-ecological conditions and markets.

a) Characteristics of high yielding crops varieties

(i) **High yields:** The improved varieties of crops give us more yields per hectare than conventionally obtained under similar climate, soils and management practices.

(i) **Dwarfness:** The high yielding varieties of crops are generally bred to be shorter or dwarf. Due to the short height, their plants are stronger and hence can withstand strong winds. The problem of lodging is less in these improved varieties.

(ii) **Better response to fertilizers:** The high yield varieties of crops give better response to fertilizers. This means that when fertilizers are supplied to high yielding varieties their yield increases substantially. This is not so in case of traditional varieties.

(iii) **Early maturation:** The high yielding varieties take less time for maturing. As a result, some additional crop can be raised in the spare time thus saved.

Limitations of high yielding crop varieties

(i) The high yielding varieties of crops require higher inputs such as more water and more fertilizers as compared to the traditional varieties of crops.

(ii) Being dwarf, the high yielding varieties result in less fodder than the tall, traditional varieties.

(iii) The high yielding varieties need more frequent weeding, or herbicides, as they may be easily choked by local indigenous weeds.

(iv) The high yielding varieties of crops need continuous use of pesticides. This is because they are less resilient against certain local pests.

(v) The high yielding varieties of crops are generally more susceptible to diseases than the traditional varieties.

(vi) Bio-safety concerns especially if new crop varieties cross-pollinate with other crops and wild plants e.g. hybrid sorghum cross-pollinating with wild grasses. This may lead to unsuitable impacts on biodiversity.

3.3 Cover crops

Cover crops are usually creeping legumes which cover the ground surface between widely spaced perennial crops such as fruit trees and coffee, or between rows of grain crops such as maize. Cover crops are popular in rain fed systems to protect the soil from erosion, improve soil fertility and shade the soil from too much heat from the sun. However cover crops can be grown in irrigated agriculture for the same reasons.

3.3.1 Advantages of cover crops

Cover crops make up a fundamental component of soil moisture conservation. They have direct and indirect effects on soil properties as for its capacity to promote an increased biodiversity in the agro-ecosystem. While commercial crops have a market value, cover crops are mainly grown for their effect on soil fertility or as livestock fodder. If well selected varieties are used, cover crops can suppress weeds, reduce high fluctuations in soil temperature and improve soil moisture storage and reduce surface crusting. They also improve soil structure and soil fertility. In regions where smaller amounts of biomass are produced, cover crops are beneficial as they:

- Protect the soil during fallow periods
- Mobilize and recycle nutrients
- Improve the soil structure and break compacted layers and hard pans
- Permit a rotation in a monoculture
- Can be used to control weeds and pests
- improve water infiltration into the soil.

Cover crops can be grown alongside the main crop or during fallow periods, between harvest and planting of commercial crops, to utilise the residual moisture in the soil. Cover crops energize crop production, but they also present some challenges. Since cover crops are grown specifically for the purpose of covering the soil, they are either removed before planting or synchronised with the main commercial crop to achieve a live mulch over the soil surface.

3.3.2 Properties of a good cover crop

Selection of criteria for a good cover crop is one with the following properties:

(i) Suitable to local climatic and soil conditions,

(ii) One which dies not cause serious competition with the herbaceous agricultural crop or a tree crop for water, nutrients or sunshine

(iii) The crop covers the soil surface quickly, and effectively

(iv) Does not transmitt or hosting pests and diseases of the main crop(s),

(v) Crop that contributes to an overall water saving or water productivity of the system.

(vi) Ability to fix nitrogen a form plants and microorganisms can use. Non-legume species recycle existing soil nitrogen and other nutrients and can reduce leaching losses.

(vii) Other economic value of the crop e.g. as livestock fodder.

3.3.3 Management and suitable species

The management practices used influence the value and effectiveness of cover crops to avoid competition with the main crop. The timing of the senescence of the cover crop is critical for productivity of the main crop. The idea is to achieve optimum amounts of live mulch to assure that the soil water conserving properties of the cover crop are maximised. On the other hand, delay in the timing of senescence of the cover crop can have adverse effects on subsequent desired crop. Cover crops should also be selected for other beneficial use, e.g. as animal fodders. There are several cover crops in use: Example of legumes includes; Calopogonium, Canavalia, Centrosema, Crotalaria, Desmodium, Mucuna, Pueraria, Stizolobium. Suitable grass species include: Tripsacum laxum, Pennisetum purpureum and Panicum maximum.

3.4 Polyculture systems

There are many techniques to improve cropping patterns to save moisture. **Polyculture** is a broad term that describes different ways of growing two or more useful plants are grown on the same land. It applies to both rain fed and irrigated agriculture. It is a suitable intervention for diversification of agricultural production in irrigated farming systems because the farmer can apply water simultaneously to different crops and plant sequencing is possible for market targeting. There are various forms of polyculture, such as:

3.4.1 Multiple cropping

Multiple cropping is the growing of more than one crop in the same land in one year. For example, maize may be grown after harvesting peas. Both crops are grown as monoculture crops, but they are planted and harvested within one year.

3.4.2 Mixed cropping

Mixed cropping is the growing of two or more crops simultaneously and intermingled, on the same field within the same growing season. Generally, there may be no rows to mark where each type of crop is located.

3.4.3 Intercropping

Intercropping is the growing of two or more crops in alternate rows, within the same growing season. Intercropping normally adopts a cereal and a legume, for example, maize alternating with bean, for optimum benefit to the soil and to boost diversity.

3.4.4 Relay planting

Relay planting is the practice of inter-planting of the maturing crop with seeds or seedlings of the following crop, such that the last few weeks of the old crop are used for the establishment of the in-coming new crop. Relay intercropping is sometimes designed as **Permaculture,** also known as **permanent soil cover** i.e. a method of land management in which the soil is never allowed to be left bare throughout the year. This means that a new annual crop is planted while an older crop is in the field, just before maturity, thus maintaining a permanent cover over the soil. Permaculture may also be practiced through the use of mulches.

3.4.5 Inter-planting

Inter-planting is the practice of planting a short-term annual crop with a long-term annual or biennial crop (Figure 3.4). For example, or beans under passion fruits or beans can be planted under papaya or citrus fruit trees. In irrigated agriculture, inter-planting is particularly useful as one way on increasing the economic productivity of water.

Figure 3.4 (a) Inter-planting irrigated cabbage with bananas *(Photos by B. Mati)*

(b) Inter-planting irrigated beans with bananas

3.4.6 Inter-culture

Inter-culture is the cultivation of one crop underneath a perennial crop, such as rice under coconut palm (Figure 3.4). This works well if raised beds are constructed. The rice is sown in floodable basins. The palms are planted on the bunds or on the mounds earthed up in the basins. The soil of the mounds is drained and aerated, in contrast to the soil in the bottom of the basins. In this way, the roots of the palms or of other plants are not in danger of being asphyxiated, as they are well aerated.

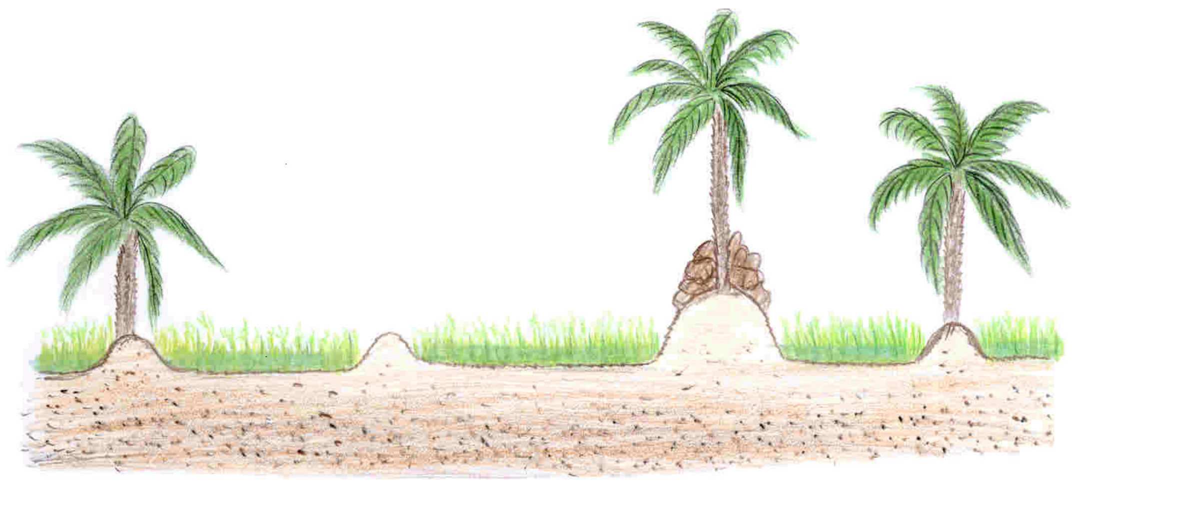


Figure 3.5 Illustration of inter-culture of paddy rice with oil palm trees *(Source: FAO, 2001)*

3.5 Crop diversification

Crop diversification, is the agronomic practice of increasing the number of different crops grown in an irrigated field, or the varieties and hybrids of a particular crop. It involves integration of different varieties of crops, including food and cash crops (figure 3.6). This means that the same water can be used for multiple enterprises, improving both crop and livestock enterprises, thus increasing the economic productivity of water. A shift to growing cash crops with irrigation earns more income, enabling the farmer to invest in upgrading irrigation systems among other interventions. Non-food crops such as bio-fuels present opportunities for crop diversification and increased income, albeit with caution since they compete with food crops for land, nutrients and water. However, there is scant information on the water productivity of bio-fuels vis a vis their economic value.

Fig 3.6 Raised beds growing vegetables in paddy rice fields *(Source: FAO, 2001)*

Crop diversification in a subsistence farming system provides an alternative means of income generation for irrigated agriculture since water is available and the options are numerous. Thus crop intensification, through mixed cropping and integration of high-value crops such as horticultural production, due to ever-increasing demand for food and alternative cropping patterns in response to market forces. All crops, whether "high value" or "low value" have inherent advantages and limitations. Crop diversification attempts to optimise the positive aspects of a given crop, while also making tradeoffs on its disadvantages by having another crop. Thus, crop diversification is planned to broadly encompass both risk averseness and economic gains by combining:

- Crop-livestock-fish-apiculture mixed systems
- High water-use crops with water-saving crops
- Low-value crops with high (economic) value crops
- Low-yielding (necessary) crops with high-yielding crops
- Single cropping to multiple or mixed cropping
- Food crop alongside market-oriented crops
- Crops that provide raw material alongside those which can be locally processed.

At the individual farm scale, the simplest measure of crop diversity is the total number of different crops per farm. Crop diversification acts to reduce susceptibility to unexpected events such as floods, water shortages, market fluctuations or crop failure. At the same time, it increases the number of marketable activities such as adding livestock to a cash crop operation or undertaking value-added processing, and hence serves to reduce farmers' risks.

3.6 Crop rotations

Crop rotation involves growing a different crop each succeeding season on the same field. It is the opposite of mono-cropping, whereby the same crop is grown on the same field season after season. Crop rotation is a beneficial practice which should be encouraged under irrigated agriculture.

Ideally, rotations should include a cereal, a legume, a vegetable, a grass or other crops. More the diversity in the rotations improved the soil condition. Crop rotation has several benefits in irrigated fields such as improved soil fertility, higher gross yields and good soil cover.

Some of the most important crop husbandry practices include:

a) **Soil fertility improvement:** Crop rotations are usually planned with due consideration for inclusion of nitrogen-fixing crop types such as legumes is preferred. The soil fertility is improved in those seasons when a legume is grown. This is taken up by the succeeding cereal crop. Such rotations keep the soil more balanced.

b) **Pest Control**: Crop rotation should leave at least two crop seasons in between the main commercial crop. This helps to drastically reduce build up of pests for most crops. Thus rotation should be of unrelated crop types to avoid viruses, moulds, blights, and selective insect pests tend to build up in the soil which occurs if similar crops are successively planted in the same place, year after year. For instance potato crop should not be used as a rotation with tomato as both suffer from similar pests and diseases. It is thus necessary to choose crop types which do not share pests.

c) **Erosion Control**: Plants which are closely spaced or which produce a thick ground cover tend to resist erosion much better than those which are sparsely spaced. Loss of soil due to erosion in a crop like maize is controlled in the next season when a different, close growing crop e.g. potatoes are grown. If possible, a grass layer should be included in the rotation.

d) **Soil structure.** When related crops are successively planted, specific soil minerals and nutrients are withdrawn faster than they can be replaced by decay or subsoil movement. This selective depletion causes a soil to be "worn out" quickly. Simple rotation of crops makes depletion more uniform so that soils "wear out" more slowly. The planting of deep or thickly rooted plants (such as grasses, sweet potato) tends to improve soil structure and draw subsoil nutrients to the surface like a natural fallow and can increase pasturage during dry periods.

e) **Distribution of labour and risk.** It is generally advisable for the subsistence farmer to grow all crops in the rotation scheme simultaneously, apportioning to each crop the fraction of fields that it requires. This helps the scheduling and distribution of labour at the bottlenecks (planting, harvesting) so that the entire crop need not be done simultaneously. There is also a reduced risk of total crop failure and increased variety/nutrition in the diet.

3.7 Weeding

Weeding refers to the removal of weeds from cropped lands. In irrigated agriculture, this can be done using by uprooting the weeds by hand, as normally done in paddy fields. However, in row crops, the hand hoe, rotary weeders, shallow plough or other implements are often used for the purpose of removing weeds. Sometimes, herbicides are used to kill weeds. Weeds, if left unchecked, result in unproductive evapotranspiration of water taken up by plants which are not useful to the farmer. Removal of such weeds controls wasteful consumptive use of the water.

Advantages of weeding

- Reduces water losses by unnecessary ET of the weeds,
- Removes competition for crop nutrients and solar radiation,
- Reduces choking or blocking by weeds, the water conveyance channels in surface irrigation.

3.8 Mulching

Mulching involves application of a covering layer of material to the soil surface of a cropped field. The material may be natural, such as crop residues, dry grass, threshings and husks, leaves, hedge or tree prunings. Mulching may also utilise inorganic covers such as plastic covers. Mulching provides a barrier between the moist soil and the dry air, thus helping to minimise evaporation from soil profile. It helps to retard the capillary fridge of the upper soil layers to reduce the upward movement of water to the soil surface and thus reduces soil evaporation. Normally, mulching should be supplemented by other measures like fertilizer application for the effect to be more productive. Suitable materials are those which are cheap, locally available, easy to transport and apply, stay in place, do not prevent air reaching the soil or damage useful organisms, act to reduce ET.

3.8.1 Advantages and disadvantages of mulching

Advantages of mulching

- Mulching reduces water loss from the soil, by evaporation as well as by runoff.
- Mulch applied to plants reduces the overall watering needs. This is especially beneficial to newly planted crops or when there are water shortages
- Mulches help to maintain a more moderate and uniform soil temperature. This allows a more uniform germination and crop growth. Together with a better water holding capacity of mulched soil it promotes edaphone (fauna & flora in the soil) development.
- Organic mulches add valuable nutrients to the soil as they decompose.
- Because mulch keeps the soil surface moist, roots will tend to stay closer to the surface.
- Mulch reduces weed incidence in the field, and the few weeds that grow are much easier to remove.

Disadvantages of mulching

- Considerable quantities of material are needed for effective mulching (e.g. 5 tonnes of dry matter/residues per hectare).
- The organic material breaks down rather quickly and has to be replaced rather often.
- The material often has to be transported to the field and needs distribution within the field.
- High labour input needed.
- Competition for organic mulches with other uses such as livestock fodder
- Mulches derived from residues of cereal crops usually "tie up" nitrogen from the soil surface as they decompose. Thus, extra nitrogen fertilizers may be needed when using fresh residues of cereal crops such as maize, rice, wheat or sorghum.
- Organic mulch layer may be a shelter for rats, mice and snakes.

There are various types of mulches suitable for irrigated agriculture as described here below:

3.8.2 Crop residues and straws

The previous season's crop residues can be used as mulch material. The residues are carefully arranged on the soil surface of cultivated fields. In irrigated fields, remnants of vegetables and other farm wastes can be used for mulching. If necessary, the mulch materials e can be out-sourced from outside the field. Grass mulches are particularly useful where there are natural grasses which are cut and taken to the farm as mulches (Figure 3.7). The grass should be dried before applying as this reduces the chance of it rooting.

Figure 3.7 (a) Cabbage mulched with crop residues conserves water *(Photos by B. Mati)*

(b) Irrigated strawberries with straw mulch conserves water

3.8.3 Live mulch

Live mulches (sometimes called green mulch or cover crop) are plants grown specifically to offer surface cover while other more commercial crop is growing. The use of live mulch is encouraged when the selected cover crop is intercropped with the crop of interest for its mulch value. Live mulches are sometimes also termed as green manure because of the ability of the companion legume to fix nitrogen in the soil. Sometimes crops grown as live much are slashed and the residues are used to cover the soil. Alternatively the legume is let to grow as a cover crop. Suitable live mulches include crops such as lablab, pumpkins, water melons and other runner plants.

3.8.4 Stone mulch

In areas where there are enough stones, they can be used to cover the soil as a stone much. Sometimes, sand, pebbles and gravel are also used. Stones, gravel or sand mulches greatly improve water infiltration into soil as well as soil moisture conservation even in layers as thin as 5 - 10 mm. They reduce erosion by wind and water. If the stones are light coloured, they cool the soil, but if dark coloured, they warm it. In the right environment, both can benefit plant growth. The main problem with stone mulches includes the cost of installation, which may require substantial labour. There is also the need to periodically redeposit the material on the surface, and interference with mechanised planting and cultivation

3.8.5 Vertical mulching

Vertical mulching involves placing of organic material, within vertical beds, which can measure about 30- 40 cm deep and 10-12 cm wide. The mulch is deposited in furrows along the contour, at intervals of 5-10 cm and buried within the soil (Figure 3.8). Vertical mulching is primarily done to increase infiltration , decrease evaporation and runoff losses. The small furrow can be opened manually or by using a special plough or augers.

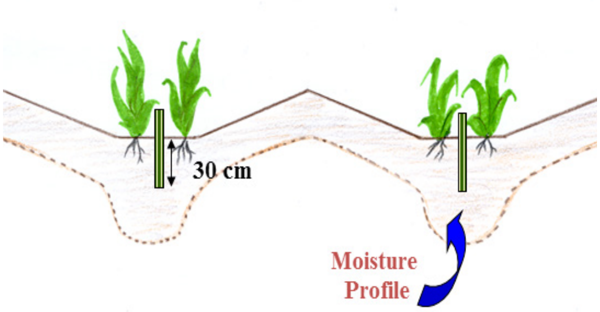


Figure 3.8 (a) Illustration of vertical mulching residues *Source: FAO, 2001*

(b) Vertical mulching of irrigated vegetables *(Photos by B. Mati)*

Vertical mulching provides many benefits, including: slowing water movement; providing open channels for water, penetration into the deep soil; shade and cover for seedlings; and providing a source of below-ground organic matter to help return the soil ecosystem to health. Various types of materials can be used for vertical mulch, including: maize, sorgum or millet stalks, straw, brush and reeds. The best choice for a given site will depend on availability and cost of materials, project demand, and severity of erosion and land stability problems.

3.8.6 Dirt mulching

Dirt mulching is a practice whereby the topsoil is disturbed to improve the water holding capacity of the soil profile under cultivation. It aims at disrupting the soil drying process with tillage techniques that separate the upper layer of the soil from the lower layers, making the soil moisture film discontinuous. In addition, the soil surface is made more receptive to water intake. Principles of dirt mulching:

- Effectiveness increases with increasing depth to a limit of 75 to 100 mm.
- Increasing the dirt mulch depth decreases the available fertile soil.
- The effectiveness of dirt mulches decrease with age. Consequently it must be recreated by shallow tillage of harrowing after each rain or each month,
- The crumb form of dirt mulch (particles greater than 1 mm) is more effective and resists wind erosion more than the dust form.
- Dirt mulches can only be properly made when the soil is moist.
- For a climate with a wet rainy growing season and a hot, windy, dry season, dirt mulching should only be performed during the rainy season and with a growing crop to slow the wind and water and hold the soil.

3.8.7 Plastic mulches

Plastic mulches generally consist of thin sheets of specially made polyethylene or a similar material placed over the ground surface between rows of a crop. Holes are cut into the plastic film at plant spacing to allow the plant vegetation to emerge. Plastic mulches may be tailor made for specific crops, e.g. pineapples, in which case the plastic sheet has holes that correspond to the crop spacing. Sometimes the farmer may create holes in the plastic sheet, or else arrange the covers between crop rows (Figure 3.9).

Plastic mulches substantially reduce the evaporation of water from the soil surface. Associated with the reduction in evaporation is a general increase in transpiration from vegetation caused by the transfer of both sensible and radiative heat from the surface of the plastic cover to adjacent vegetation. The transpiration rates under mulch may increase by an average of 10-30% over the season as compared to using no mulch. Plastic mulches can be transparent, white or black. Colour influences albedo mainly during the early stages of the crop. The soil temperatures under transparent plastic sheets are higher than under black sheets. Opaque or non-transparent plastic mulches are effective in controlling weeds.

Figure 3.9 (a) Laying the plastic mulch before planting the crop *(Source FAO, 2001)*

(b) Plastic mulch with vegetable crop

Advantages of plastic mulches

- Improves soil moisture conservation;
- Plastic mulch prevents heavy weed growth and ensures water conservation
- Reduces labour requirements for weeding, so larger land areas can be managed;
- Reduce soil erosion and soil susceptibility for erosion;
- Enhances light distribution; warms up soil (in cool season);
- Promotes plant establishment and growth, particularly in the initial growth stage.

Major disadvantages of plastic mulch include

- Expensive and not easily available
- Can result in excessive runoff especially from rainfall
- Gas exchange between soil and atmosphere hindered
- Difficult to dispose of – environmental pollution concerns.

3.8.8 Other chemicals mulches

Other hydrocarbon based mulches in use, mostly under desert conditions include latex, asphalt, and oil mulches. They are used primarily to conserve soil moisture, to concentrate water (by creating runoff), and to suppress the movement of wind-driven sand long enough for plants to get established. These mulches have been used commercially to establish vegetation on water-bearing sand dunes in deserts. By retaining the heat absorbed during the day, they can keep desert soils warm during cool nights. This increases the chances of survival for plants whose roots must otherwise withstand large daily temperature fluctuations. However, these are expensive materials and used where the cost warrants the investment.

3.9 Kitchen waste water re-use

Kitchen waste water can be treated and used for supplemental irrigation of small gardens, potted plants including bag gardens. However, kitchen must first be treated as it contains high organic material from the food well as oil and grease, soap and detergents. If these impurities are not removed, they could seal up soil pores, preventing water from infiltrating the soil and resulting in a puddle of gray, smelly, anaerobic and potentially pathogenic water. In the rural setting, kitchen waste water can be put in a drum dedicated for that purpose, and clean ashes added (the ashes should not have contained paraffin). This enables some of the impurities to settle. The water is then drained and passed through a filter. A simple oil and grease trap can be used to remove oils, and the water used to irrigate small gardens.

3.9.1 Vertical (bag) gardens

A vertical garden (bag garden or tower garden), is a garden created by filing a bag with soil with holes drilled on the sides and a crop planted through the holes (Figure 3.10). Vertical gardens come in many shapes and sizes, but mostly they are kitchen gardens, which may utilise kitchen waste water. A typical garden is prepared utilising a recycled jute bag, especially those used in packaging sugar or cereals. Holes are first punched on the bag, about 2 cm in diameter and at a spacing of 0.25 m-0.30 m, starting about 0.15 m from the bottom. The bag is then filled with soil that contains about 20 percent well decomposed manure. A watering shaft is created by placing three posts at the centre of the bag, then packing the space in between with gravel or straw. This shaft acts like a vertical piped sub-irrigation conduit. Vegetable seedlings such as kales, tomato or spinach are planted through the holes as well as at the top of the bag, which is covered with mulch. Depending on bag size and crop type, a plant population of 20-50 is possible. The bag garden is kept in the sunshine and may be placed on a pedestal to keep it out of reach from pests, chicken and other predators. Vertical gardening forms an economical way to grow vegetables on limited spaces, as it utilises air space above the physical limits of the farm. The gardens are suitable for both rural and urban areas, including families living in flats. In addition, pests and diseases are fewer and easier to control. It is a water saving technology as only small amounts of water are needed for irrigation.

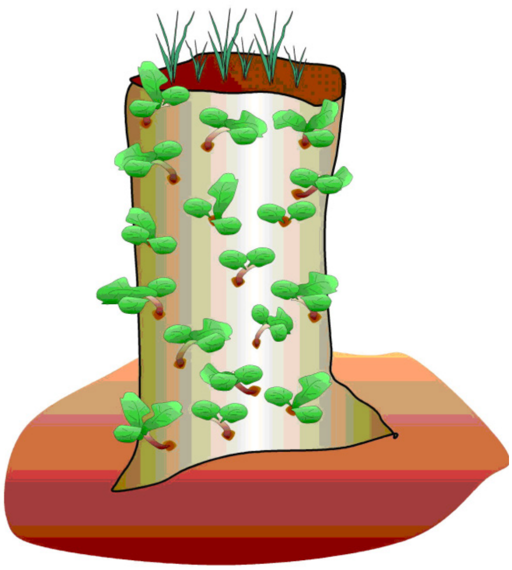


Figure 3.10 (a) Sketch of a vertical (bag) garden	**(b) A vertical bag garden with vegetables** *(photo by B. Mati)*

3.9.2 Key-hole garden

A key-hole garden is a kind of tower garden but made using stones. It is normally used as a kitchen garden to grow vegetables. In construction, stones are packed on each other to create a circular structure, about 1.5 m diameter. The circle contains a small gap enough for a person to walk into the garden, thus giving the structure the shape of a "key hole". Soil is mixed with well composted manure and put in the garden. A watering shaft is created at the centre of the garden by placing posts or twigs in a circle at the centre of the bag, then packing the space in between with gravel or straw. The height of the garden is about 1 m high. Vegetables are grown at the top of the garden. The main advantage is to keep out chicken, domestic animals e.g. goats, and other predictors and certain soil-borne pests. Small quantities of water are added daily to the garden, which may also utilise kitchen waste water.

	
Figure 3.11 (a) Key-hole garden with vegetable crop (*photos by B. Mati*)	**(b) A variation of a vertical garden with home-made drip**

3.10 Precision Agriculture

Precision Agriculture (PA) is "an integrated information- and production-based farming system designed to increase long term, site-specific and whole farm production efficiency, productivity and profitability while minimising unintended impacts on wildlife and the environment". The approach can be used to manage irrigation water and inputs on a site-specific basis such as land preparation for planting, seed, fertilizers and nutrients, and control while reducing waste, increase profits, and maintain environmental quality.

PA involves site-specific agriculture while retaining the economies of scale of farm operations. As such, it accounts for spatial variability in a field on a micro scale. This variability can include soil pH, soil moisture, soil depth, soil type, soil texture, topography, pest populations, nutrient levels, organic matter content, expected yield. Key tools that have catalyzed the development of PA include Global Positioning Systems (GPS), Geographic Information Systems (GIS), yield monitoring and mapping, real-time in-situ soil testing, crop scouting, remote sensing of crop and soil status, real-time weather information, map-based variable-rate technology (VRT), and sensor-based VRT.

One form of PA involves using spectral radiometers that analyse crop colour. These can be mounted directly on fertilizer applicators and used to control variable-rate nitrogen applications. Systems that utilise sensors to assess colour and health of crop plants, as well as variable-rate nutrient applications based on soil management zones and aerial photography, should find success with multiple types of feed stocks.

4. EFFICIENT IRRIGATION WATER MANAGEMENT

4.1 Overview of interventions to conserve irrigation water

There are several water and land management techniques that facilitate the reduction of amount of water used in irrigation, yet achieve optimum crop yields for almost any crop type. These encompass both infrastructural changes as well as water management and conservation practices. Generally, these interventions include;

(i) Reducing water conveyance losses in surface systems, which often exceeds 50% of total water conveyed. The losses are caused primarily by seepage losses and use of water by phreatophytes or aquatic weeds. The simplest way is to line canals. It could also involve converting conveyance system from canals to piped systems.

(ii) Reducing evaporation losses in sprinkler systems. One way is to schedule applications during periods of reduced wind, during high humidity, or irrigation at night. Using drip systems instead of sprinklers, where applicable, also reduces evaporative losses.

(iii) Efficient application of irrigation water - may require converting from wasteful surface methods to more efficient ones, e.g. from basin to furrow, furrow to sprinkler, sprinkler to drip.

(iv) Subsurface drip irrigation systems minimise the amount of water lost due to evaporation and runoff by being buried directly at the crop root zone and applying water directly to the roots, thus keeping the soil surface dry.

(v) Rainfall harvesting, which helps to supplement the water made available by conventional irrigation

(vi) Re-use of irrigation tail waters and reclaimed water can also lead to more efficient agricultural water use.

(vii) Reduction of runoff and percolation losses due to over-irrigation. Such runoff may also cause soil erosion and is also wasteful of nutrients.

(viii) Reduce unnecessary transpiration by weeds, keeping the inter-row strips dry and weed control measures

(ix) Increasing water absorption into the soil. To prevent a crust from forming at the soil surface, by creating a stubble mulch on the surface, making the field as level as possible to enable uniform wetting and infiltration.

(x) Reduce runoff losses from both irrigation and natural rainfall by constructing conservation structures such as terraces, or contour bunds to reduce soil erosion

(xi) All tillage and plantings must run across (or perpendicular to) the slope of the land. Such ridges will impede the downward movement of water.

(xii) Adoption of special irrigation technologies/practices such as system of rice intensification (SRI) or deficit irrigation, which are economical on irrigation water.

4.2 Reducing water conveyance losses

4.2.1 Preventing water losses in canals

Canal seepage varies with the nature of the canal lining; hydraulic conductivity; the hydraulic gradient between the canal and the surrounding land; resistance layer at the canal perimeter; water depth; flow velocity; and sediment load. Thus, canal seepage can be determined using empirically developed formulae or solutions derived from analytical approaches. It can also be estimated on the basis of Table 4.1. Excessive seepage can occur due to poor canal maintenance. Any seepage in excess of the aforementioned figures needs to be regarded as unreasonable. Canals can be made more efficient by regular de-silting or lining with concrete (Figure 4.1)

Table 4.1 Seepage losses from canals based on lining conditions

Types of canal	Seepage losses (%)
Unlined canals	20-30
Lined canals	15-20
Unlined large laterals	15-20
Lined large laterals and unlined small laterals	10-15
Small lined laterals	10
Pipelines	0

Source: FAO, 2002

Figure 4.1 (a) Canal de-silting improves its efficiency *(Photos by B. Mati)* **(b) Concrete lined canal reduces seepage losses**

4.2.2 Replacing canal with piped water conveyance

Another way of reducing conveyance losses is to replace canal based irrigation system with piped water supply, or rather, to design irrigation schemes with piped water conveyance instead of canals (Figure 4.2). Delivering water by pipeline has many advantages over canal systems, as follows:

a) Benefits of water conveyance with pipes

- Water is conveyed with minimum water losses, such as seepage or evaporation. A piped system can achieve 100% conveyance efficiency if well maintained.
- Water is delivered at some pressure, which can be used for sprinkler or drop irrigation, further improving overall efficiency.
- Piped delivery can be delivered across hilly and rugged terrain, and crosses valleys and obstructions easily
- There are no seepage losses, so long as leaks are prevented

- Piped water is cleaner and hence amenable to drip irrigation.
- Pipes can be buried so that they do not physically impeded other infrastructure such as roads, buildings and farming operations.
- Pipe take much less space and thus saving land
- Since water in a pipe is enclosed, it does not pose adverse environmental impacts e.g. mosquito breeding or salinisation as compared to canal conveyance systems.

Figure 4(a) Water delivery using canals has higher losses *(Photos by B. Mati)*   **(b) Piped water delivery is more efficient**

b) Limitations of piped water conveyance

The main limitations associated with pipe water conveyance include:

- o The initial cost can be more expensive than canal excavation.
- o Pipes handle smaller water quantities than canal based systems, and thus, may not be suitable for large irrigation schemes.
- o A higher pressure is needed to move water through pipes, and this could be limiting where water source and irrigated fields are all on level ground.
- o Pipes sometimes corrode and require replacement after some years, while canals can last for centuries.

4.3 Choice of irrigation method

The choice of irrigation method that minimises evaporation (but not transpiration) is likely to increase the efficiency of water utilization by the crop. Thus, micro irrigation or methods that introduce water directly into the root zone without sprinkling the foliage or wetting the entire soil surface are optimum (Figure 4.3). Such partial-area irrigation methods offer the additional benefit of keeping the greater part of the soil surface (between the rows of crop plants) dry. This discourages the growth of weeds, that would otherwise not only compete with crop plants for nutrients and moisture in the root zone and for light above ground, but also hinder field operations and the control of pests.

To improve irrigation efficiency, designing for the most efficient application method is usually recommended. This is ultimately drip irrigation (Figure 4.3). However, drip irrigation may not suit all conditions, hence design should accommodate improvements over conventional surface irrigation methods. This is because field application efficiencies in most traditional irrigation schemes is very low, typically less than 50 percent and often as low as 30 percent. Excessive application of water generally entails losses due to surface runoff from the field as well as to deep percolation below the root zone within the field. Both runoff and deep percolation losses are difficult to control under flood or furrow irrigation, where a large volume of water is applied all at once. They can, however, be minimised if the water application method is changed. For instance, a shift from border irrigation to furrow system can save up to 50% of irrigation water (Figure 4.4).

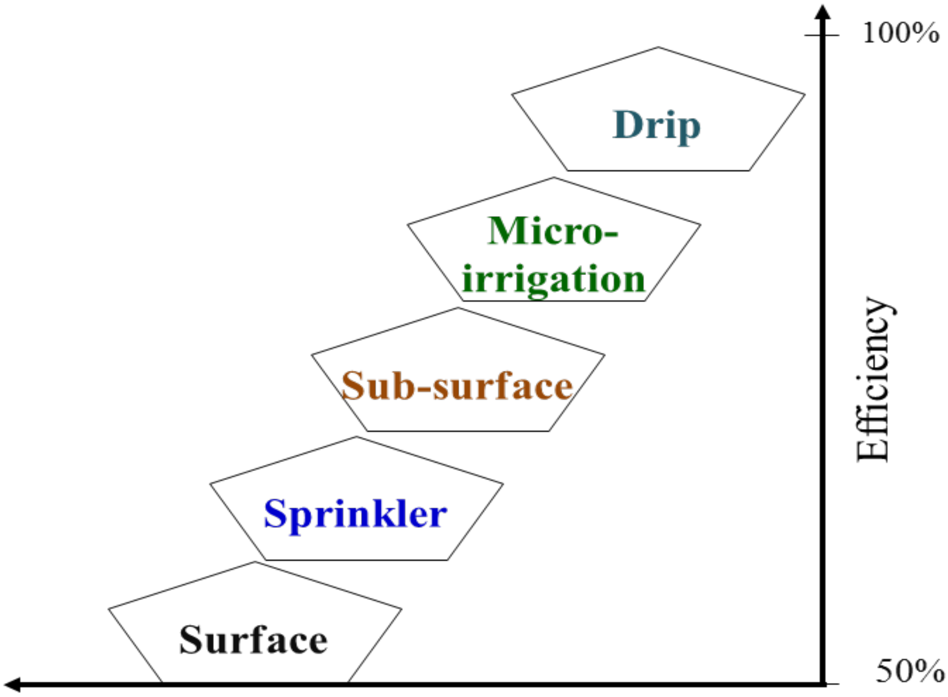


Figure 4.3 The basic irrigation methods arranged according to their average efficiencies *(Source: FAO, 2000)*

Figure 4.4 (a) Surface irrigation uses too much water *(Photos by G. Alemerew)*

(b) Drip irrigation pipes being laid for vegetable crop – optimum water use

Even with the best irrigation practices, however, field application efficiency values cannot attain 100 percent. The aim is not to attain 100% efficiency since a certain fraction of the water applied must be allowed to seep downwards and leach the salts that would otherwise accumulate in the root zone. However, with careful management, field water application efficiency values approaching 90 percent are possible, and values of 80 percent are practicable, by some of the methods described in this publication.

4.4 Improving irrigation scheduling

Irrigation scheduling is the overall plan of how a field is watered, including the timing, quantities and duration of each water application event. It should be organised to replace the water requirement of the crop. Irrigation scheduling has conventionally aimed to achieve an optimum water supply for productivity, with soil water content being maintained close to field capacity.

4.4.1 Applying optimum amounts of water

Irrigation scheduling is based on water balance calculations where the soil moisture status is measured or estimated to determine the need for irrigation. The change in soil moisture over a period is given by the difference between the inputs (irrigation plus precipitation) and the losses (runoff plus drainage plus evapotranspiration). Seasonal crop water requirements of various crop enterprises (Table 4.2) can then be determined to provide and overall basis for the water requirement of an irrigation scheme. Applying the optimum water content, i.e. field capacity for each cop should be done to avoid wasting water.

Table 4.2: Seasonal crop water requirement ranges for selected field crops

Crop	Seasonal crop water requirement (mm/total growing period)
Beans	300 – 500
Citrus	900 – 1200
Cotton	700 – 1300
Groundnut	500 – 700
Maize	500 – 800
Sorghum/millet	450 – 650
Soybean	450 – 700
Sunflower	600 – 1000

Source: FAO, 1986

The actual tissue water potential at any time depends both on the soil moisture status and on the rate of water flow through the plant and the corresponding hydraulic flow resistances between the bulk soil and the appropriate plant tissues. The plant response to a given amount of soil moisture therefore varies as a complex function of evaporative demand, encompassing the crop properties as well as those of the field environment.

4.4.2 **Alternate furrow irrigation**

Alternate furrow irrigation is a method of irrigation water scheduling designed to save water. It involves irrigating alternate furrows rather than every furrow. For instance, instead of irrigating every furrow after 10 days, furrows are irrigated after 5 days and the alternate furrows irrigated within the next 5 days. Thus the crop receives some water every 5 days instead of a large amount every 10 days. Small amounts applied frequently in this way are usually better for the crop than large amounts applied after longer intervals of time. When there is a water shortage, it is possible to limit the amount of irrigation water applied by using alternate furrow irrigation.

4.4.3 Surge irrigation

Surge irrigation involves water application to furrows in small intermittent discharges during irrigation. Due to the reduced stream flow, the method is economical on water. Surge irrigation can therefore reduce water losses because it is implemented through faster furrow advances. To further improve an advance time, large furrows may be used. However, care should be taken to avoid furrow erosion. Rapid advance allows better water distribution efficiency and smaller application amounts, which can reduce deep percolation losses and improve overall irrigation efficiency.

4.4.4 Automated water scheduling

Most modern irrigation systems, especially those running on drip irrigation and commercial farms, have automated irrigation scheduling programmes. Generally, these involve use of electronic sensors in the soil which can detect soil moisture deficits and trigger the opening of valves so that the soil is wetted with just the optimum amount of water needed to attain field capacity. These systems are components of "smart irrigated agriculture" or "precision agriculture", and are operated using computers.

4.5 Supplemental irrigation

Supplemental irrigation (SI) is the application of limited amounts of irrigation water to a crop to supplement natural. The additional amount of water alone is inadequate for crop production. Hence, the essential characteristic of SI is the supplemental nature of rainfall and irrigation. SI is normally considered to be a rain fed method of irrigation, whereby the extra water to top up the rainfall deficit, is normally obtained from rainfall harvesting.

Supplemental irrigation is the opposite of full or conventional irrigation (FI). In the latter, the principal source of moisture is fully controlled irrigation water, and highly variable limited precipitation is only supplementary. SI is dependent on the precipitation of a basic source of water for the crop. In conventional irrigation, it is recommended to adopt supplemental irrigation whenever possible, so as to make use of natural rainfall and to save water (Figure 4.5). Thus, surface runoff and ground water should be reasonably factored into the irrigation water scheduling, to increase the efficiency by using all available water resources.

4.5.1 Conditions that favor supplemental irrigation

SI in areas with limited water resources is based on the following three premises:

- Water is applied to a rain fed crop which would normally produce some yield without irrigation.
- Since precipitation is the principal source of moisture for rain fed crops, SI is only applied when precipitation fails to provide essential moisture for improved and stabilized production.
- The amount and timing of SI are not scheduled to provide moisture-stress-free conditions throughout the growing season, but to ensure that the minimum amount of water required for optimal yield is available during the critical stages of crop growth.

4.5.2 Sources of water for supplemental irrigation

Water for supplemental irrigation comes mainly from surface sources, the principal source being rainfall especially obtained through rainwater harvesting. However, shallow groundwater aquifers increasingly are being used. Other non-conventional water resources that have potential for SI include such as treated sewage are also important. Low quality waters, including slightly saline water, can be tapped appropriately and cleaned, and can also be used for supplemental irrigation. In an irrigation scheme utilising canal conveyance system, the same canals can be used for channelling excess rainfall runoff for storage in impoundment structures or other areas for infiltration into the soil. In irrigated fields dependent on water extracted from shallow wells, rainfall runoff can be channelled to recharge shallow water aquifers/water tables, thus increasing the amount of water available for irrigation during the dry season, under supplemental irrigation..

Figure 4.5 (a) Supplemental irrigation of maize using shallow well *(Photos by B. Mati)* **(b) Supplemental irrigation using harvested rainwater**

4.6 Subsurface irrigation

Subsurface irrigation involves watering the plant from within the subsoil either through deep ditches or burred pipe. The buried pipe minimises the amount of water wasted in irrigation as it is not exposed to evaporation and runoff. Also, water is applied directly to the roots, thus keeping the soil surface dry.

4.6.1 Buried pipe irrigation

Sub-surface irrigation (or sub-irrigation), is a method of irrigation in which water is applied beneath the ground to minimise evaporation and percolation losses, in arid and semi arid areas. This is done by creating and maintaining an artificial water table at some depth, usually 30 to 75 cm, below the ground surface. Water is introduced into soil profile through open ditches, mole drains, tile drains or perforated buried pipes. Subsurface irrigation with clay pipes involves burying porous clay pipes in the ground and supplying water to pipes so that it seeps into the soil and root zone (Figure 4.6). Optimising the performance of porous clay pipe subsurface irrigation requires the development of guidelines and design criteria for system management and installation. Once installed, water is delivered using plastic piping and a crop grown over the surface. The water is sucked by the plant roots as the moisture then moves upwards towards the land surface by capillary action to meet the crop roots.

(a) **The clay pipes before installation** (b) **Installation of clay pipes in trenches**

	
(c) Water diversion into buried clay pipes	(d) A crop is grown over the buried pipes
Figure 4.6 Preparation of buried clay pipes for subsurface irrigation of vegetables *(Source: Siyal and Skaggs, 2000)*	

4.6.2 Pitcher irrigation

Pitcher (buried porous clay pot) irrigation is an adaptation of traditional drip in which a buried porous clay pot is buried adjacent a growing tree crop. Water is put in the pot, from where it seeps out slowly due to the pressure gradient across the wall of the pitcher, created by the plant roots. Depending on porosity of the pot and the soil characteristics, a pot holding about 10 litres of water can support a fruit tree for about a month. A framer can apply water to one or two pots per day where water is very limiting, and this method can establish trees with very little water. Using pitcher irrigation is recommended for plants/trees with deeper roots. The water in the pot is kept at a depth of 20-30 cm (Figure 4.7). The roots penetrate in depth, in search of moisture. The top of the pitcher pot can be glazed to make the surface impermeable, in which case the water oozes only through the lower walls.

		
Figure 4.7 (a) Illustration of pitcher pot irrigation	(b) **Watering a buried pot,**	**(c) Crops grown around buried pot** *(Source: http://www.continentaldrift.net)*

a) **Benefits of pitcher pot irrigation**

- Pitcher pots are up to 10 times more efficient than watering plants from above with a watering can or bucket and because less water is needed it is more feasible to do with a rainwater catchment system and a cistern as water source. In Mexico, it has enabled farmers to grow two crops of maize in a year, where before they could grow only one
- It works well with transplants or direct seeding, and helps improve seed germination and establishment even in very hot, dry conditions
- It's less work for the farmer. There will be less water to fetch and carry, and less weeding to do because the water in the pot is given to the crop, not to weeds. Using buried clay pot irrigation with a treadle pump attached to a hosepipe makes for further labour savings

- It is good for the soil structure. Because water is not poured on to the soil, the seedbed stays loose and plenty of air can circulate
- Soil amendments like manure, compost or inorganic fertilizer can be placed where they will help the crop and not the weeds.
- It's cheaper and more reliable than many high tech drip irrigation systems, which are more likely to be clogged up by insects or damaged by animals and usually require flat fields. The whole system can be made with locally available materials and skills, and doesn't need a
- pump to work. As long as the farmer keeps checking the pots, the system cannot fail.
- It's good for business. The people who make the pots can sell more pots and lids.

b) **Limitations of pitcher pots**

- The pots may need to be moved if the soil is to be tilled. During installation or removal, they must be handled with care to avoid breakage during installation or removal
- The buried clay pots may clog up over time, especially if left dry for a long time. If this happens, they need to be removed from the soil and scrubbed, or soaked, or refired to clean out the pores
- The clay mixture, firing time and temperature and choice of clay need to be right to be sure that the pot is porous enough for this method. Fortunately, it is easy to test pots and refine the mixture and firing times
- If silty muddy water is used, it blocks the tiny holes in the clay pot and stop it from working as well
- The system does not work very well with some types of clay soils, but mixing sand and/or organic matter in to the soil when "planting" next to the clay pots can help make it work.

4.6.3 Vertical pipe irrigation

Vertical pipe irrigation is a simple method of subsurface irrigation suitable for arid and semi-arid zones and which is adaptable by smallholder farmers. The system comprises an open vertical pipe driven into the soil within the root zones of a tree crop. The pipe has inlets at the base of each tree crop. A gravel-pocket is packed around the vertical pipe outlet to enhance water release to the soil. Water is replenished directly through the vertical pie (Figure 4.8). It is an efficient sub-surface irrigation method for tree crop. Subsurface irrigation has been discussed in greater detail in Training Manual 7 of these series.

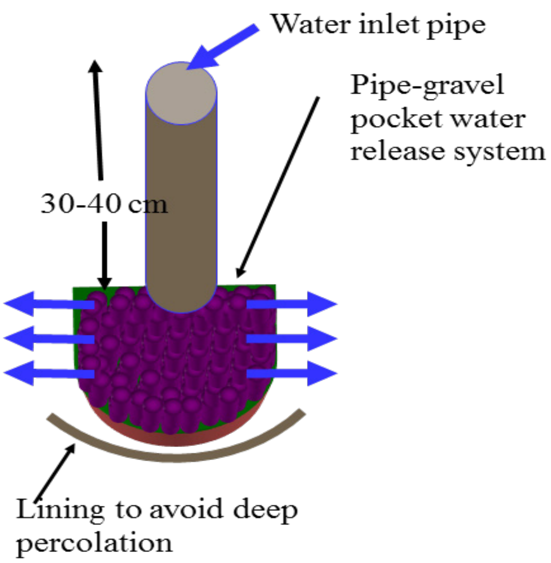


Figure 4.8 (a) Sketch illustrating a vertical pipe irrigation system *(Source FAO, 2000)*	(b) Vertical pipe sub-surface irrigation *(Photo: Prinz , 2001)*

4.7 Micro-irrigation systems

Micro-irrigation systems are those which apply in small quantities either directly to the plant or in the vicinity of the plant. The most commonly used methods include micro-sprinklers and drip irrigation methods. Generally, micro-irrigation utilises less water than conventional sprinkler irrigation. There are many variations of micro-irrigation kits and these have been discussed in Training Manual 7 of these series. However, due to the importance of drip irrigation as a water saving technology, it is mentioned here more tacitly.

4.7.1 Mini sprinklers

A mini sprinkler (sometimes called micro-sprinkler) irrigation system is a variation of conventional sprinkler system, whereby water is applied to smaller or localized cropped areas using mini sprinklers or spray jets. Thus, smaller quantities of water are applied and the diameter of wetting is smaller. Mini sprinklers utilise lower operating pressures and are capable of higher uniformity coefficient. These systems are suited to irrigation of widely spaced tree crops as they can irrigate just the tree root zone and avoid wetting unnecessary spaces between the trees. Mini sprinklers are also used for irrigation of seasonal crops like vegetables, onions, potato and nurseries. The working parts are usually made of engineering plastic and they can be available in different connection options. Compact design for easy installation, riser can be used to increase the height up to 1.50 m. They help to save water by irrigating only the necessary cropped area.

4.7.2 Drip irrigation

Drip or trickle irrigation involves applying water in the form of small droplets to each plant, usually from a lateral pipe fitted with drip emitters. It is characterized low flow rate, long duration irrigation, frequent irrigation, water applied near or into plant's root zone, and low-pressure delivery systems. Drip irrigation has high efficiency rates (Figure 4.9) as much as 95%. Drip irrigation in particular, holds promise as a very good option increasing water-use efficiency, reducing labour requirements and improving harvests in both quality and quantity. It is best suited for horticultural crops, especially high-value vegetables and fruits. Drip irrigation has been discussed in greater detail in Training Manual 7 of these series.

Figure 4.9 (a) Drip irrigation of beans and maize in the open field *(Photos by B. Mati)* **(b) Drip irrigation of potted tomatoes within green house**

4.7.3 Deep placement subsurface drip kit

The deep placement subsurface drip kit is a technology bearing the trade name Irrigasc, developed for desert agriculture to stimulate deep rooting and help fight desertification. The technology is mainly used for tree establishment in semi-arid zones. It works by encouraging tree roots to grow downwards vertically, to seek water through hydrotropism, thus encouraging deep rooting of the tree. Fully irrigated roots can go 50 cm deep –the limit between a dry infertile soil and a wet soil, favourable soil for crop growth.

In design, Irrigasc comprises a small, 1 litre polypropylene bucket attached to a 1 metre-long polyethylene shaft (Figure 4.10). The Irrigasc system is introduced into the soil with an auger and the ground and covered with soil. Once the system is buried in the ground, 1 litre of water is poured into the plastic container three times a week. The water percolates through thin orifices at the base of the polythene tube, creating a wet bulb at the base. This wetness attracts the tree roots downwards, making them grow longer and deeper into the soil. After about two years, the tree root system should have reached at least 50 cm deep and the plant can be left to grow autonomously without the need for watering. The deeper tree roots access water better and make the plant more resilient against dry spells.

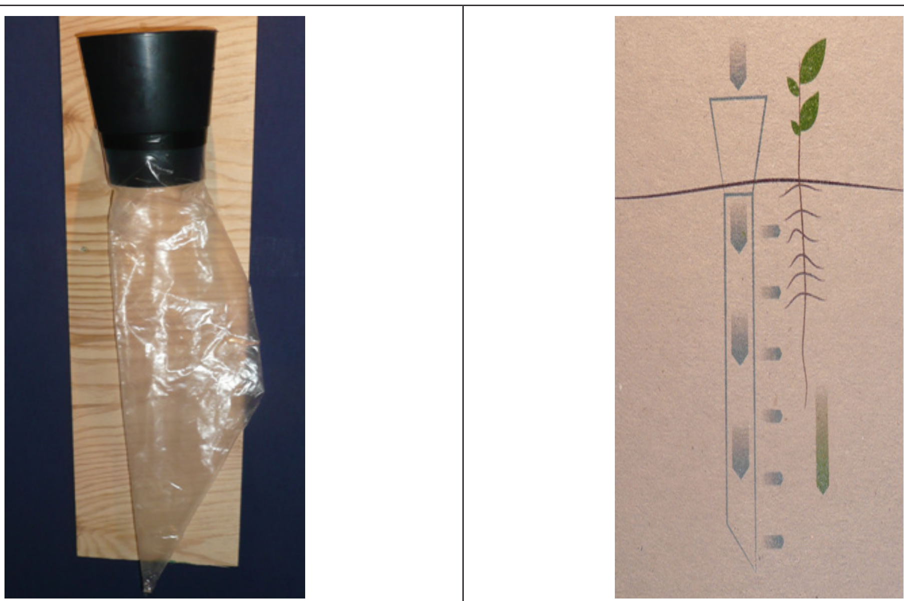


Figure 4.10 (a) Irrigasc micro irrigation drip kit before installation	(b) Illustration of Irrigasc deep placement micro irrigation system

4.8 Greenhouse farming

A greenhouse (also called a glasshouse) is a building in which plants are grown. They are framed or inflated structures covered with transparent or translucent material large enough to grow crops under partial or fully controlled environmental conditions to get optimum growth and productivity. A greenhouse may be constructed using different types of covering materials, such as a glass or plastic roof and walls; with structures which range in size from small sheds to very large buildings. Commercial greenhouses are often high-tech production facilities containing other equipment such as screening installations, heating, cooling, lighting, and may be automatically controlled by a computer.

4.8.1 Functions of a greenhouse

A greenhouse functions by heating up because incoming visible solar radiation (for which the glass is transparent) from the sun is absorbed by plants, soil, and air inside the building. The warmer air as well as the structures and plants inside the greenhouse re-radiate some of their thermal energy in the infrared spectrum, to which glass is partly opaque, so some of this energy is also trapped inside the glasshouse. However, this latter process is a minor player compared with the former (convective) process. Thus, the primary heating mechanism of a greenhouse is convection. Greenhouse farming is suited to cultivation of high value crops, particularly horticulture.

4.8.2 Benefits of greenhouse farming

Growing crops under greenhouses has many advantages, among them the ability to produce huge quantities on a small piece of land and continuous harvesting. For instance, it takes a shorter period e.g. two months for greenhouse-produced tomatoes to mature, compared to a minimum of three months in the field. Due to controlled irrigation and temperatures, greenhouse crops can have a continuous output of flowers and fruits, all at different stages thus providing production for longer periods. Other benefits of using greenhouses include:

(i) Crop yields can be increased by up to 10-12 times higher than from field cultivation depending on the type of greenhouse, type of crop, environmental control facilities and management.

(ii) Conserves water by reducing evaporation losses

(iii) Easier control of water scheduling and management

(iv) Useful in controlling the stability of plant ecological system

(v) Reliability of crop yield increases due to controlled environment

(vi) Year round production of horticultural crops.

(vii) Off-season production of vegetable and fruit crops.

(viii) Reduction of pest and disease infestation

(ix) Efficient utilisation of fertilizers, pesticides and other additives

(x) Production of quality produce free of blemishes.

(xi) Modern techniques of Hydroponic (soil-less agriculture), aeroponics and nutrient film techniques are possible only under greenhouse cultivation.

4.8.3 Classification of greenhouses

Greenhouse structures can be of various types, designed to meet the specific needs. Thus, greenhouses can classified based on shape, utility, material and construction details as follows:

a) Greenhouse type based on construction details

The type of construction predominantly is influenced by structural material, although the covering material is also a factor. The higher the span, the stronger should be the material used as well as a large number of structural members to achieve a strong structure (Figure 4.11). For smaller spans, simple designs like hoops can be followed. Therefore, depending on construction, greenhouses can be classified as:

(i) Wooden framed structure.

(ii) Pipe framed structure.

(iii) Truss framed structure.

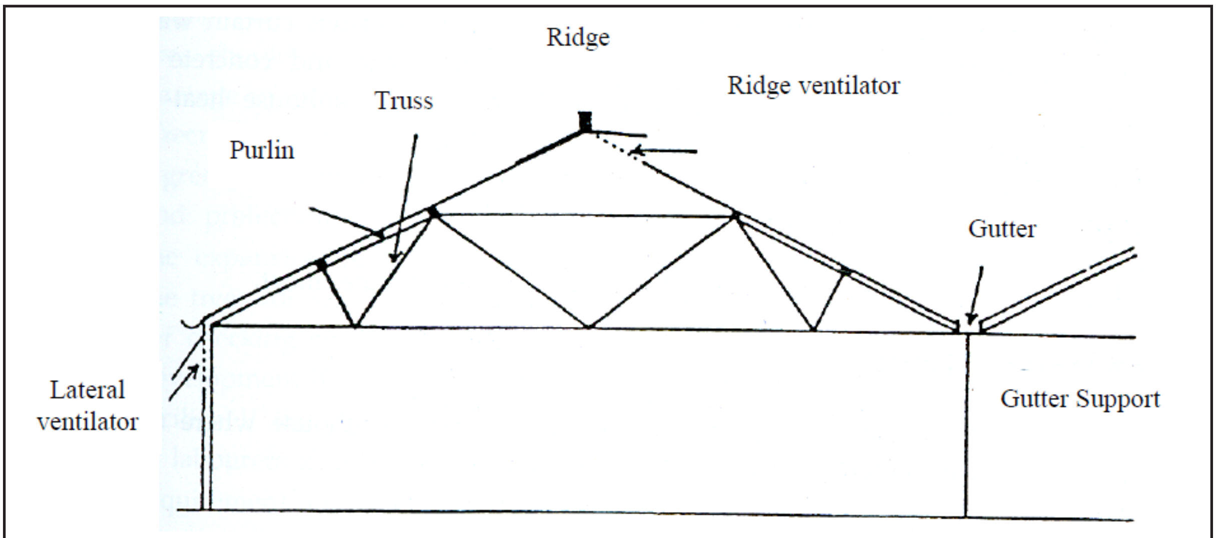


Figure 4.11 Basic components of a typical greenhouse

b) Greenhouse type based on shape

The uniqueness of cross sectional shape of a greenhouse can vary considerably, based on material used, air flow arrangements and preferences of the user. The commonly followed shapes of greenhouses include (See Figure 4.12):

(i) Lean to type greenhouse.

(ii) Even span type greenhouse.

(iii) Uneven span type greenhouse.

(iv) Ridge and furrow type.

(v) Saw tooth type.

(vi) Quonset greenhouse.

(vii) Interlocking ridges and furrow type Quonset greenhouse.

(viii) Ground to ground greenhouse.

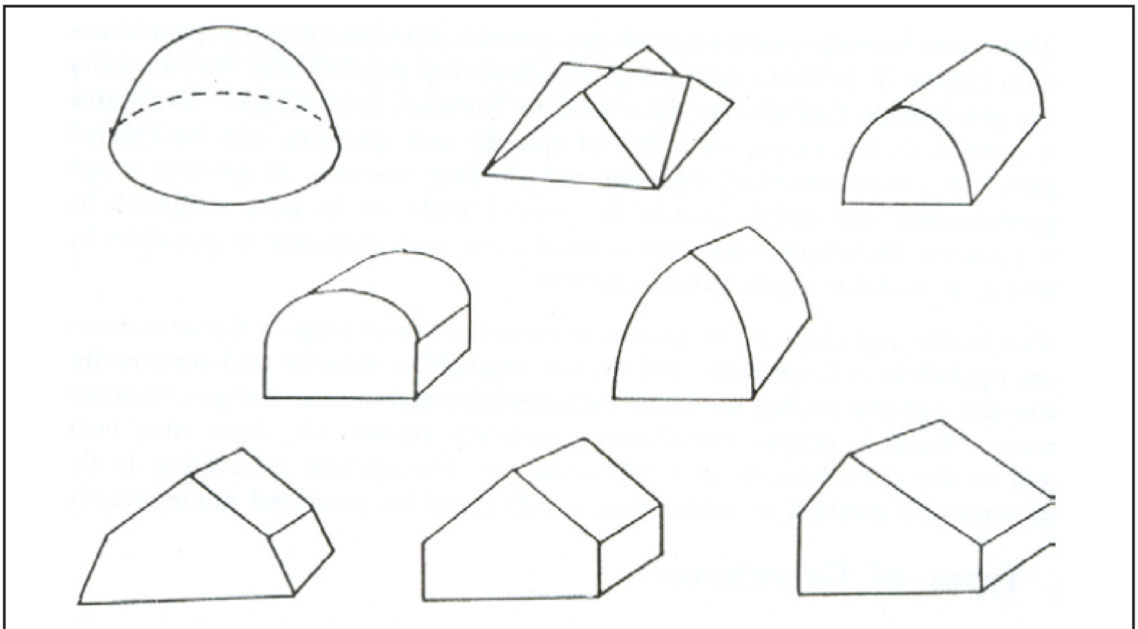


Figure 4.12 Different shapes of greenhouses

c) Greenhouse type based on utility

Greenhouses can be constructed to serve different functions or utilities. The most common utility includes artificial heating or cooling, and these types can be more expensive and elaborate. In this classification are to two types.

(i) Greenhouses for active heating.

(ii) Greenhouses for active cooling.

d) Greenhouse type based on covering material

Covering materials used in greenhouses are the most important component of its functionality. They have direct influence on greenhouse effect, i.e. the extra heating achieved inside the structure, by affecting the air temperature inside. The types of frames and method of fixing also varies with covering material. Based on type of covering material, greenhouses may be classified as:

- Glass glazing.
- Fibre glass reinforced plastic (FRP) glazing

i. Plain sheet

ii. Corrugated sheet.

- Plastic film

i. UV stabilized LDPE film.
ii. Silpaulin type sheet.
iii. Net house.

e) Greenhouse type based on cost of construction

The cost of construction of a greenhouse is affected by the other factors mentioned above e.g. construction material glazing or size. However, based on cost and sophistication, greenhouses can be classified as:

(i) High cost greenhouse

(ii) Medium cost greenhouse, and

(iii) Low cost greenhouse.

Generally, local weather conditions and individual necessities play a major role in the selection of a given greenhouse type.

Figure 4.13 (a) Commercially manufactured medium-cost green house (*photos by B. Mati*) **(b) Low-cost green house made locally (in Kenya) using available materials**

4.8.4 Greenhouse farming in smallholder agriculture

Until recently, greenhouse farming was considered the preserve of large commercial farms and "hobby farming" requiring high capital investments beyond the reach of smallholder African farmers. However, this perception is changing as more affordable greenhouses can be purchased or locally made by smallholder farmers. However, greenhouse farming is still expensive by local standards, but made profitable when used to grow high value marketed crops. Under optimal growing conditions, vegetables and fruits can produce up to ten times more than rain fed conditions. This is one of the reasons making greenhouses popular among smallholder farmers. Greenhouse farming is particularly amenable to conditions of water scarcity, i.e. farmers lacking enough quantities of irrigation water, e.g. those using shallow wells or rainwater harvesting with small storages such as tanks and ponds.

Some smallholder farmers adopt simple, locally constructed structures or purchase commercially made greenhouses (Figure xxx) through credit schemes. Most of the commercially available greenhouses come along as complete "kits" which include accessories such as pumps, filters, drip irrigation equipment and supply tank raised about 2 m above the ground. Some of the commercially available green houses for smallholder use measure about 6 m by 12m to 8 m by 60 m. Construction works for the greenhouses require experienced and technically qualified personnel. Most smallholder greenhouses incorporate a low-head drip irrigation system using water from different sources. Farmers training and technical support are usually included to enable proper utilisation and management of the greenhouse, and the produce grown therein.

4.9 Other methods of reducing evaporation losses

There are many other ways to reduce unproductive evaporation of irrigation water. They range from agronomic methods (discussed in Chapter 3), to management of the watering regime, e.g. applying irrigation water at night on when temperatures are low, as well as irrigation scheduling. More importantly, the choice of water application method, whether drip or furrow, has great implications on the water available for direct evaporation. Apart from green houses, other methods include shelterbelts and shade nets.

4.9.1 Shade nets

Shade nets are fine nets usually purchased from agro-dealers and used for covering nursery beds of various crops. But shade nets can be used to reduce water losses in smallholder irrigation of high value crops, such as strawberries, sugar snaps, chillies and other vegetables. Shade net covers reduce direct solar radiation on the soil as well as wind, thereby conserving water otherwise lost in unproductive evaporation. The main limitation with shade nets is their high costs. Also, although they can protect the crop from large predators e.g. birds, they do not offer adequate protection from very small insects and diseases. Otherwise, combined with drip irrigation, shade nets provide a major water-saving intervention for irrigated agriculture.

4.9.2 Shelterbelts

Water losses by evaporation are greatly affected by strong winds over an irrigated field. This can be curtailed substantially by reducing the wind speeds. This may involve erecting windbreaks or shelter belts of trees or shrubs, to reduce wind speeds and cast shadows which can reduce evaporation by about 10 to 30 percent by itself. The shelterbelts are also effective against wind erosion during the dry season. Sometimes, shelterbelts are made using shade nets and other commercially available materials. In some cases, the field may be fenced, further helping to break the wind speed and reduce evaporation of irrigation water (Figure 4.14).

Figure 4.14 (a) Shade net garden before planting *(photos by B. Mati)*

(b) Shelter belt of trees across the wind direction, protecting irrigated artemisia

5. DEFICIT IRRIGATION

5.1 What is deficit irrigation?

Deficit irrigation (regulated deficit irrigation or drought irrigation), is a method of irrigation in which the amount of water used is kept *below* the maximum level and the minor stress that develops has minimal effects on the yield. Generally, the crop is subjected to a certain level of water stress, either during a particular period in its growth stages or throughout the whole growing season, so as to save water. It is one way of maximising water use efficiency/ water productivity. In times of water shortage or drought, deficit irrigation can bring about higher economic gains in comparison to maximising yields per unit water for a given crop.

5.1.1 How deficit irrigation functions

Deficit irrigation is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop. Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water. Water restriction is limited to drought-tolerant phenological stages, often the vegetative stages and the late ripening period. Total irrigation application is therefore not proportional to irrigation requirements throughout the crop cycle. This inevitably results in plant drought stress and consequently in production loss. However, it is expected that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. Thus, deficit irrigation aims at stabilizing yields and at obtaining maximum crop water productivity rather than maximum yields. Generally, a 25 percent deficit, can result in water use efficiency about 1.2 times that achieved under normal irrigation practices. Irrigation scheduling based on deficit irrigation requires careful evaluation to ensure enhanced efficiency of use of scarce irrigation water.

5.1.2 Why deficit irrigation works

Deficit irrigation works as a result of:

(i) Reduction in water losses by unproductive evaporation,

(ii) Increased proportion of marketable yield since the water saved can irrigate a larger area,

(iii) By increasing the proportion of total yield production due to hardening of the crop - although this effect is limited due to the conservative relationship between biomass production and crop transpiration,

(iv) Due to accrued benefits of less water in the soil such as concentration of fertilizers at the root zone, and,

(v) By avoiding unnecessary wetness during crop growth and thus reduction in water logging in the root zone, pests and diseases.

5.1.3 Advantages of deficit irrigation

The correct application of deficit irrigation has several advantages. They include:

- Deficit irrigation is a water-saving technology – less water is used in irrigation
- It allows economic planning and stable income due to a stabilization of the harvest in comparison with rain fed cultivation;
- decreases the risk of certain diseases linked to high humidity (e.g. fungi) in comparison with full irrigation;
- Reduces nutrient loss by leaching of the root zone, which results in better groundwater

quality and lower fertilizer needs as for cultivation under full irrigation;

- Improves control over the planting date and length of the growing period which can be independent from the onset of the rainy season, thus improving agricultural planning.
- Deficit irrigation hardens plants making them more drought resistant
- The quality of harvested crop is enhanced, e.g. higher concentration of crude proteins, less spotting and wholesome colours and flavors of produce.

5.1.4 Limitations of deficit irrigation

A number of limitations can be faced when applying deficit irrigation:

- For certain crops where crops are sensitive to drought stress throughout the complete season, such as maize, the application of deficit irrigation can result in a lower water use efficiency and poor yields.
- Since less irrigation is applied, the risk for soil salinisation is higher under deficit irrigation as compared to full irrigation
- A very good understanding of the actual crop response to water stress is necessary, but sometimes such information requires a lot of scientific verification.
- A minimum quantity of water should be guaranteed for the crop, below which deficit irrigation may have no significant beneficial effect.
- There should be sufficient flexibility in access to water during periods of high demand i.e. during the drought sensitive stages of a crop.
- In group based irrigation schemes, deficit irrigation works if practiced by all the farmers in a synchronised manner. However, that may be difficult to implement where farmers grow diverse crops.

5.2 Conditions favouring deficit irrigation

The management of deficit irrigation requires a good knowledge of the weather, available water supplies and the crop water use properties. This makes it possible to determine the level of allowable water deficiency that would not significantly reduce crop yields. The main objective is to increase the WUE of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

5.2.1 Crop types suited to deficit irrigation

Before implementing a deficit irrigation programme, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season High-yielding are more sensitive to water stress than low-yielding varieties. For instance, deficit irrigation had a more adverse effect on the yields of hybrid crop varieties than on those of traditional varieties. Crops or crop varieties that are most suitable for deficit irrigation are those with a short growing season and are tolerant of drought (Figure 5.1). These include; cotton, maize, wheat, sunflower, potato, common bean, soybean, groundnut and sugar cane. Deficit irrigation may involve certain changes in agronomic practices, such as wider crop spacing, application of less fertilizer, flexible planting dates and selection of shorter-duration crop varieties.

Figure 5.1 (a) Soya beans under deficit irrigation *(Photo by B. Mati)* **(b) Deficit irrigation of vegetables** *(Photo by N. Lusaka)*

5.2.2 Crop growth stages applicable for deficit irrigation

Crops have certain phenological phases in which they are tolerant to water stress. Thus, the timing of when to impose deficit irrigation during the crop season is just as important as the selection of crop type and variety. Certain field crops such as cotton, maize, wheat, sunflower, sugar beet and potato are well suited for deficit irrigation applied either throughout the growing season or at pre-determined growth stages. For example, deficit irrigation imposed during flowering and boll formation stages in cotton, during vegetative growth of soybean, flowering and grain filling stages of wheat, vegetative and yielding stages of sunflower provide minimal and acceptable yield reductions yet using smaller quantities of irrigation water.

In certain cases, deficit irrigation works better if it is imposed early in the crop growth stages. It has been observed that inducing an artificial "drought" through deficit irrigation earlier in the crop season causes the plants to physiologically adapt to a stressful drought environment, hardening them. This makes the plants better able to cope with drought that may occur later in the growing season. Deficit irrigation may be implemented together with conservation tillage as this has been found to greatly reduce crop water requirement.

5.2.3 Soils suited to deficit irrigation

In order to ensure successful deficit irrigation, it is necessary to consider the water retention capacity of the soil. In sandy soils plants may undergo water stress quickly under deficit irrigation, whereas plants in deep fine textured soils may have ample time to adjust to low soil water matric pressure, and may remain unaffected by low soil water content. Therefore, deficit irrigation is more suitable on clay soils and finely textured soils such as loams.

5.3 Water scheduling for deficit irrigation

The proper application of deficit irrigation practices can generate significant savings in irrigation water allocation. But deficit irrigation is allowable in situations where the reduction in yields is related to actual yields obtained with deficit irrigation by the following equation:

$$^{Y}/_{Y_m} = 1 - k_y[1- (^{ET_a}/_{ET_m})]$$

Where:

Y = Yield under deficit irrigation

Y_m = Maximum crop yield with full irrigation

ET_a = Actual evapotranspiration under deficit irrigation

ET_m, = Maximum evapotranspiration assuming full irrigation

k_y = A crop yield response factor that varies depending on species, variety, irrigation method and management, and growth stage when deficit evapotranspiration is imposed.

The crop yield response factor gives an indication of whether the crop is tolerant to water stress. A response factor greater than unity indicates that the expected relative yield decrease for a given evapotranspiration deficit is proportionately greater than the relative decrease in evapotranspiration. For example, soybean yield decreases proportionately more where evapotranspiration deficiency takes place during flowering and pod development rather than during vegetative growth. The crop water use efficiency (WUE) is related to crop yields by the following equation:

$$\boxed{E_c = \frac{Y}{ET_a}}$$

where:

E_c = Crop water use efficiency

Y = Crop yield (kg/ha)

ET_a = Actual evapotranspiration (mm)

The crop response factors and the probable increases in irrigation WUE, corresponding to a 25 percent relative evapotranspiration deficit for major field crops are summarized in Table 5.1. Under the defined conditions, the relative yield decrease is proportionately less than the decreased application of irrigation water.

When the planned ET deficit is imposed throughout the season, the total irrigation water saved can be determined from the total crop water requirement. However, if the stress is imposed during a specific growth stage, it becomes necessary to determine the total water requirement (i.e. crop water consumption) during that stage to quantify the water saved. As crop yield response factor (k_y) increases, the field WUE decreases, which in turn implies that benefit from deficit irrigation is unlikely.

Table 5.1 Relative yield and water use efficiencies for a deficit irrigation of 25 percent

Crop	Stage when ET deficit occurred	k_y	Irrigation method	Expected relative yield	Relative water use efficiency
Common bean	Vegetative; Yield formation	0.57 0.87	Furrow	0.86 0.78	1.14 1.04
Cotton	Whole season; Boll formation and flowering	0.86 0.48	Drip Furrow	0.79 0.88	1.05 1.17
Groundnut	Flowering	0.74	Furrow	0.82	1.09
Maize	Whole season	0.74	Sprinkler	0.82	1.09
Potato	Whole season; Vegetative	0.83 0.40	Drip Furrow	0.79 0.90	1.06 1.20
Soybean	Vegetative	0.58	Furrow	0.86	1.14
Sugar beet	Whole season; Mid-season	0.86 0.64	Furrow	0.79 0.84	1.05 1.12
Sugar cane	Tillering	0.40	Furrow	0.90	1.20
Sunflower	Whole season; Vegetative yielding	0.91 0.83	Furrow	0.77 0.79	1.03 1.06
Wheat	Whole season; Flowering and grain filling	0.76 0.39	Sprinkler Basin	0.81 0.90	1.08 1.20

Source: FAO, 1979

5.4 Impacts of deficit irrigation

Deficit irrigation enables more efficient water utilisation, and when combined with a selection of the more water efficient crops, net gain can be greatly increased. In most crops, drought tolerance varies significantly between different species, and even within a species, based on the cultivar. Most plant responses to water stress have adverse effects on crop growth and productivity, but some plants also have complex systems that help them survive water scarcity. Some crops have certain levels of drought tolerance or resistance, whereas others have mechanisms of compensatory growth that alleviate water stress. While the greatest crop productivity is obtained under optimal water supply and high soil fertility, many crops can adapt to water stress during periods of water shortage and will produce a high yield with less water.

6. SYSTEM OF RICE INTENSIFICATION (SRI)

6.1 What is SRI?

The System of Rice Intensification (SRI) is a set of practices that change the management of plants, soil, water and nutrients used in growing irrigated rice in order to improve the water productivity and yields of rice. The practices under SRI are innovative in that they differ from the conventional way of growing rice in continuously flooded paddies. In other words, SRI is a package of practices especially developed to improve the productivity of rice grown in paddies. Unlike the conventional method of continuous flooding of paddy fields, SRI involves intermittent wetting and drying of paddies as well as specific soil and agronomic management practices. SRI can be adapted for growing rice in rain fed systems as well as other crops.

6.1.1 What SRI is not

SRI is not a new type of rice. It is not a variety and nor does it modify the genetic make-up of rice. SRI is not about growing upland rice varieties, albeit they too can adopt SRI practice. SRI is also not about growing rice in lines without all the other practices. SRI is not a technology. It is a set of practices.

6.2 Key practices under SRI

SRI is most easily visualised in terms of certain practices that are recommended to farmers for trying out on their own rice fields to improve the productivity of their rice crop. These practices are based upon important insights and principles that constitute SRI. SRI recommendations change what are often age-old methods for growing irrigated rice. This means that even though the practices are simple, they may not be readily adopted. It is important always to emphasize the reasons for making changes in practice: to promote bigger, healthier root systems that support larger, more productive plants that grow in more fertile soil systems. The practices discussed below which are recommended for SRI are in effect the 'signature' of SRI. The specific operational practices can be stated as follows:

a) **Land preparation**

The land preparation for SRI follows the same process as that of conventional paddy. It starts with primary tillage using a tractor, animal drought or hand hoe. This is followed by flooding the field for at least a week, harrowing and rotavation using whatever means is available to ensure clods are broken. The paddy field is then subjected to proper levelling and addition of organic fertilizers. SRI works well with properly levelled fields so that water management can be effective during the wetting and drying phases.

b) **Nursery preparation**

SRI seedlings are raised in un-flooded nurseries, which may be made on the paddy field or at home. The seeds should not be densely planted and are well-supplied with organic matter. There is an option of direct-seeding, but transplanting is most common.

c) **Seedlings age at transplanting**

Transplant young seedlings (Figure 6.1), preferably 8 - 12 days, while still at the 2–3 leaf stage, certainly within 15 days of nursery sowing, before the start of the 4th phyllochron of growth. Transplant quickly, within 30 min of gently removing seedlings from their nursery, and carefully and shallow (1–2 cm), taking care to have minimum trauma to roots, not inverting plant root tips upward which delays resumption of growth.

(a) **Conventional flooded nursery**

(b) **SRI dry nursery**

(c) **Transplanting conventional rice seedlings**

(d) **Transplanting SRI young seedling**

Figure 6.1 Comparing conventional paddy nursery with SRI Practice *(Photos by B. Mati)*

d) Plant population in the field

Transplant just one seedling per hill. This gives each rice plant space to have more sunshine as well as better rooting, which further stimulates a thriving tillering process, stronger stems and leaf development. Rice is a tillering plant and the larger number of tillers from a single seedling produce more grain.

e) Crop spacing

The crop is transplanted with wider spacing and in a square pattern. The wider spacing enables plants to get increased exposure to sunlight, air and nutrients, allowing profuse growth of roots and canopies. These in turn produce stronger stalks and more tillers. The spacing varies with crop variety and climate, but as a starting point, a 25 x 25 cm can be recommended as a typical square planting distance for SRI. This spacing allows easier use of rotary weeder, and is relatively wide enough compared to conventional practice. However, crop spacing should be determined through experimentation to achieve the optimum spacing for highest yields for local conditions.

f) Water application

Water application under SRI adopts a cyclic "wetting and drying" system. Only a minimum amount of water is applied during the crop vegetative growth stage. Do not continuously flood the soil (Figure 6.2). This is because soil saturation causes plant roots to degenerate and suppresses soil organisms that require oxygen. Instead watering can be organised as application of small amounts of water daily, to keep soil moist but not saturated. It may also be organised as a full ponding of the paddy field till the crop root zone is completely wetted, then allowing the field to dry out for about 6-10 days without irrigation, before the next water application. Irrigation scheduling depends on soil type and profile characteristics, climate and water availability. The idea is to ensure the soil is mostly aerobic and not saturated. This concept has been scientifically proven to allow plant roots to grow more profusely due to presence of more oxygen in the soil, leading to effective nutrient uptake, which in turn results to healthier plants. The drying and wetting cycles continue till panicle initiation. After panicle initiation, maintain just a thin layer of water, 1–2 cm, until 15 days before harvest, when the field should be drained, for the rice to ripen and harden for harvesting.

(a) **Conventional flooded paddy- wastes water**

(b) **SRI Intermittent wetting and drying**

(c) **Women weeding conventional paddy field**

(d) **Rotary weeding of SRI paddy field**

Figure 6.2 Comparing field management practices *(Photos by B. Mati)*

g) **Weed control**

To control weeds, use of a mechanical rotary weeder (rotary hoe or cono weeder) is recommended. This churns up the soil surface and buries young weeds. It also helps aerate the soil. Other benefits of rotary weeding have been cited as root renewal due to root trimming that inadvertently occurs when the crop is being weeded. Weeding should start 10–12 days after transplanting, to pre-emptively curb weed growth and to aerate and fertilize the soil, and should be done several times before the canopy closes.

h) **Soil fertility management**

The above SRI methods should be accompanied by use of organic fertilizers, by applying compost, mulch, manure, wherever possible. This is because organic fertilizers have other beneficial effects such as improving water holding capacity and long term sustainability of soil fertility of the soil. If organic manures are not available, conventional inorganic fertilizers at the normal recommendation rates should be used. SRI is not necessarily an "organic" cultivation system. Thus, chemical fertilizers can be used with SRI, but the best results have come with organic soil amendments.

6.2.1 Other beneficial practices

The SRI practices discussed above are mutually reinforcing. They nurture the growth of roots and canopies (leaves and tillers), and they reinforce each other through better nutrient acquisition and photosynthesis. There are a number of other practices that are beneficial when used together with any cultivation methods and thus complement SRI practices, including:

(i) **Land levelling**: Soil should be well worked and well-levelled so that there is good soil structure, and plant roots can grow easily. Correct levelling helps farmers to achieve uniform wetting of their soil through irrigation with a minimum application of water.

(ii) **Varietal selection**: Choose a variety, improved or traditional, that is well-suited to local conditions (soil, climate, drainage, etc.), being resistant to anticipated problems like pests or irregular water supply, and having desired grain characteristics.

(iii) **Seed selection:** Only the best seed, with good density and formation, should be used. Submerging the seed in a pail of water, with enough salt dissolved in it to make a salt solution in which an egg will float, enables farmers to separate and discard any light and inferior seeds as these will float. Just use the good seeds that sink to the pail's bottom.

(iv) **Seed priming:** This practice of soaking seed before planting has been found to enhance the rate of germination and seedling emergence.

(v) **Nursery solarisation:** Where there are soil health problems, such as fungal pathogens or root-feeding nematodes, it will be beneficial to cover the nursery for seedlings for 2-8 weeks before sowing with clear plastic in order to raise the soil temperature by as much as 10°C. This can eliminate many organisms that have adverse impacts on young seedlings. It will enable the nursery to produce seedlings with greater health and vigour and this will improve subsequent crop performance.

(vi) **General care of the field and crop -** Other agronomic practices should be adhered to such as ensuring the field is clean and the crop is protected against pests and diseases. At panicle initiation, the field is flooded continuously till grain filling and senescence starts. At maturation of the grains, the field is drain as usual to allow rice to dry before harvesting. Harvesting, threshing and milling follow conventional practice.

6.3 Advantages and limitations of SRI

6.3.1 Advantages of SRI

(i) SRI gives higher yields - more tons of rice per hectare. Depending on variety and management, rice yields can increase by as little as 15 percent to as much as double or triple yields compared to conventional flooded paddy.

(ii) The method promote the growth of more productive and robust plants

(iii) SRI saves water, using about 25-50% less water than under conventional paddy, hence improving the water productivity of rice (Figure 6.3).

(iv) SRI uses less seed, which can be less than 25 % of seed used under conventional paddy cultivation. This is because the wider spacing and single seedling require minimal nursery.

(v) SRI enables the farmer to save on fertilizer, by using about 40-50% less fertilizer than conventional paddy. This is because placement fertilizer against each plant is possible using the lines, and the wider spacing means there are fewer plants per unit area.

(vi) SRI makes use of what the farmer has, as it may not be necessary to purchase any extra external inputs or new seeds.

(vii) SRI ensures more water is available to more farmers and other beneficial use

(viii) SRI is a form of deficit irrigation whereby water is saved which can be used for irrigation elsewhere.

(ix) SRI works with almost all rice varieties, albeit some varieties respond better than others.
(x) A better quality of grain is obtained, which has stronger aroma due to concretion of aromatics as a result of reduced flooding during crop growth.
(xi) SRI rice grain is harder, and thus does not easily break during milling.
(xii) SRI rice is heavier when compared per volume basis with conventional paddy rice.
(xiii) SRI rice plants have a stronger stem and plant vigour, and are not easily logged in case of flooding or excessive wind speeds.
(xiv) Because the rice is grown in lines (square pattern), mechanised weeding and harvesting is made possible/easier as compared to conventional methods.

Figure 6.3(a) SRI yields more rice **(b) SRI grain quality is better**
(Photos by B. Mati)

6.3.2 Limitations of SRI

(i) Increased incidence of weeds – due to the drying phases of the practice, normal non-aquatic weeds invade the paddy and these can be a distraction

(ii) Handling of the young seedlings at 8 days old requires care as they can be easily destroyed.

(iii) In very heavy clay soils, drying the paddy to requisite moisture contents at transplanting makes it difficult to work the soil.

(iv) Sometimes, it is no easy to weed a heavy clay soil unless thoroughly wetted, thus losing some of the benefit of incorporating air in the soil during weeding.

6.3 SRI is a methodology

SRI is referred to as a *system* or as a *methodology*, a system of practices based on a coherent set of concepts and principles that produce desired results. SRI is not a '*technology*' because this term implies something that is *fixed and final*, something to be used as instructed -- rather than as something still evolving and improving, season by season, as more experience is gained and as more farmers, scientists and others apply their intelligence and insights to making rice production more efficient and sustainable. Indeed, it has been suggested that SRI stands for '**System of Rice Improvement**." SRI, is still a work in progress.

SRI methods are particularly accessible to and beneficial for poor and smallholder farmers, who need to get the maximum benefit from their limited land, labour, water and capital. Although there is an added demand on labour, especially for weeding, this labour is made effectively more productive due to higher yields. Some farmers have reported reduced labour under SRI, especially when rotary weeding is introduced. Also, transplanting may require less labour depending on how it s organised.

SRI concepts and practices can be adapted and used with any scale of production, from small-scale to large-scale farms, whether manually operated to mechanised farming. In an unprecedented way, SRI methods raise the productivity of land, of labour, of water and of capital all at the same time. SRI's higher productivity is making more rice available, at better grain quality, with prospectively lower prices and with widely distributed benefits.

6.4 System of crop intensification (SCI)

The system of crop intensification (SCI), is an adaptation of the practices perfected under SRI to other crops. SCI is also inclusive of SRI. These practices when applied to other crops yield similar advantages. SCI works particularly well when applied to small grain crops and vegetables. Each crop is grown differently, but carrying certain core practices under SRI/SCI, such as wider spacing, single seedling per hill, raising seedlings in nurseries even for crops like sugarcane and maize, planting very young seedlings and organic fertilization. The crops under SCI practice include, but are not limited to the following:

(i) Wheat – System of wheat intensification (SWI)
(ii) Teff – System of teff intensification (STI)
(iii) Sugarcane – System of sugar intensification (SSI)
(iv) Finger millet - System of finger millet intensification (SFI)
(v) Maize - System of maize intensification (SMI)
(vi) Vegetables - System of vegetable intensification (SSI).

Much of the work on SCI is still under experimentation, but the innovation is spreading, to cover more farmlands and to include more crops.

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